DESIGN AND DYNAMIC ANALYSIS OF KINETIC ENERGY RECOVERY SYSTEM FOR TOYOTA HILUX 4X4

BY

Fitsum Tadesse

A Thesis submitted to

The Department of Mechanical Systems and Vehicle Engineering School of Mechanical, Chemical and Materials Engineering

Presented in partial fulfillment of the requirement for the degree of Master of Science in Automotive Engineering

Adama Science and Technology University

ADAMA (ETHIOPIA)

June, 2019

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APPROVAL SHEET

APPROVED BY THE EXAMINERS BOARD

We, the undersigned, members of the Board of Examiners of the final open defense by Fitsum Tadesse Soramo have read and evaluated his thesis entitled " Design and Dynamic analysis of Kinetic Energy Recovery System for Toyota Hilux 4x4" and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master of Science in Automotive Engineering.

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Internal examiner	Signature	Date
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External examiner	Signature	Date

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the thesis entitled ‘Design and Dynamic analysis of the Kinetic Energy Recovery System for Toyota hilux 4x4 in partial fulfillment of the requirements for the award of the degree of Master of Science in Automotive Engineering is an authentic record of my own work carried out from October 2018 to June 2019 under the supervision of Mr. Mekonnen Liben (Asst. Prof.) Department of Mechanical System and vehicle Engineering, Adama Science and Technology University, Ethiopia.

The matter embodied in this thesis has not been submitted by me for the award of any other degree or diploma. All relevant resources of information used in this thesis have been duly acknowledged.

Name	Signature	Date
Fitsum Tadesse	____________________	_________________
(Candidate)		

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief. This thesis has been submitted for examination with my approval.

Name	Signature	Date
Mr. Mekonnen Liben (Asst. Prof)	____________________	_____________
(Advisor)		

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ABSTRACT

In the present scenario, energy crisis is one of the major challenges to the existing world. The fossil-fuel resources are being depleted at a tremendous rate due to their disproportionate consumption. This has put forth the widespread assumption that if resources are being used at current rate, the time is no longer when all our resources will expire. Thus, there is a need to develop the technology that saves the energy from getting wasted. Traditionally, regenerative braking with the ability to generate energy has been promising but the amount of energy saved is highly insignificant. A considerable amount of energy, which is generated by the engine, is lost while braking even in case of regenerative braking. The regenerative braking involves direct conversion of the Kinetic energy to Electrical Energy; however, a promising alternative is present while storing the Kinetic Energy of the vehicle in the form of Mechanical Energy of a rotating cylindrical flywheel. This thesis states the advantages of storing the Kinetic Energy of the Vehicle in Mechanical form rather than direct conversion for the design of this kinetic energy storing device some calculation are done for the vehicle at different resistance load, torque, speed and calculation for selection of the planetary gear, design of flat spiral spring are considered and also using solid work software some parts of the system are designed. By taking the velocity of the vehicle from 8.34m/sec to 27.8 the kinetic energy loss of the vehicle is increasing with the increase of velocity but efficiency of the kinetic energy recovery system will decrease. Braking the Vehicle with velocity of 8.34m/sec has 219KJ of kinetic energy loss and energy stored by flat spiral spring is 201.4KJ and the system is 91.9% and can save 0.00464L of fuel from 0.005L which will be consumed at 8.34m/sec. But vehicle moving at 27.8m/sec the kinetic energy loss is 2434.4KJ and the stored energy is 201.4KJ and the kinetic energy recovery system is 8.3%. So using of flat spiral spring kinetic energy recovery is effective and recommendable for vehicle which has high stop and go times.

Keywords: planetary gear, kinetic energy recovery, flat spiral spring, vehicle brake

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LIST OF ACRONYMS

KERS	Kinetic Energy Recovery System
ICEs	Internal Combustion Engine System
HEV	Hydraulic Electric Vehicle
EV	Electric Vehicle
RBS	Regenerative Braking System
BHP	Brake horse power
Kmph	Kilo meter per hour
GRi	Gear Ratio gear box
GRfd	Final drive gear ratio
CVT	Constant Variable Transmission
Nm	Newton Meter
Ft	Traction force
PHRBV	Parallel Hydraulic Regenerative Brake Vehicle
BLDC	Brush Less Direct Current
RBLA	Regenerative Brake and Launch Assist
CG	Center of Gravity

SYMBOLS

F_t	Traction force [N]
F_i	Inertial force[N]
F_s	Road slope force [N]
F_r	Road load force [N]
F_a	Aerodynamic drag force[N]
T_e	Engine torque [Nm]
i_x	Transmission gear ratio
i_0	Final drive ratio
η_d	Driveline efficiency
r_{wd}	Dynamic wheel radius
m_v	Total vehicle mass[kg]
a_v	Vehicle acceleration [m/s^2]
f_m	Mass factor
m_{cv}	Curb vehicle mass[kg]
m_d	Driver mass[m]
g	Gravitational acceleration[m/s^2]
α_s	Road slope angle[rad]
μ	Friction coefficient
c_l	Rear axle load coefficient
ρ	Air density [kg/m^3]
c_d	Air drag coefficient
A	Vehicle frontal area [m^2]
v	Vehicle speed[m/s]
C_r	Road load coefficient

CHAPTER ONE

INTRODUCTION

This chapter consists of the background of the study, statement of the problem, objectives, significance of the study, Beneficiaries, delimitation of the study, and organization of the study.

1.1. Background

Kinetic energy recovery systems are a collection of parts which takes some of the kinetic energy of a vehicle under deceleration, stores this energy and then releases this stored energy back into the drive train of the vehicle, providing a power boost to that vehicle. For the driver, it is like having two power sources at his disposal, one of the power sources is the engine while the other is the stored kinetic energy. KERS store energy when the vehicle is braking and return it when accelerating. During braking, energy is wasted because kinetic energy is mostly converted into heat energy or sometimes sound energy that is dissipated into the environment. Vehicles with KERS are able to harness some of this kinetic energy and in doing so will assist in braking. By a proper mechanism, this stored energy is converted back into kinetic energy giving the vehicle extra boost of power. There are two basic types of KERS systems i.e. Electrical and Mechanical. The main difference between them is in the way they convert the energy and how that energy is stored within the vehicle. Battery-based electric KERS systems require a number of energy conversions each with corresponding efficiency losses. On reapplication of the energy to the driveline, the global energy conversion efficiency was 31–34%. The mechanical KERS system storing energy mechanically in a rotating flywheel eliminates the various energy conversions and provides a global energy conversion efficiency exceeding 70%, more than twice the efficiency of an electric system [15].

Kinetic Energy Recovery System is related to the flywheel energy system that is generally used in a sports vehicle. The concept of this system is to store the energy that is lost in any other form and then again use this stored energy whenever required. Various Kinetic Energy Recovery Systems differ from each other as a result of different storing element used. The below-discussed KERS system makes use of Flat Spiral Spring as an energy storing element and planetary gear system for transmission of power to and from the spring to the shaft.

1.2. Statement of the problem

Both fuel economy and high performance are the two most important demands for modern automobile buyers and manufacturers. When braking the vehicle there is a loss of kinetic energy in the form of heat. Braking is one of the key features of the vehicle which implies producing force that opposes the motion of the wheel, thereby reducing vehicle's speed or bringing it to a halt. When the brakes are applied, hydraulic pressure actuates in the master cylinder as a result of which brake pads under pressure rub against the surface of a rotor. Thus, the friction comes into play and kinetic energy of the rotor and eventually wheel gets hampered. In this process, kinetic energy gets converted into heat energy which is dissipated to the surroundings. The total amount of energy lost in this process depends on how often, how hard and for how long the brakes are applied. Conventional methods use friction brakes for retarding the vehicle which is a total loss of momentum of the vehicle. Braking the Vehicle with velocity of 8.34m/sec has 219KJ of kinetic energy loss and energy stored by flat spiral spring is 201.4KJ and the system is 91.9% and can save 0.00464L of fuel 0.005L which will be consumed at 8.34m/sec. so to minimize the total loss of energy, the flat spiral spring energy recovery has to be design for Toyota Hilux 4x4.

1.3. Objectives

1.3.1. General Objective

The general objective of this thesis is to design and simulate the kinetic energy recovery system which helped to store the lost energy and reuse it for Toyota Hilux 4x4

1.3.2. Specific Objectives

The specific objectives were:

- ❖ To prepare the part and assembly drawing of the system using solid work software
- ❖ To analyze dynamic analysis of the main design parameters

1.4. Significance of the thesis

The significance of the proposed thesis work is the following

- ➢ Reduce the loss of kinetic energy of the vehicle during breaking so that it will be reused.

- Ability to be installed with not much modification in an existing vehicle transmission system.
- Simple structure kinetic energy storage
- Maintenance cost is low because it has no electrical parts

1.5. Beneficiaries

Automotive industries, vehicle owners, researchers, society and country as a whole get benefited with this work.

1.6. Delimitation (Scope)

The research undertaken in this project focused on specifically on Toyota Hilux 4x4 vehicles powered by ICEs. The scope of the thesis is to design and simulate the mechanical parts of the kinetic energy recovery system and to show the saved energy that the system will save. There will be a limitation on the scope to ensure that the project is both manageable and through in the time period.

1.7. Organization of the study

The thesis will be organized with the following chapters.

Chapter one: Introduction

Chapter two: Literature review

Chapter three: Material and Methods

Chapter four: Result and Discussion

Chapter five: Conclusion and Recommendation

CHAPTER TWO

LITERATURE REVIEW

This chapter consists of introduction to braking and regenerative system, review of previous art, Modes of kinetic energy recovery, working principle of the kinetic energy recovery system, Flat Spiral Spring, Basic components of the brake system

2.1. Introduction

Braking is one of the key features of the vehicle which implies producing force that opposes the motion of the wheel, thereby reducing vehicle's speed or bringing it to a halt. When the brakes are applied, hydraulic pressure actuates in the master cylinder as a result of which brake pads under pressure rub against the surface of a rotor. Thus, the friction comes into play and kinetic energy of the rotor and eventually wheel gets hampered. In this process, kinetic energy gets converted into heat energy which is dissipated to the surroundings. Hence, a part of the energy extracted from the engine gets wasted and further energy is required to accelerate the vehicle [1].

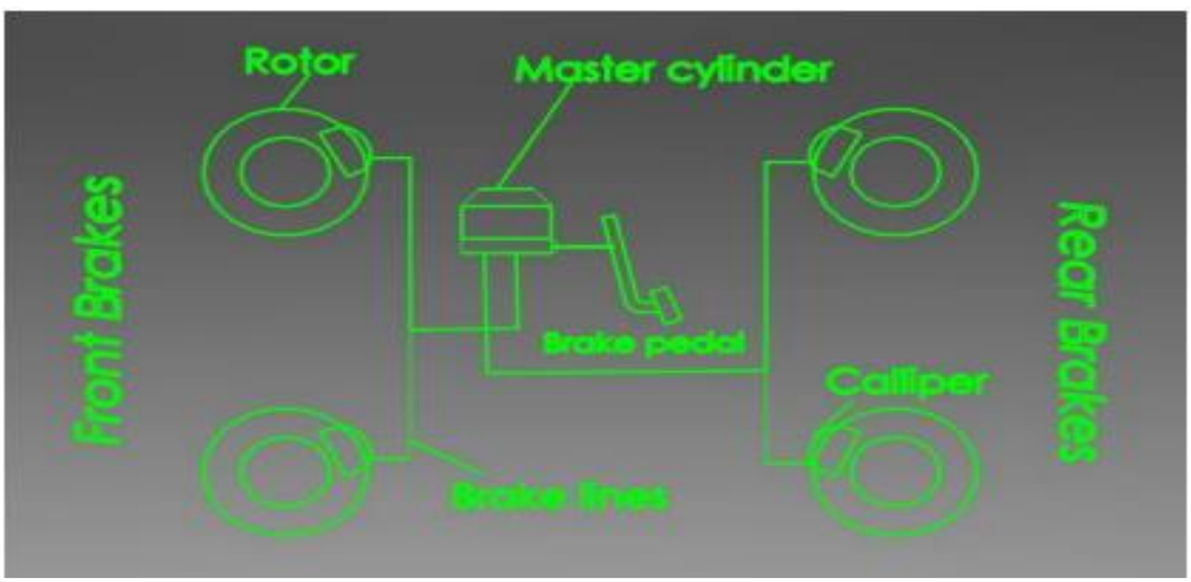


Figure 2.1 Conventional braking systems in four wheels [1]

The Internal Combustion Engine has played an incomprehensible role in contemporary society ever since its invention. Oil shortages will almost certainly eventually lead towards a search for propulsion from renewable sources, but for the time being there is no sign of any significant alternative for everyday transport. Any product that offers a fuel economy improvement is of benefit to both the individual and the environment. As vehicles speed up, they convert stored energy into kinetic energy. As the mass or velocity increases, the kinetic energy will also increase. It is for this reason that light commercial vehicles on our roads have so much kinetic energy when traveling at speed. The concept of being able to recover this energy when braking is the foundation for regenerative braking or Kinetic Energy Recovery. The energy captured is then stored to be used in the future: in most cases, it is converted back into kinetic energy to bring the vehicle back to speed. The technology is particularly effective in drive cycles consisting of frequent stop-start driving.

2.1.1. Regenerative braking system

The regenerative braking system is an energy recovery system that recovers a significant amount of kinetic energy of vehicle that unnecessarily gets wasted during braking. The recovered energy is stored in a suitable storage system (battery or flywheel). “Stop and go”, “decelerate and accelerate”, that’s usually the scene of traffic in the city which results in a lot of braking. In the regenerative braking mode, the motor slows downhill the car. When apply force to the pedal or brake, then the car gets slow down and motor works in reverse direction. When running in invalidate direction motor acts as the generator and thus charge a battery [2].

The possibility of recovering vehicle kinetic energy is one inherent advantage of electric and hybrid electric vehicles. When a vehicle drives in heavy traffic, more than half of the total energy is dissipated in the brakes, Therefore, recovering braking energy is an effective approach for improving the driving range of EV (Electric Vehicle) and the energy efficiency of HEV (Hybrid Electric vehicle) [5].

Developments in Hybrid Electric and pure Electric Vehicles are intended to improve the operational efficiency of road vehicles. Regenerative braking, which has long been established in rail vehicles, is integral to efficiency improvement, with up to 30% of overall traction energy demand satisfied by the energy saved during deceleration [2].

Regenerative braking allows electric vehicles to use the motor as a generator when the brakes are applied, to pump vehicle energy from the brakes into an energy storage device.

Regenerative braking is an effective approach to extend the driving range of EV and can save from 8% to as much as 25% of the total energy used by the vehicle, depending on the driving cycle and how it was driven. Generally, the regenerative braking torque cannot be made large enough to provide all the required braking torque of the vehicle. In addition, the regenerative braking system may not be used under many conditions, such as with a high state of charge or a high temperature of the battery. In these cases, the conventional hydraulic braking system works to cover the required total braking torque. Thus, cooperation between the hydraulic braking system and the regenerative braking system is the main part of the design of the EV braking control strategy and is known as torque blending [6].

2.2. Review of previous researches

Vishwakarma and Chaurasia (2016). Studied the two different methods of recovering energy that generally gets wasted, by converting it into either electrical or mechanical energy. The kinetic energy gets converted into electrical energy with the help of electric motor whereas flywheel harnesses the kinetic energy by converting it into mechanical energy. The discussed storage system proves flywheel as a better energy storage system. There was always a scope for improvement in terms of technology. Thus, the effort should be made to layout an appropriate design of flywheel which can bear a large amount of the stress developed in a flywheel.

Gupta et al. (2014). developed a product that stores the energy which was normally lost during braking and reuses it. The use of the regenerative braking system in automobiles provides them the means to balance the kinetic energy of the vehicle to some extent which was lost during the process of braking. The authors of the paper have discussed and presented two methods of using the kinetic energy which generally gets wasted by converting it into either mechanical energy or into electrical energy. A flywheel was used for converting the kinetic energy to mechanical energy. Also, Electric Motor was used to convert Kinetic Energy into electrical energy.

Carlin (2015). Focused to investigate the feasibility of a mechanical Kinetic Energy Recovery System for implementation via a retrofit on existing light commercial vehicles. In order to be effective, the system must be cost-effective and easy to implement. The dissertation was found that a flywheel-based regenerative braking solution for light commercial vehicles was a commercially viable technology. The project concludes that the final solution was able to be fitted to multiple vehicle platforms and with more research; the system could be made lighter and more efficient. The models presented were a representation of the potential fitment to vehicles.

Khavdu (2015). Discussed various systems of the kinetic energy recovery in the form of mechanical energy by using flywheels, hydraulic energy by using accumulator and electrical energy by using a capacitor and high voltage battery. The regenerative braking system was able to reduce fuel consumption in a hybrid vehicle and lower the environmental pollution. By developing a new capacitor, which had frequent charging and discharging capacity with compact and durable high voltage battery and electronic control system more braking waste energy can be recovered in the future.

Malode and Adware. (2016). Proposed an easy but useful method of regenerative braking in the electric vehicle. Electric vehicle's used the mechanical brake to boost the roughness of wheel for the deceleration purpose. However, from the point of view of saving energy, mechanical brake increases out much energy while the EV's kinetic energy was renewed into the thermal one. The braking system for a vehicle was based on hydraulic braking technology. They found out traditional braking methodology caused a lot of wastage of energy since it produced unwanted heat during braking. They concluded that, the creation of regenerative braking had risen above the disadvantages; in addition, it helped in to save energy and provided higher efficiency for a car. The main aim that had been the focus of having an influence on brake energy regeneration that was usable was discussed.

Godfrey and Sankaranarayanan (2018). Proposed new electric braking system for a brushless DC (BLDC) motor driven electric vehicle (EV) on stopping time and energy regeneration. The new braking system was developed by combining various regenerative methods and plugging. Other than the existing performance measures such as boost ratio, braking torque, and maximum conversion ratio; stopping time and energy recovery for various methods were studied for different running conditions. It was observed that the stopping time was less for plugging and increases in the order of two, three and single switch method. The proposed strategy was able to stop the vehicle at any speed with possible energy regeneration. Simulation and experimental results were presented to show the effectiveness of the proposed method.

Abhale and Nigam (2015). Focused on Electric vehicle which is an upcoming interest in the market. The traditional braking topologies are now a day used. These braking techniques have a lot of wastage of energy during the braking in the form of heat. Thus, regenerative braking is the prime method to be a focus as it is an energy saving method. It increases the efficiency of the electric vehicle by saving of waste energy. In regenerative braking mode of the electric vehicle, the kinetic energy of wheels was converted into electricity and stored in batteries or capacitors. The method was improved by using a flywheel, DC-DC converter, ultra-capacitor as well as a super-capacitor. In this paper principle and various types of controllers had been studied to improve energy saving of electric vehicles.

Behera et al. (2016). Focused about the increased concerns over the impact of the conventional car (ICE –Internal Combustion Engine) on the environment had led to renewed interest and advancement in the Electric Vehicle (EV). The need to improve the overall efficiency of the vehicle had led to the design of the regenerative braking system (RBS). The RBS had been used to convert the car’s mechanical energy and also the heat that would have been lost during braking into electrical energy. Brake energy regeneration systems convert a vehicle's kinetic energy into electricity as the car decelerates. The electricity was then stored for later use. It could be used to power the headlights, climate control, audio system, or any other electrical equipment. This reduces the need for the engine to burn extra fuel in order to generate electricity and thereby improves fuel economy.

Singh and Ali (2016). In their paper research related to electric vehicles was gaining importance due to the energy crisis. Used regenerative braking when braking, improved the efficiency of an electric vehicle as it recovered energy that could go to waste if mechanical brakes were used. A novel regenerative braking system for neighborhood electric vehicles was designed, prototyped and tested. The proposed system utilizes a seesaw system to capture energy whereas the conventional systems regenerate to the batteries. The user has direct control over the amount of current regenerated and hence the amount of negative torque applied for braking. The research had shown that the proposed regenerative braking system was significantly better in recovering energy and slowing the vehicle compared to a commercially available regenerative braking system.

Perrotta et al. (2012). Proposed a mathematical model for an electric bus power train implemented in a simulation platform. They intend to analyze the consumption of energy according to the route specifications and other performance measures. The potential for regenerative braking will be evaluated for different routes since it depends significantly on them. It was expected that a "pattern" can be observed in that concerning the potential of the system to recover back some energy spent in its operation. Moreover, the use of super-capacitors to make this braking energy absorption was investigated.

Kumar (2012). Presented a new configuration of the parallel hydraulic regenerative brake vehicle (PHRBV) to improve the braking energy regenerated potential and engine work efficiency. Based on the analysis of optimal energy distribution for the proposed PHRBV over a representative urban driving cycle, a fuzzy torque control strategy based on the vehicle load changes was developed to real-time control the energy distribution for the proposed PHRBV. Simulation result was demonstrated that the proposed PHRBV with torque control strategy takes advantage of the high-power density and efficiency characteristics of the hydraulic regenerative braking system minimize the disadvantages of low energy density and effectively improve the fuel economy of PHRBV.

Śliwińsk (2016). Drew attention to the increasing environmental pollution caused by the development of vehicle transport and motorization. Historical design solutions concerning energy recovery devices in mechanical vehicles which used flywheels to accumulate kinetic energy were shown. Developmental tendencies in the area of vehicle manufacturing in the form of hybrid electric and electric devices were discussed. It requires little time to store kinetic energy and it was safe when compared to kinetic energy accumulators used flywheels as means of kinetic energy storage.

Dave and Bhardwaj (2013). Focused the Kinetic Energy Regeneration system harnessed the power and then used the same while accelerated had been discussed. The major energy storing element in the system was a spring that would store energy by compression and torsion. The use of spring ensured permanent storage of energy until called upon by the driver, unlike current mechanical regeneration systems in which the energy stored reduces with time and was eventually lost. The continuously variable transmission would have been used in order to make the energy released uniform which would lead to safe usage. More research and development in the field will result in cost and size reduction of the component.

Nieman (2014). Studied on the development of a regenerative brake and launch assist (RBLA) mechanism that store energy in an elastic medium. The RBLA concept implement clutches gears, a ratchet, and a spring. The mechanism was captured energy from and releases energy to, an additional shaft allowed the axle to rotate in one direction. Governing equations were formulated and validated by dynamic simulation. In creating the detailed design, an optimization determined ideal spring and mechanism dimensions. The design equations were also used to optimize and size the design. Finally, the optimized design was simulated to validate the device and find its true effect on the vehicle.

Menon et al. (2013). Used the mechanical kinetic energy recovery system by means of a flywheel to store the energy which was normally lost during braking, and reused it to help propel the rider when starting. The rider could charge the flywheel when slowing or descending a hill and boost the bike when accelerating or climbing a hill. On the study they found that the flywheel had been increased maximum acceleration and nets 10% pedal energy savings during a ride where speeds were between 12.5 and 15 mph.

Nandy et al. (2017). Focused their study on the kinetic energy recovery system on a bicycle, When riding a bicycle, a great amount of kinetic energy is lost while braking, making start up fairly strenuous. Their study used a mechanical kinetic energy recovery system by means of a flywheel to store the energy which was normally lost during braking, and reuse it to help propel the rider when starting. The rider can charge the flywheel when slowing or descending a hill and boost the bike when accelerating or climbing a hill. The flywheel increases maximum acceleration and nets 10% pedal energy savings during a ride where speeds are between 12.5 and 15 mph.

Zaman and Hasan (2017). Focused to validate the proposed design from the experimental result, it was found that the wheel of the model could quickly gain its speed after releasing the brake which suggested the validity of the proposed design. Implementation of the new design could reduce muscle effort along with improved efficiency of conventional bicycle without compromising the performance. Model analysis and the experimental result confirms the validity of the design proposed in the paper

Utsav et al. (2015). Studied the Kinetic Energy Recovery System in the case of automobiles, energy conservation can be done by using regenerative braking systems (RBS). When driving an automobile, a great amount of kinetic energy is wasted when brakes are applied, which then makes the startup fairly energy consuming. In case the of automobiles, energy conservation can be done by using regenerative braking systems (RBS) by the kinetic energy recovery system. So the target of recovering the energy lost in braking is completed under the various types of Kinetic Energy Recovery System (KERS). The vehicle may be built using various KERS designs, based on the type of KERS used. The paper shows a detailed description of KE.RS.

Kumar (2015). Studied the regenerative braking concept in order to find an optimal way to combine regenerative braking with a conventional frictional braking system to achieve maximal energy recuperation. The study described the principle, design, and working of regenerative braking systems. A typical regenerative braking pattern was investigated for evaluating the availability of braking energy recovery. The results were indicated that in a vehicle with active regenerative braking control, a significant amount of braking energy can be recovered, and the brake system did not need much changing from the brake systems of conventional passenger cars.

Manjunath et al. (2018). Studied to use a much simpler system using dynamo's which can be used in any conventional vehicle irrespective of its size. In the system, part of brake was applied due to contact made by dynamo wheels and the vehicle was brought to a complete stop by use of regular friction brakes. That helped in generating power lost due to friction and also protects the brakes. That simple braking system was comparatively more cost-effective and flexible to almost all kind of vehicle with slight modification. By considering the wheel was moving with a speed „N‟ rpm as the speed varied due to driving conditions the brake force applied differs hence the rotation of the coil in the dynamo varied so that the power output depended on the speed of the wheel.

Guoqing et al. (2011). Studied fuzzy-logic-based regenerative braking strategy (RBS) integrated with series regenerative braking was developed in the paper to advance the level of energy-savings. From the viewpoint of securing car stability in braking operations, the braking force distribution between the front and rear wheels to accord with the ideal distribution curve were considered to prevent vehicles from experiencing wheel lock and slip phenomena during braking. The article had analyzed the braking effectiveness and braking stability and presented a fuzzy RBS to improve braking performance.

Price (2009). Studied to implement an effective regenerative braking system on the Lotus Elise Renewable Energy Vehicle. The research was carried out to investigate the best possible way to implement such a system. From the research, a parallel regenerative braking system was chosen and theoretical analysis was conducted to ensure that the vehicle remained safe with the new system. The analysis showed that the regenerative braking system would enhance the braking performance of the REV Elise while making it safer at the same time.

Ahmad et al. (2017). Studied the calculation of the energy involved in braking and calculation of the Energy that could be saved by storage of the energy in the mechanical form and comparison between the proposed method and the traditional Regenerative Braking included the use of separate gearbox which changes the gear ratio of the KERS and thus helped the KERS to provide energy inversion into the system during cruising by providing the additional torque after slight deceleration to recover the initial speed.

Therefore, as explained in literature reviews above some research have taken with an extensive experimental and numerical investigation of kinetic energy recovery system however no research has been taking to light vehicles with simple structure and low-cost system that can compatible to the existing vehicle with little modification on vehicle transmission system.

2.3. Modes of kinetic energy recovery

2.3.1 Energy recovery braking using a flywheel.

A flywheel is a component which is used to store mechanical energy and then release the stored energy when needed for acceleration. The flywheel is a heavy, high-speed rotating disc that builds up kinetic energy as it spins. The amount of energy stored depends upon how heavier it is and how fast it rotates. Heavier weight and faster rotation results in higher energy storage. It winds-up, building an increasing store of force and energy as it spins, and then releases the disc and sends it flying through the air. The method of transmission of energy directly to the vehicle is more efficient rather than first storing it in the battery, as it does not consist of the conversion of energies. During the recharging of the battery, mechanical energy is converted into electrical energy and during discharging vice-verse. So, due to these conversions` transmission losses occur and the efficiency reduces. As, in the other case, there are no transmission loses since mechanical energy stored in the flywheel is directly transferred to the vehicle in its original form. As the energy is supplied instantly and efficiency is high, these types of systems are used in F-1 cars [24].

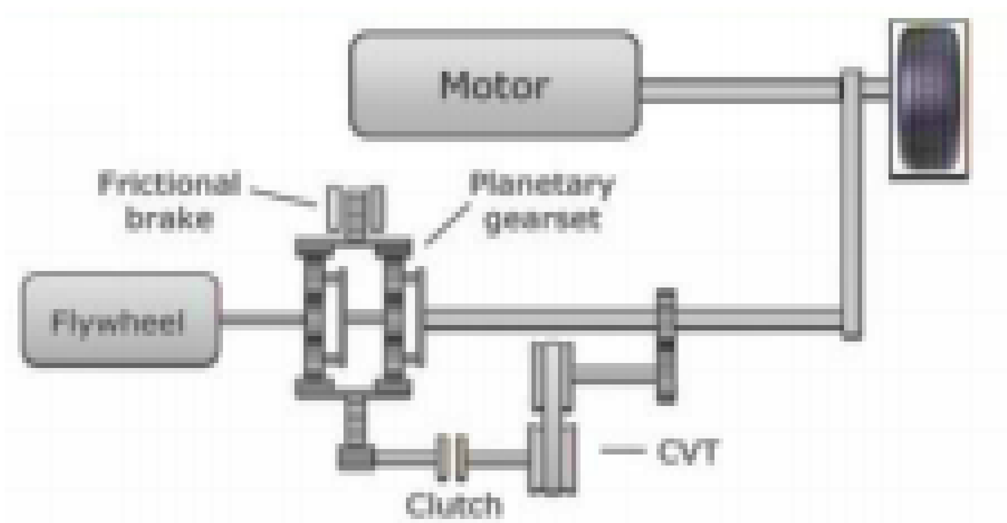


Figure 2.2. Flywheels regenerative braking [24]

2.3.2. Energy recovery braking using the motor/generator,

The most common form of regenerative brake involves using an electric motor as an electric generator. The working of the regenerative braking system depends upon the working principle of an electric motor, which is an important component of the system. The electric motor gets activated when some electric current is passed through it. But, when some external force is applied to activate the motor (during the braking), then it behaves as a generator and generates electricity. This means that whenever motor runs in one direction, the electric energy gets converted into mechanical energy, which is then used to accelerate the vehicle and whenever the motor runs in the opposite direction, it performs functions of a generator, which then converts mechanical energy into electrical energy, which makes it possible to utilize the rotational force of the driving axle to turn the electric motors, which results in regenerating electric energy for storage in the battery and simultaneously reducing the speed of the car with the regenerative resistance of the electric motors. This electricity is then used for recharging the battery.[24]

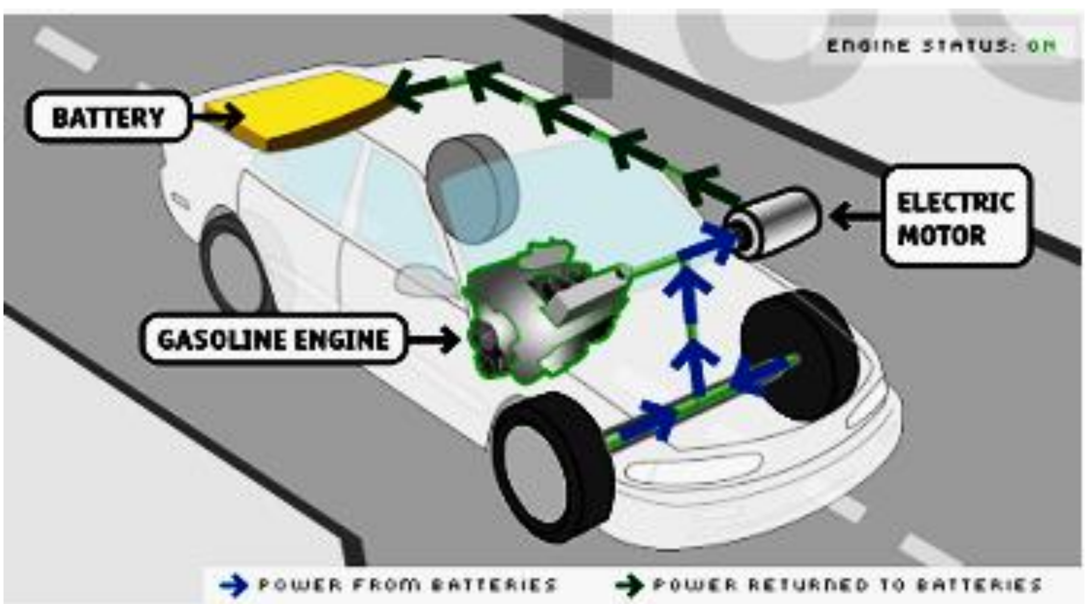


Figure 2.3. Energy recovery braking using the motor/generator [24]

2.3.3. Energy recovery braking using hydraulic braking

An alternative regenerative braking system is being developed by the Ford Motor Company and the Eaton Corporation. It's called Hydraulic Power Assist or HPA. With HPA, when the driver steps on the brake, the vehicle's kinetic energy is used to power a reversible pump, which sends the hydraulic fluid from a low-pressure accumulator (a kind of storage tank) inside the vehicle into a high-pressure accumulator. The pressure is created by nitrogen gas in the accumulator, which is compressed as the fluid is pumped into space the gas formerly occupied. This slows the vehicle and helps bring it to a stop. The fluid remains under pressure in the accumulator until the driver pushes the accelerator again, at which point the pump is reversed and the pressurized fluid is used to accelerate the vehicle, effectively translating the kinetic energy that the car had before breaking into the mechanical energy that helps get the vehicle back up to speed. It's predicted that a system like this could store 80% of the momentum lost by a vehicle during deceleration and use it to get the vehicle moving again. This percentage represents an even more impressive gain than what is produced by current regenerative braking systems. Like electronic regenerative braking, these kinds of brakes HPA systems are best for city driving, where stop-and-go traffic is common [24].

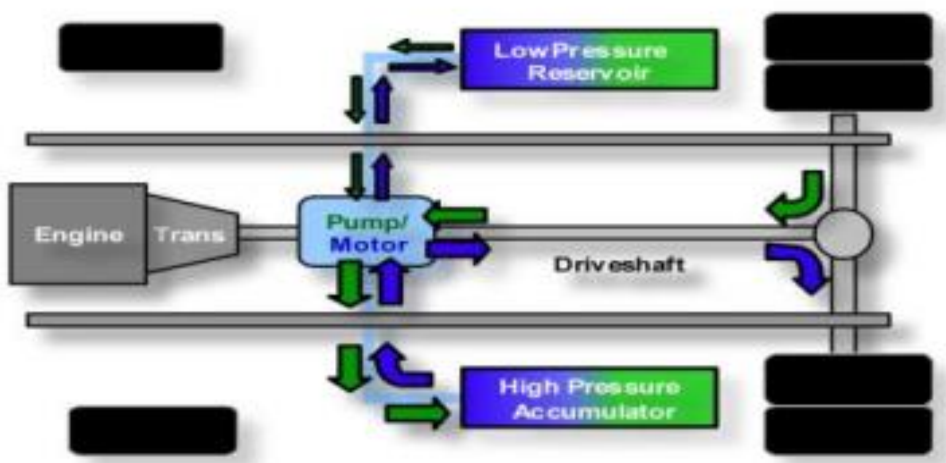


Figure 2.4. Hydraulic power assisted the regenerative braking system [24].

Characteristics of ideal regenerative braking system

To be successful a regenerative braking system should ideally have the following properties:

- Efficient energy conversion
- An energy stores with a high capacity per unit weight and volume
- A high-power rating so large amounts of energy can flow in a short space of time

- ✧ Not require over complicated control systems to link it with the vehicle transmission
- ✧ Smooth delivery of power from the regenerative system
- ✧ Absorb and store braking energy in direct proportion to braking, with the least delay and loss over
- ✧ A wide range of road speeds and wheel torques [9].

2.4. Working principle of the kinetic energy recovery system

On the axle of a light commercial vehicle wheel, there is sun gear and it rotates as the rotation of the vehicle and on the sun gear planetary gear is applied to rotate on the sun gear and the ring gear after all planet carrier is there.

When the car spinning along the high way the planetary gear is idling if the red light is on or during braking the kinetic energy storage is starting to work. By applying the brake pedal, the brake pedal locks the planet carrier then the ring gear is negatively spun. The Flat Spiral Spring is outside of the ring gear and stores the kinetic energy because of negative spinning of the ring gear. In regards, the original disk brake of the vehicle is working at the same time. The normally-off clutch and the storage one-way clutch stop to not turn Flat Spiral Spring back.

The driver steps on the gas the normally-on clutch will engage and normally-off clutch will open then the Flat Spiral Spring is released and the torque is passing to the axle. The car is driven by kinetic energy storage. After Flat Spiral Spring be released the normally-on clutch will be reset and also prevent Flat Spiral Spring from releasing kinetic energy in an accident.

2.5. Flat Spiral Spring

A flat spring is a long thin strip of the elastic material wound like a spiral as shown in Fig. 5. These springs are frequently used in watches and gramophones etc. When the outer or inner end of this type of spring is wound up in such a way that there is a tendency in the increase of the number of spirals of the spring, the strain energy is stored into its spirals. This energy is utilized in any useful way while the spirals open out slowly. Usually, the inner end of spring is clamped to an arbor while the outer end may be pinned or clamped. Since the radius of curvature of every spiral decreases when the spring is wound up, therefore the material of the spring is in a state of pure bending [25].

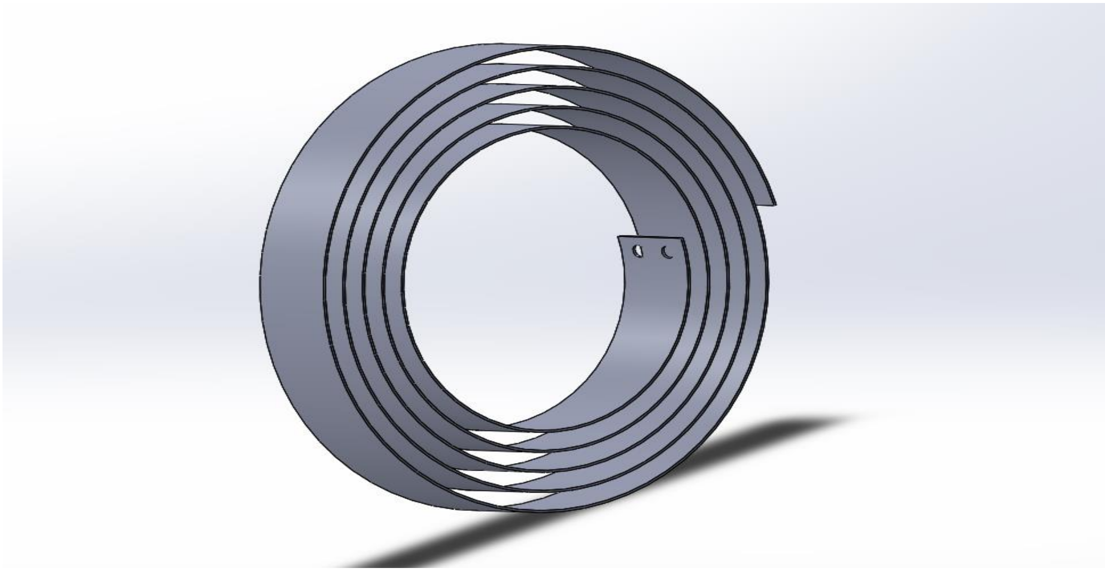


Figure 2.5. Flat spiral spring

2.6. Basic components of the brake system

The brake system is composed of the following basic components: the energy-supplying device, the control device, the transmission device, the brake and additional retarder device, brake line (connecting different devices), and ABS (Anti-lock Braking System)

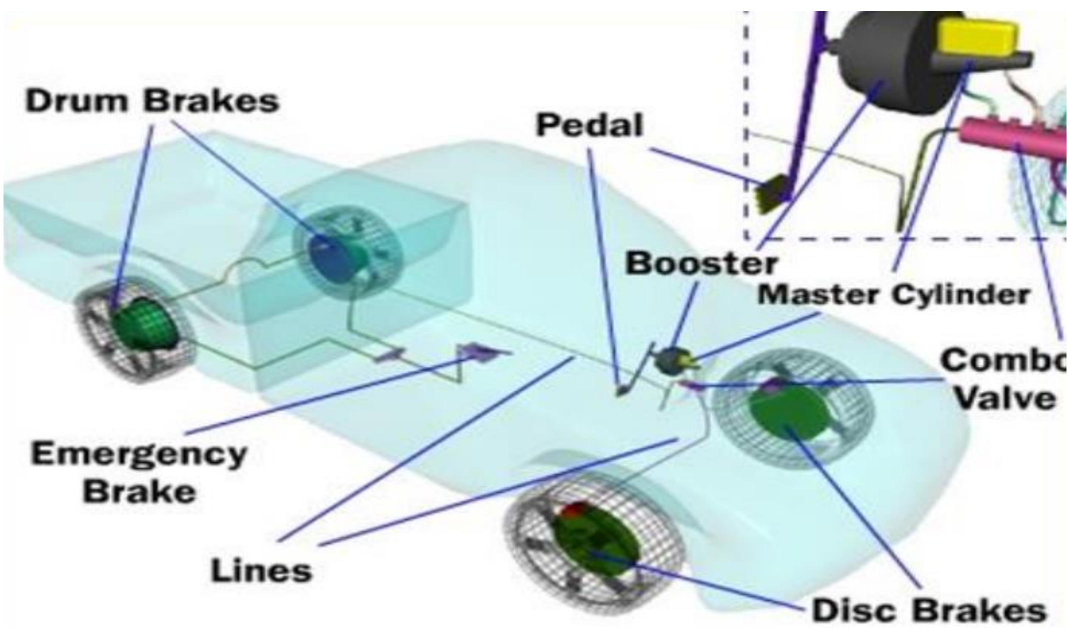


Figure 2.6. Brake system components [26].

2.6.1. The energy-supplying device

The energy-supplying device means supplying and adjusting the necessary energy of braking. According to the types of energy-supplying, there are three types used in automobile braking system:

Muscular energy braking system (non-power braking system) When driver step the brake pedals or the handbrakes, the cars transmit the force from our feet or hands to the brakes. The force from the driver supplies the basic energy to brakes. This is non-power braking; it just uses the force from a human. For example, the bicycle is only using the no-power braking system to supply energy. Energy assisted braking system (power assisted braking system)

The power-assisted braking system uses the force from drivers and the kinetic energy of engines together. The braking force of the power-assisted system increases through using the vacuum booster unit. Atmospheric pressure helps to push the brake pedal. Thus, less muscle effort is required. In spark-ignition engines, the vacuum is generated through connecting intake manifold to the engine, while the diesel engines use the vacuum pump. Non-muscular energy braking system (power braking system) The power braking system only uses the engines for transforming the kinetic energy into the potential energy of the atmospheric pressure or the hydraulic pressure [26].

2.6.2. The control device

The main two control devices of braking systems are the service braking system and the parking braking system. They have separate control and transmission devices. The services braking system is foot-operated, while the parking braking system is hand-operated. The service brake acts to slow, stop, or hold the vehicle during normal driving. They are foot-operated by the drivers pressing or releasing the brake pedal. The primary purpose of the brake is to hold the vehicle stationary while it is unattended. The parking brake is mechanically operated when a separate parking brake foot pedal or hand lever is set [26].

2.6.3. The transmission device

The transmission device is used to transmit the brake energy to brake actuator components. According to different transfer modes, the transmission device includes a mechanical braking system, a hydraulic braking system, and a pneumatic braking system [26].

2.6.4. Types of brake system

According to the different functions of the braking system, two types of brakes are used in modern cars: drum brakes and disc brakes. All cars used disc brakes on the front wheels, most cars use drum brakes on the rear wheels. In other words, the typical brake system consists of disc brakes in front and either disc or drum brakes in the rear connected by a system of tubes and hoses that link the brake at each wheel to the master cylinder. The basic components of drum brakes include: brake drum, an expander, pull back springs, a stationary back plate, two shoes with friction linings, and anchor pins [26].

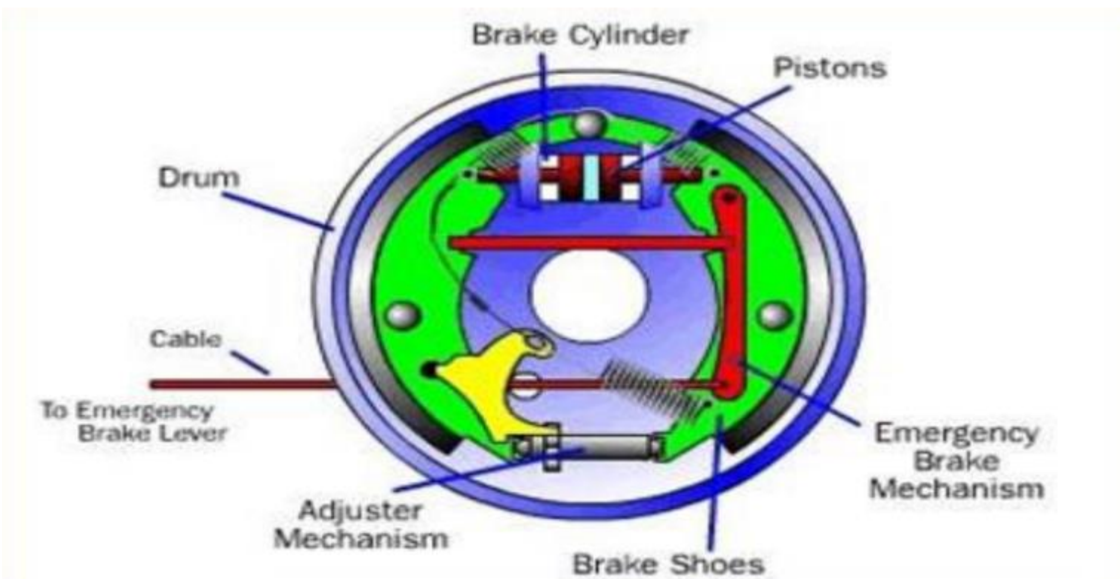


Figure 2.7. The composition of the drum brake [26].

2.7. Disc brake system

Front disc brakes are standard on all modern cars and light trucks, and disc brakes are often utilized for the rear brakes as well. The main advantages of disc brakes compared to drum brakes are:

- Increased resistance to brake fade
- Quicker shedding of water from the friction surfaces
- Self-cleaning of dust and debris
- Self-adjusting

A disadvantage of disc brakes is that they require significant force to clamp the pads against the brake rotor. This increases the effort of the driver to slow and stop the vehicle. Because of this, disc brake equipped cars require the use of a power assist system to decrease driver effort and fatigue [26].

2.7.1. Disc Brake Basic function and Operation

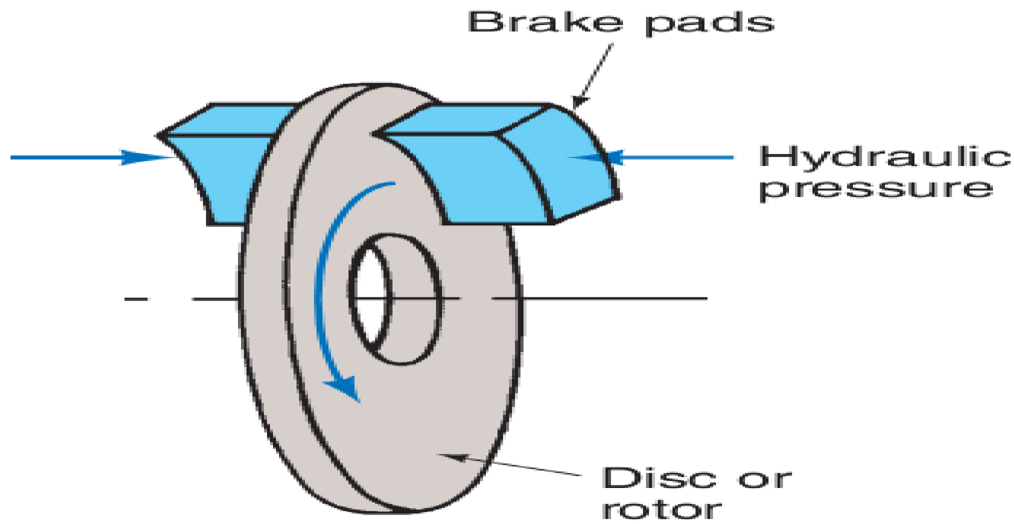


Figure 2.8. The basic operation of the disc brake system [26].

All disc brakes are similar in operation: pressurized brake fluid forces the caliper piston outward from the caliper bore, which applies pressure against the brake pads. This squeezes the two brake pads against the rotor or disc, as illustrated in Figure. The pads pressing against the rotor create friction and heat. The friction slows the disc, which in turn slows the wheel and tire. The heat is dissipated into the air [26].

Brake Balance

The braking of a vehicle occurs at ground level, so effective braking force acts on the ground. Vehicle weight and kinetic energy of the vehicle act through the center of gravity, which is above ground level. This causes the vehicle to pitch forward as the brakes are applied. As a result of this action, some vehicle weight is effectively transferred from the rear wheels to the front wheels. Consequently, the front brakes must absorb more kinetic energy than the rear brakes. The maximum transfer of weight amounts to [27].

$$W t = \frac{\mu h}{b} W ---------------------------------(2.1)$$

When deceleration of the vehicle is considered the weight transfer becomes

$$W t = \frac{h}{b} \cdot \frac{f}{g} W ------------------------------2.2)$$

Where

W_t = Dynamic weight transferred (N)

μ = coefficient of friction

h = height of C.G. from the ground (m)

W = vehicle gross weight

b = wheel base (m)

f = deceleration of vehicle (m/s^2)

g = acceleration due to gravity (m/s^2)

This weight is added to the static weight on the front wheels and subtracted from the static weight on the rear wheels. The front wheel static weight is normally 55% of the vehicle weight. Front brakes are designed to absorb this extra brake effort by selecting shoe-drum or shoe-disc,

combination type, brake size, lining coefficient of friction, wheel cylinder size and differential hydraulic actuating pressures. With full braking, it is desirable to have the front brakes lock up slightly ahead of the rear brakes. This causes the car to go straight ahead and to not spin out [27].

Stopping Distance

Stopping distance is extremely important for emergency braking. The stopping distance is based on the deceleration rate. Also, it is affected by the Tyre deflection, air resistance, braking efforts and the inertia of the driveline. Distance traveled by the vehicle during application of brake can be obtained from the following equations of motion assuming the brake efficiency as 100% [27].

$$S = U_t - (1/2)\, ft^2 ---------------------------------(2.3)$$

And

$$V^2 - U^2 = -2\, fS -------------------------------(2.4)$$

Where

S = distance moved by the vehicle (m)

U = initial velocity of the vehicle (m/s)

V = final velocity of the vehicle (m/s)

t = duration of application of bake (s)

f = deceleration of the vehicle (m/s^2)

If the vehicle comes to stand still due to the application of the brake, the final velocity, $V = 0$ in the above equations, then stopping distance, S is given by the relations [27].

$$S = U^2 /2f. \qquad (2.5)$$

The stopping distance remains same with the same Tyre and road conditions when the wheels are locked and skidding, regardless of the weight, number of wheels or vehicle load. Maximum braking force occurs when the wheels are brake just before the locking point or point of impending skid. Non-skid brake systems are designed to operate at or below this point. Any changes in load on a wheel change the point of impending skid.

Vehicle dynamics

Determining the axle loading on a vehicle under arbitrary conditions is a first simple application of Newton`s Second Law. It is an important first step in the analysis of acceleration and braking performance because the loads determine tractive effort obtainable at each axle, affecting the acceleration, gradeability, maximum speed, and drawbar effort. While designing kinetic energy recovery by flat spiral spring as energy storage the most important things taken into consideration are maximum velocity (V_{max}), the maximum gradability(ϕ_{max}), the maximum vehicle acceleration(a_{max}) and the minimum fuel consumption(FC_{min}) [27].

- The maximum vehicle velocity is limited by the maximum power available at the driving wheels. The maximum engine (brake) power depends on the maximum power available at the driving wheels. The maximum power available at the driving wheels, in turn, depends on the maximum total road resistance and maximum vehicle velocity.
- The maximum gradability(ϕmax): vehicle acceleration depends mainly on the maximum vehicle tractive force. The maximum vehicle tractive force in turn depends on maximum

torque available at the driving wheels. The maximum torque available at the driving wheels, in turn, depends on power and angular speed available at the driving wheels.

- The minimum fuel consumption: is limited by the brake power and the brake specific fuel consumption of the engine.
- The maximum torque at the driving wheels(T_{w-max}) depends on the maximum engine brake torque(T_{b-max}), the gear ratios of the gearbox(GR_i) and the final drive (GR_{fd}) and the efficiency of the gearbox (η_{Gi}) and final drive(η_{fd}).

$$T_{w-max} = T_{b-max}\ x\ GR_i\ x\ GR_{fd} x\ \eta_{Gi} x\ \eta_{fd} \text{-----------------------(2.6)}$$

The maximum power available at the driving wheels (P_{w-max}) depends on the maximum engine brake power(Pb-max) the efficiency of the gearbox(ηG_i) and final drive(η_{fd}).

$$P_{w-max} = P_{b-max} x\ \eta_{Gi}\ x\ \eta_{fd} \text{---(2.7)}$$

Component parts of Power Train and Power Flow.

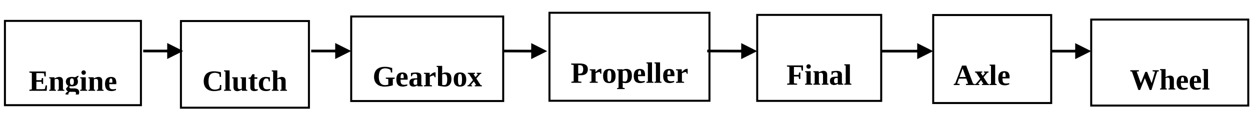
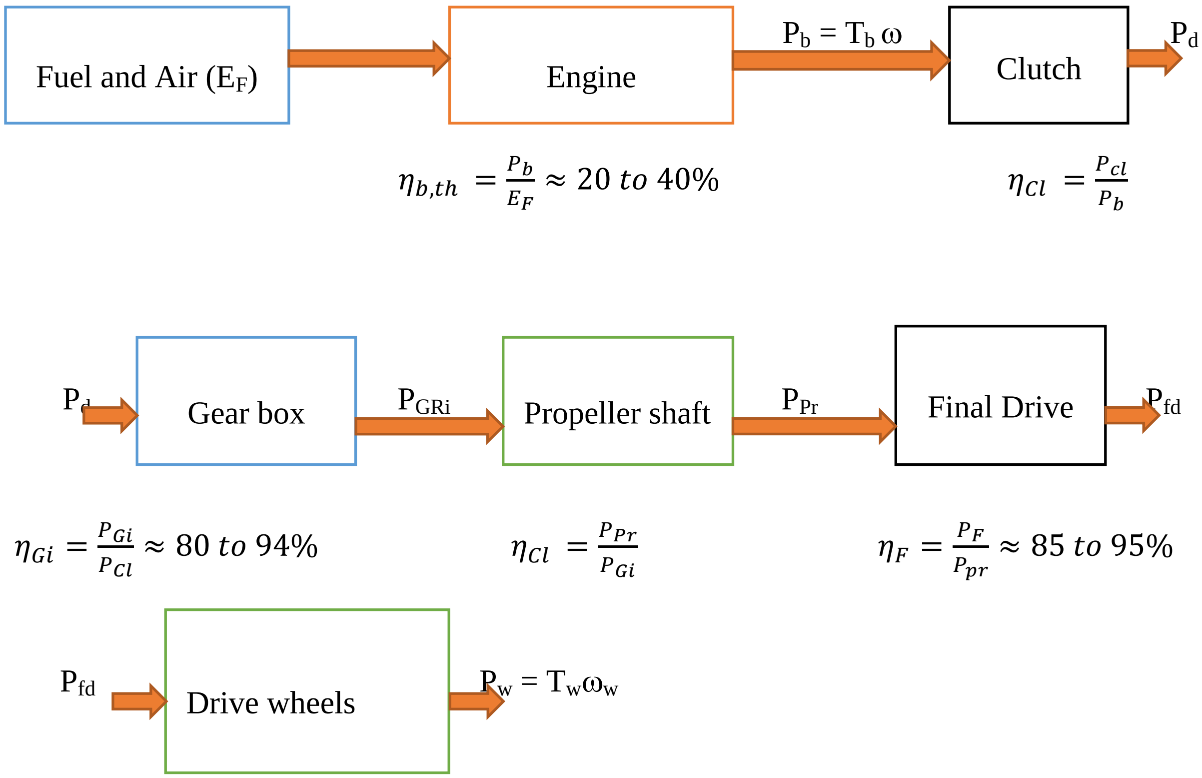


Figure 2.9. Components of the power train and power flow

The Engine (Motor) is the ‘powerhouse’ of a motor vehicle (automobile). The engine output is called the brake power (P_b). The Clutch is used to connect and disconnect (engage and disengage) the engine to the rest of the power train (driveline). The Gearbox is used to change the gear ratios (GR_i) or torque and angular speed of the engine depending on the driving conditions. The Propeller shaft is used to connect the gearbox to the final drive (differential). The propeller shaft does not exist in Front-engine, Front-wheel-drive, and Rear-engine, Rear-wheel-drive motor vehicles. In such vehicles, the differential is integrated with the gearbox as a unit which is called ‘Transaxle’. The Final drive is a kind of gearbox, used to adjust the speed of ‘propeller shaft’ with the speed of ‘wheel and tire’. The differential is used to allow the drive wheels to rotate at different speeds to handle the motor vehicle in a curved path (road). The Axle shafts are used to transmit power (torque and speed) from the final drive (differential) to the ‘wheel and tire’. The Drive wheels (Wheel and tire) are used to transform the engine power (torque and speed) into a tractive force (F_{tr}) which is used to drive or propel the vehicle. The input and the output: power (P), torque (T) and angular velocity (ω) for each component part of a power train are illustrated below (Fig. 10) [27].



$$\eta_{b,th} = \frac{P_b}{E_F} \approx 20\ to\ 40\%$$

$$\eta_{Cl} = \frac{P_{cl}}{P_b}$$

$$\eta_{Gi} = \frac{P_{Gi}}{P_{Cl}} \approx 80\ to\ 94\%$$

$$\eta_{Cl} = \frac{P_{Pr}}{P_{Gi}}$$

$$\eta_F = \frac{P_F}{P_{pr}} \approx 85\ to\ 95\%$$

$$\eta_W = \frac{P_W}{P_{fd}}\ or\ \eta_t = \eta_{Gi} * \eta_{fd} = \frac{P_W}{P_b} \approx 70\ to\ 90\%$$

Figure 2.10. Power transmission from engine to drive wheels

CHAPTER THREE

MATERIALS AND METHODS

This chapter consists of material, methods, specification of vehicle, design and simulation, vehicle dynamics, selection of standard gear for sun gear, planet gear, and ring gear, design of carrier, carrier pin, ratchet, and drum with solid works, and design of flat spiral spring,

3.1. Materials

Material that is used for this thesis work is Solid work software for design and simulation of parts of kinetic energy recovery system. Microsoft excel is used for finding the table and graphs.

3.2. Methods

First defining the problem that the thesis has to solve and detail background research that have done before and related subjects which helps in work progress after that by specifying the requirements which are the basic ones by brainstorming with the idea, doing some evaluation after all choosing the solution, after all the design and simulation work is done and finally communicate with the result that is found.

3.2.1. Specification of the vehicle

The necessary data for kinetic energy recovery system will be collected by following methods-

From various automobile industries and experts in the industries.

By visiting various websites in the area of vehicle design and dynamic analysis, SAE and other publications

Toyota Hilux 4x4 for design requirements that the flat spiral spring based kinetic energy recovery system.

Table 3.1Vehicle technical specification

Model	Hilux	Transmission-type	Manual
Power	150 hp/3400 rpm.	Number of ratios	6-speed
Max. ower(/KW@rpm)	148/110@3400	Ratios	1^{st} 4.784; 2^{nd} 2.423; 3^{rd} 1.443; 4^{th} 1.000; 5^{th} 0.777; 6^{th} 0.643; Rev 4.066
Max.torque (Nm@rpm)	400Nm/1600-2000rpm.		
Max.speed(kmph)	106		
Acceleration 0 - 62mph (sec)	13.2		
Fuel consumption-combined(mpg)	40.4		
Gross vehicle weight Kerb weight	3150 kg. 1915-1965Kg		
Axle(front/rear)	Rated load 1000kg/2150kg	Differential gear ratio(final drive)	3.583
Fuel tank volume	80 L		
Drag coefficient (Cd)	0.394		
Tire size	265/65 R17		
Wheel rims size	7.5J x 17		
Front brakes	Ventilated discs		
Rear brakes	Drum		

Height of vehicle sprung mass CG above the ground h = 762 - 889mm that is a typical value for small cars let’s take 825.5mm

3.2.2. Design and simulation

After reviewing the literature, design, and simulation of kinetic energy recovery components will be carried out. Here conceptual design process which helps to study a variety of mechanisms and select the appropriate design path by considering different criteria is done. Once the efficient the design path is determined to design of individual parts of the mechanism will be done so that it can withstand the applied loads. After accomplishing the design of parts; simulation of the system will be done using solid work software.

3.2.3. Vehicle dynamics

3.2.3.1. Vehicle Parked Car on a Level Road

When a car is parked on level pavement, the normal force (F_z), under each of the front and rear wheels, $2F_{z1}$, $2F_{z2}$, are [27].

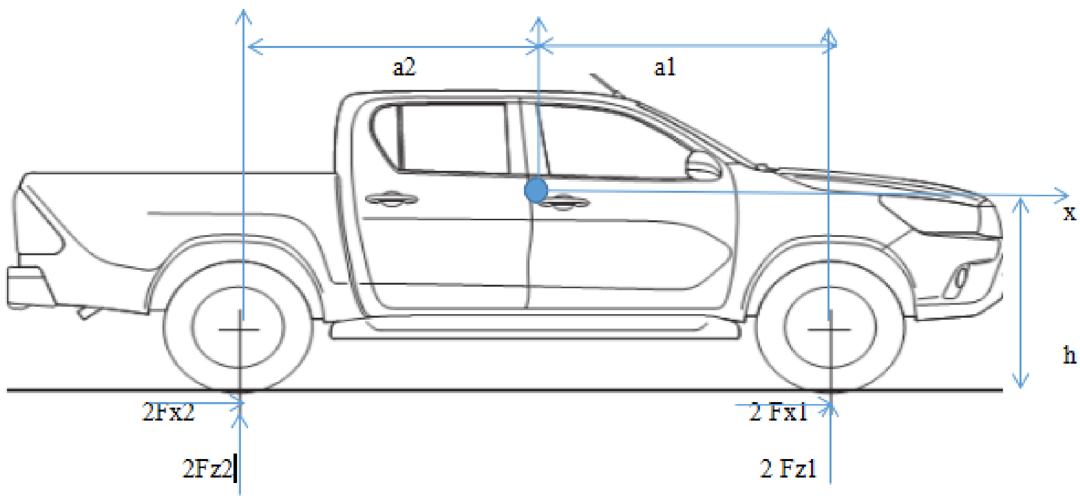


Figure 3.1. The vehicle parked on a level road.

$$F_{z1} = \frac{1}{2} mg \frac{a_2}{l} \text{ --- (3.1)}$$

$$4905 = \frac{1}{2} 3150 * 9.81 \frac{a_2}{3.085}$$

$$a_2 = 0.979m$$

$$F_{z2} = \frac{1}{2} mg \frac{a_1}{l} \text{ --- (3.2)}$$

$$10545.75 = \frac{1}{2} 3150 * 9.81 \frac{a_1}{3.085m}$$

$$a_1 = 2.106m$$

Where,a_1 is the distance of the car's mass center, C, from the front axle,a_2 is the distance of C from the rear axle, and L is the wheelbase.

$$l = a_1 + a_2 \text{--(3.3)}$$

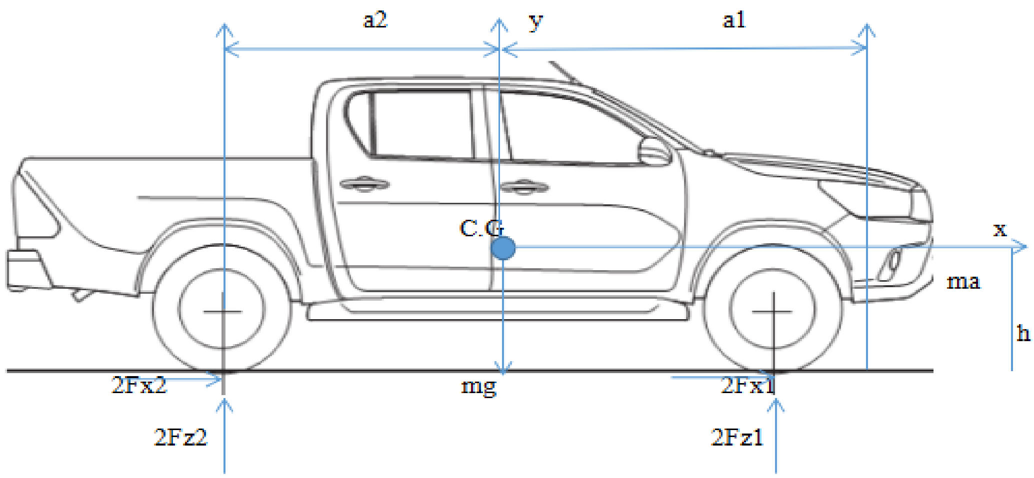


Figure 3.2. Vehicle accelerating on a level road.

3.2.3.2. Vehicle accelerating on a level road

Certain acceleration can be achieved by adjusting and controlling the longitudinal forces Fx1 and Fx2. The optimal longitudinal forces under the front and rear tires to achieve the maximum acceleration are [28].

$$F_{z1} = \frac{1}{2}mg\frac{a_2}{l} - \frac{1}{2}mg\frac{h}{l}\frac{a}{g} \text{-------------------------------(3.4)}$$

$$F_{z2} = \frac{1}{2}mg\frac{a_1}{l} + \frac{1}{2}mg\frac{h}{l}\frac{a}{g} \text{-------------------------------(3.5)}$$

Maximum acceleration of a car is proportional to the friction under its tires. Assuming the friction coefficients at the front and rear tires are equal and all tires reach their maximum tractions at the same time

$$F_{x1} = \pm\mu_x F_{z1} \text{------------------------------------(3.6)}$$

$$F_{x2} = \pm\mu_x F_{z2} \text{------------------------------------(3.7)}$$

The maximum acceleration and deceleration depend directly on the friction

$$a = \pm \mu_x g ------------------------------(3.8)$$

$$a = \pm 0.6x9.816 m/s^2$$

$$a = 5.886 m/s^2 \approx 6 m/s^2$$

Vehicle movement is described by the longitudinal force equation

$$F_t = F_i + F_s + F_r + F_a ------------------------------(3.9)$$

Where

F_t = traction force [N]

F_i = inertial force [N]

F_s = road slope force [N]

F_r = road load force [N]

F_a = an aerodynamic drag force [N]

The traction force can be regarded as a "positive" force, trying to move the vehicle forward. All the other forces are resistant "negative" forces, which are opposing the motion to slow down the vehicle.

As long as the traction force will be higher than the resistance, the vehicle will accelerate. When the traction force is smaller compared with the sum of resistant forces, the vehicle will decelerate (slow down). When the traction force is equal with the sum of resistant forces, the vehicle will maintain a constant speed.

From those inefficiencies, the gearbox and drive lines are a common one and the efficiency of the gearbox and final drive taken as 0.82 and 0.85 respectively [27]. So

$$\eta_t = \eta_{Gi} \times \eta_{fd} = \frac{Pw}{Pb} = 0.82 \times 0.85 = 0.697 ----------(3.10)$$

$$Pw = Pb \times \eta_t$$

$$Pw = 110KW \times 0.697 = 76.67KW$$

The change of the torque at the wheel (T_w) and the wheel angular velocity (ω_w) depend on the value of the engine brake torque (T_b), the gear ratio of the gearbox (GR_i), the gear ratio of final drive (GR_f), the efficiencies of the gearbox (ηG_i) and the final drive (η_F). Hence. From equation (2.6)

$$T_w = T_b \times GR_i \times GR_F \times \eta_{GI} \times \eta_F$$
$$T_w = 400Nm \times 1 \times 3.583 \times 0.82 \times 0.85$$
$$T_w = 998.9Nm$$

$$\omega_w = \frac{\omega}{GR_i \times GR_{fd}} ------------------------(3.11)$$

Where

N is the engine speed in rpm

ω is the engine angular velocity in rad/sec

$$\omega = \frac{2\pi \times N}{60} ------------------------------(3.12)$$

ω_w is the wheel angular velocity in rad/sec

The vehicle velocity (V) or the wheel velocity (V_w) and the angular velocity of the wheel (ω_w) can be related as

$$V = V_w = \omega_w x\, r_w --(3.13)$$

r_w is the effective wheel or tire radius

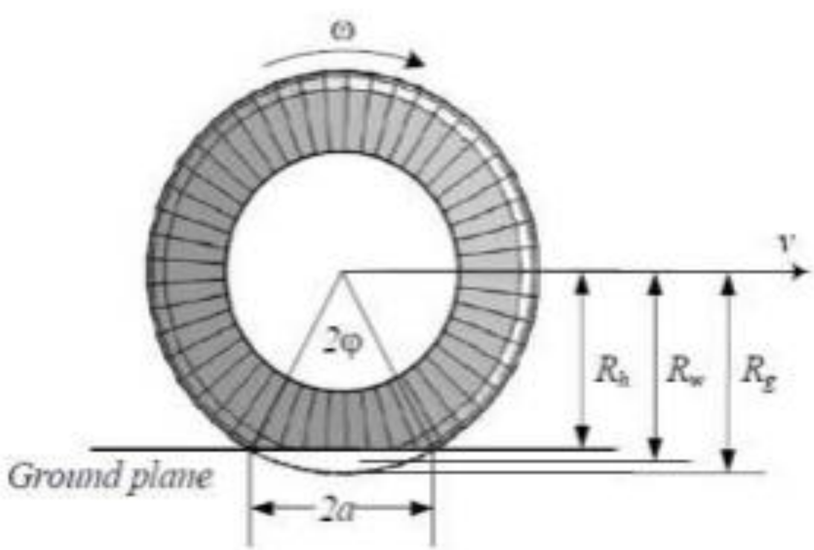


Figure 3.3. Effective radius rw compared to tire radius rg and loaded height rh

The effective radius r_w is given by equation(3.14)

$$r_w \approx r_g - \frac{r_g - r_h}{3} \text{-------------------------} (3.14)$$

The vertical stiffness of radial tires is less than non-radial tires under the same conditions. So, the loaded height of radial tires, R_h, less than the non-radials. However, the effective radius of radial tires R_w, is closer to their unloaded radius R_g. As a good estimate, for a non-radial tire, $R_w \approx 0.96R_g$, and $R_h \approx 0.94R_g$, while for a radial tire, $R_w \approx 0.96R_g$ and $R_h \approx 0.96R_g$.[28]

The power (P_w), the torque (T_w) and the tractive force or effort (F_t) available at the driving wheels can be related as

$$T_w = \frac{P_w}{\omega_w} \text{--------------------------------} (3.15)$$

$$\omega_w = \frac{P_w}{T_w} \text{--------------------------} (3.16)$$

$$\omega_w = \frac{76.67}{2 \times 998.9}$$

$$\omega_w = 38.38 rad/s$$

$$V_w = \omega_w \; x \; r_w \text{--} (3.18)$$

= 38.38rad/s x 0.33m

= 12.67m/s ≈ 13m/s

$$F_t = \frac{T_w}{r_w} = \frac{998.9Nm}{0.34m} = 2937.9$$

The centripetal force of the tire (Fcp) is equal to the centrifugal force (Fcf)

$$F_{cp} = F_{cf} = \frac{mv^2}{R} \text{---------------------------} (3.19)$$

$$\frac{(1000) \times (13.05)^2}{0.34} = 500.89KN$$

Engine speed

$$N_e = N_w \times GR_t \text{-------------------------} (3.20)$$

$$N_w = \frac{N_e}{GR_t} \text{-------------------------------} (3.21)$$

$$N_w = \frac{34000}{1 \times 3.583} = 948.9$$

$$GR_t = GR_T \times GR_F \quad \rightarrow \quad GR_T \approx 1:1 \text{ and } GR_F \approx 2. \text{ to } 4$$

$$\frac{Ne}{v} = 2.65 \times \frac{GR_t}{r_w} \text{---------------------------} (3.23)$$

Where

N_e = engine speed (RPM)

v = the vehicle speed

N_w= wheel speed in rpm

The inertial (resistant) force [N] is given by the equation:

$$F_i = m_v \; x \; a_v \text{--} (3.24)$$

$=3150Kg \times 6m/s^2$

= 18900N

Where

m_v = total vehicle mass [kg]

a_v = vehicle acceleration[m/s2]

3.2.4. Resistance load to the vehicle

3.2.4.1. Road slope resistance

The road slope (resistant) force [N] is given by the equation:

When a vehicle goes up or down a slope its weight produces a component, which is always directed to the downward direction, as shown in the figure 15.

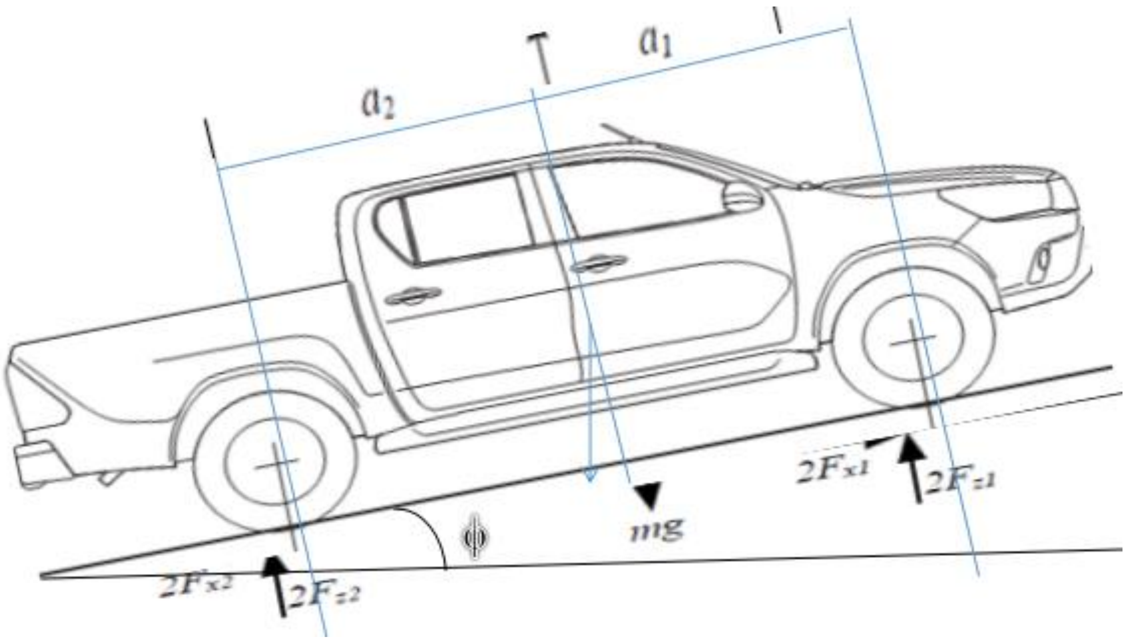


Figure 3.4. Vehicle on grade [27].

In vehicle performance analysis, the only uphill operation is considered. This grading force is usually called grading resistance. The grading resistance, from the below Figure, can be expressed as:

$$F_g = m_v g \sin\phi \text{ ------------------------------ } (3.25)$$

$$F_g = 3150 \times 9.81 \sin\phi$$

$$F_g = 30901.5 \sin\phi$$

Where

g = gravitational acceleration [m/s^2]

ϕ = road slope angle

3.2.4.2. The rolling resistant force [N]

Rolling resistance always opposes vehicle motion it aids the brake. The rolling resistance forces rolling resistance force are nominally equivalent about 0.01g deceleration (0.3fit/sec) [27].

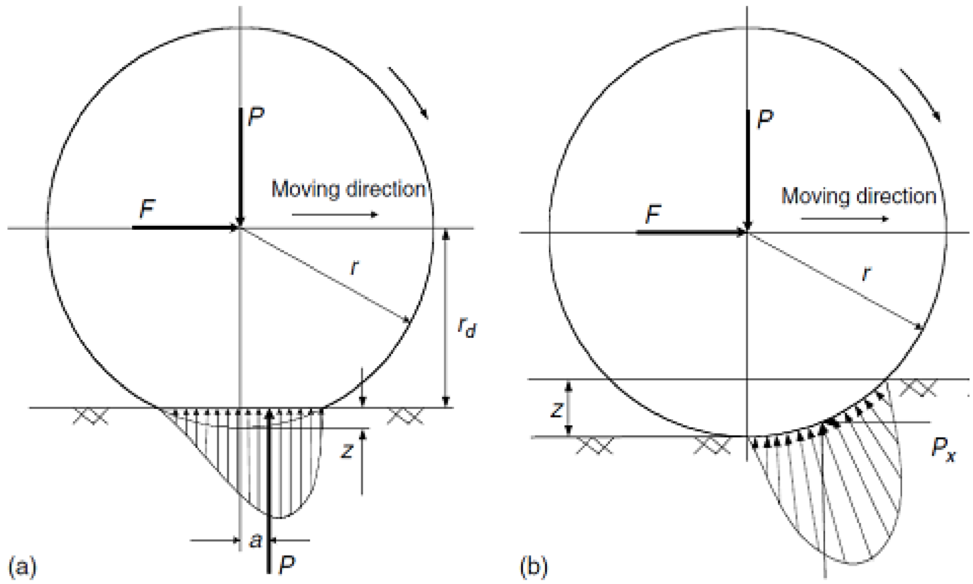


Figure 3.5.Tire deflection and rolling resistance on (a) hard and (b) soft road surface

$$F_r = m_v \ x \ g \ x \ c_r \ x \ cos(\alpha s) \text{-----} (3.26)$$

Where c_r = road load coefficient

Rolling resistance moment

$$Tr = Pa \text{-----} (3.27)$$

To keep the wheel rolling a force F, acting in the center of the wheels is required to balance the rolling resistance moment. This force is expressed as

The equation predicts the values of fr with acceptable accuracy for speeds up to 128 km/h.

$$F_r = \frac{T_r}{r_w} = \frac{Pa}{r_w} \text{-----} (3.28)$$

$$f_r = 0.01\left(1 + \frac{V}{100}\right) \text{-----} (3.29)$$

3.2.4.3. Air resistance (Ra)

A vehicle traveling at a particular speed in air encounters a force resisting its motion. This force is referred to as aerodynamic drag. It mainly results from two components: shape drag and skin friction.

Shape drag: The forward motion of the vehicle pushes the air in front of it.

Skin friction: Air close to the skin of the vehicle moves almost at the speed of the vehicle while air far from the vehicle remains still. In between, air molecules move at a wide range of speeds. The difference in speed between two air molecules produces a friction that results in the second component of aerodynamic drag. Aerodynamic drag is function of the vehicle speed V, vehicle frontal area Af, the shape of the vehicle, and air density ρ. Aerodynamic drag is expressed as: So the aerodynamic drag (resistant) force [N] is given by the equation:[27].

$$R_a = \frac{1}{2} \times \rho_a \times C_D \times A_{FP} \times v^2 \quad ---------------------- \quad (3.31)$$

$$R_a = \frac{1}{2} \times 1.05 \times 0.394 \times 2.69 \times (13.05^2)$$

$$R_a = 94.76N$$

$$\rho_a = \frac{p_a}{R_a \times T_a} \approx 1.05 \text{ kg/m}^3 \text{ is the density of the local air in 'kg/m}^3\text{'.}$$

$$C_D \approx 0.3 \text{ to } 0.6 \text{ is the drag coefficient.}$$

$$A_{FP} = SF \times W_2 \times H \text{ is the Projected Frontal area in 'm}^2\text{'.}$$

where, $SF \approx 0.75$ to 0.85 is the Shape Fact

Where

ρ = air density at 20 °C[kg/m^3]

cd = air drag coefficient

A = vehicle frontal area [m2]

v = vehicle speed[m/s]

The traction force is limited by the wheel friction coefficient in the contact patch. The maximum friction force [N] that allows traction is: [27].

$$F_f = m_v x\ g\ x\ \mu\ x\ cl \text{--}(3.32)$$

Where

μ = friction coefficient

cl = rear axle load coefficient

$$a_v = 1/m_v[F_t - (F_s + F_r + F_a + F_i)]$$ ---(3.33)

By integrating equation obtain the vehicle speed [m/s]:

$$V = 1/m_v \int [F_t - (F_s + F_r + F_a + F_i)]dt$$ ---------------------------------------(3.34)

3.2.5. Energy Absorbed by a Brake

The function of the braking system is to retard the speed of the moving vehicle or bring it to rest in the shortest possible distance whenever required. The vehicle can be held on an inclined surface against the pull of gravity by the application of the brake. Brakes are mechanical devices for increasing the frictional resistance that retards the turning motion of the vehicle wheels. It absorbs either kinetic energy or potential energy or both while remaining in action and this absorbed energy appears in the form of heat. When moving down a steep gradient the vehicle is controlled by the application of brakes. In this case, brakes remain in action for a longer period making it imperative to dissipate the braking heat to the atmosphere as rapidly as possible.

3.2.5.1. Energy of Motion

Kinetic energy is the force that keeps the vehicle moving. This energy is provided by the engine in order to accelerate the vehicle from a standstill to the desired speed. Kinetic energy is dissipated as heat by the brakes during application of breaks. The kinetic energy of a vehicle during braking is given by:

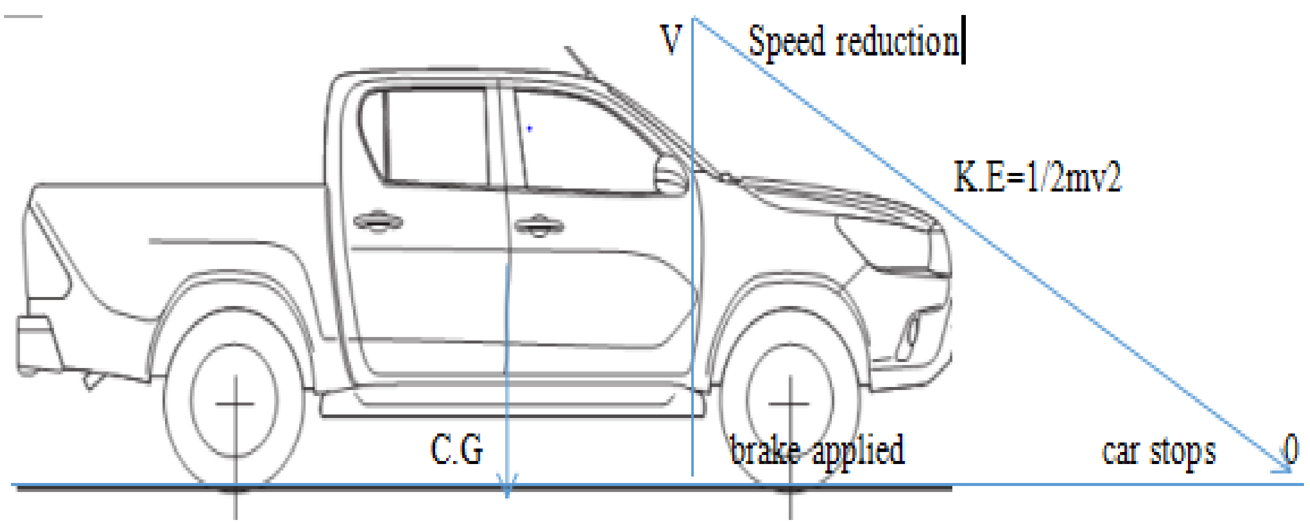


Figure 3.6. Vehicle during braking

The energy absorbed by a brake depends upon the type of motion of the moving body. The motion of a body may be either pure translation or pure rotation or a combination of both translation and rotation. The energy corresponding to these motions is kinetic energy. Let consider these motions as follows : [25].

When the motion of the body is a pure translation, consider a body of mass (m) moving with a velocity U m/s. Let its velocity is reduced to Vm/s by applying the brake. Therefore, the change in kinetic energy of the translating body or kinetic energy of translation,

$$E_1 = (1/2)\, m\, [(U)^2 - (V)^2] \text{--} (3.35)$$

This energy must be absorbed by the brake. If the moving body is stopped after applying the brakes, then V = 0, and

$$E_1 = (1/2)\, m\, (U)^2 \text{--} (3.36)$$

When the motion of the body is pure rotation, consider a body of mass moment of inertia I (about a given axis) is rotating about that axis with an angular velocity ω_1 rad/s. Let its angular velocity is reduced to ω_2 rad/s after applying the brake. Therefore, the change in kinetic energy of the rotating body or kinetic energy of rotation,

$$E_2 = (1/2)\, I\, [(\omega_1)^2 - (\omega_2)^2] \text{--} (3.37)$$

This energy must be absorbed by the brake. If the rotating body is stopped after applying the brakes, then $\omega_2 = 0$, and

$$E_2 = (1/2)\, I\, (\omega_1)^2 \text{---} (3.38)$$

When the motion of the body is a combination of translation and rotation, consider a body having both linear and angular motions, e.g. in the locomotive driving wheels and wheels of a moving car. In such cases, the total kinetic energy of the body is equal to the sum of the kinetic energies of translation and rotation.

Total kinetic energy to be absorbed by the brake,

$$E_T = E_1 + E_2 \text{--} (3.39)$$

Coefficient of Friction.

Frictional force opposes the motion of the vehicle. Consequently, it consumes power and produces heat. Frictional force occurs between the sliding tire and the road surface when wheel rotation is locked by brakes. The ability of a vehicle to stop depends on the coefficient of friction between the contacting surfaces. Maximum usable coefficient of friction occurs between the Tyre and road surface. Light commercial car brakes have coefficient of friction from 0.3 to 0.5.

The amount of energy that can be absorbed by the brakes depends upon the coefficient of friction of the brake materials, brake diameter, brake surface area, shoe geometry, and the pressure used to actuate the brake. Stopping a car suddenly means very high friction, resulting in high brake temperature [25].

Power absorbed

The power absorbed by the brakes during a stop can be calculated as,

$$P = \frac{KE}{1000t} \text{--}(3.40)$$

Where P = power absorbed(KW)

KE = kinetic energy(Nm or J)

T = time(s)

Work Done in Braking

The kinetic energy possessed by a moving vehicle depends on the weight and speed of the vehicle. This energy must be partially or totally dissipated when the vehicle is slowed down or brought to a standstill. The brake converts the kinetic energy possessed by the vehicle at any one time into heat energy by means of friction.

The kinetic energy possessed by the vehicle is given by the equation, KE= $1/2mu^2$

The work done bringing the vehicle to rest is given by

$$WD = FS \text{---}(3.41)$$

Where WD = work done (J)

F = average braking force (N)

S = distance traveled (m)

When braking a moving vehicle to a standstill, the work done by the brake drums must equal the initial kinetic energy possessed by the vehicle so that

$$KE = WD \text{---} (3.42)$$

$$FS = 1/2mu^2 \text{---} (3.43)$$

Therefore, the average brake force,

$$F = (mu^2)/2S \text{---} (3.44)$$

Sometimes, the brake has to absorb the potential energy given up by objects being lowered by hoists, elevators, etc. Consider a body of mass m is being lowered from a height h1 to h2 by applying the brake. Therefore, the change in potential energy,

$$E_3 = m.g\,(h_1 - h_2) \text{---} (3.45)$$

Since the energy absorbed (or heat generated) and the rate of wear of the brake lining at a particular speed is dependent on the normal pressure between the braking surfaces, therefore it is an important factor in the design of brakes. The permissible normal pressure between the braking surfaces depends upon the material of the brake lining, the coefficient of friction and the maximum rate at which the energy is to be absorbed. The energy absorbed or the heat generated is given by:

$$E = Hg = \mu.RN.v \text{---} (3.46)$$

$$E = \mu.p.A.v\ (in\ J/s\ or\ watts) \text{ ---} (3.47)$$

Where μ = Coefficient of friction,

RN = Normal force acting at the contact surfaces, in newton,

p = Normal pressure between the braking surfaces in N/m^2,

A = Projected area of the contact surfaces in m^2, and

V = Peripheral velocity of the brake drum in m/s.

The heat generated may also be obtained by considering the amount of kinetic or potential energies which is being absorbed. In other words,

$$Hg = EK + EP \text{---} (3.48)$$

where EK = Total kinetic energy absorbed, and

EP = Total potential energy absorbed.

The heat dissipated (Hd) may be estimated by

$$Hd = C\,(t_1 - t_2)\,Ar \text{ --(3.49)}$$

where C = Heat dissipation factor or the coefficient of heat transfer in W /m^2 / °C

$t_1 - t_2$ = Temperature difference between the exposed radiating surface and the surrounding air in °C, and

Ar = Area of radiating surface in m^2 [25].

Selection of standard gear

Considering, Total depth of teeth =5 mm We know,

Addendum + Dedendum = Total depth of teeth   i.e. 5mm

Assuming 20^0 full depth involute system, using Imperial relations given for 20^0 full depth involute system[25].

Addendum=1m, Dedendum =1.25m

$$1m + 1.25m = 5$$

$$2.25m = 5\ Module$$

$m = 2.22$ standard module (m) =2.25

A. Number of teeth on sun gear ,

$$m = D/T - - - - - - - - - - \ (D = \ Pitch\ circle\ diameter)$$

$$2.25 = 36/T$$

$$T = 16$$

A. Number of teeth on planet gear,

$$m = D/T - - - - - - - - - - \ (D = \ Pitch\ circle\ diameter)$$

$$2.25 = 51.75/T$$

$$T = 23$$

B. Number of teeth on ring gear,

$$m = D/T - - - - - - - - - (D = \ Pitch\ circle\ diameter)$$

$$2.25 = 144/T$$

$$T = 64$$

0) Face width = 1inch =20mm

2) Tooth thickness $= 1.5708m - - - - - - - - - (m = module)$

$$= 1.5708 * 2.25$$

$$5.53\, mm$$

3) Minimum clearance $= 0.25m ------ (m = module)$

$$= 0.25 * 2.25$$

$$= 0.56mm$$

4) Working depth = $2m ----------- (m = module)$

$$= 2 * 2.25$$

$$= 4.5mm$$

Diameter of shaft = 20 mm

1. For Sun Gear

   Pitch circle diameter of sun gear = 36mm

   Outer diameter of sun gear = 40.6mm

   Inner diameter of sun gear = 30.5mm

2. For Planetary gear

   Pitch circle diameter of planetary gear =51.75mm

   Outer diameter of planetary gear =57mm

   Inner diameter of planetary gear =48.5mm

3. For Ring Gear

   Pitch circle diameter of ring gear =144mm

   Outer diameter of ring gear =150mm

   Inner diameter of ring gear =139.88mm

Wheel torque = 998.9 say 1000Nm

Wheel speed = 948.9 say 950rpm

By the given data steel is selected from standard

3.2.6.4. Design of spring

A flat spring is a long thin strip of the elastic material wound like a spiral as shown in Figure 3.7. These springs are frequently used in watches and gramophones etc. When the outer or inner end of this type of spring is wound up in such a way that there is a tendency in the increase of a number of spirals of the spring, the strain energy is stored into its spirals. This energy is utilized in any useful way while the spirals open out slowly. Usually, the inner end of spring is clamped to an arbor while the outer end may be pinned or clamped. Since the radius of curvature of every spiral decreases when the spring is wound up, therefore the material of the spring is in a state of pure bending.

Material selection

Stainless steel wire, hardening 17-7, NiCr,A2E6

Young`s modulus (E) = 208Gpa

Density (ρ) = 8.03g/cc

Maximum service temp = 3230C

Factor of safety =2

Tensile strength (σt) = 1800Mpa

Assumption for design purpose of spring

Width (b)	= 44mm
Thickness (t)	= 1.5mm
Internal diameter (d)	= 183 mm
External diameter (D)	= 310mm

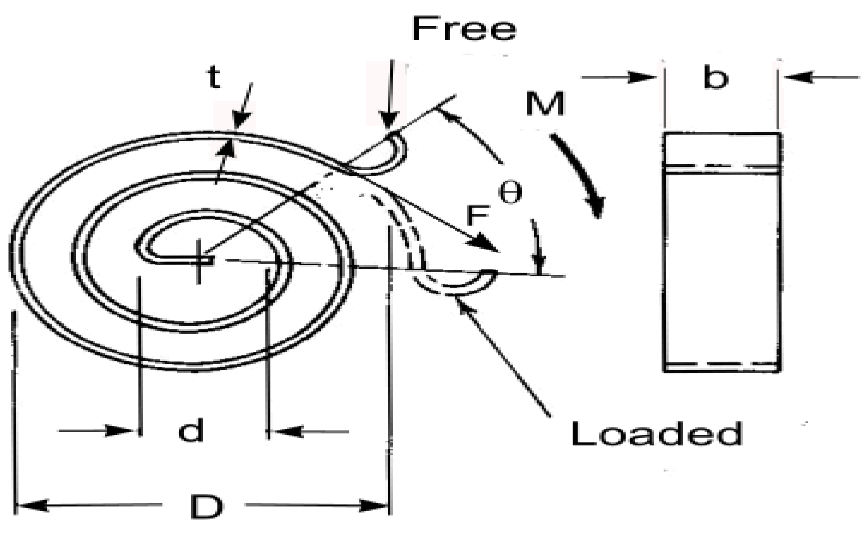


Figure 3.7. Dimension of flat spiral spring

Let W= Force applied at the outer end A of the spring,

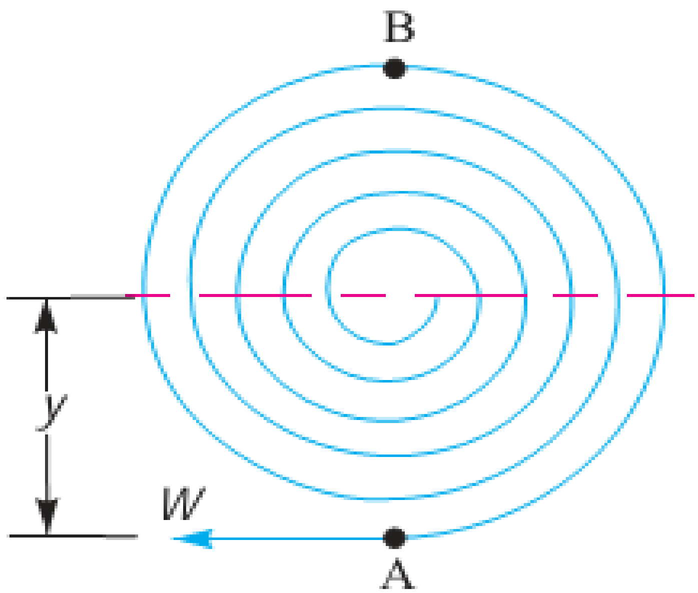


Figure 3.8. Flat spiral spring

y = Distance of center of gravity of the spring from A,

l = Length of strip forming the spring,

$$Z = \frac{1}{y} = \frac{b\,t^3}{12 \times t/2} = \frac{b\,t^2}{6} ------------------------(3.52)$$

$$Z = \frac{44 \times 1.5^2}{6} = 16.5\,mm^3$$

$$I = \frac{b.t^3}{12} --------------------------------(3.53)$$

$$I = \frac{44.1.5^3}{12} = 12.375\,mm^4$$

When the end A of the spring is pulled up by a force W, then the bending moment on the spring, at a distance y from the line of action of W is given by

$$M = W \times y\text{---}(3.54)$$

$$M = 2937.9\,x\,310/2 = 455374.5N.mm\ or\ 455.37N.m$$

The greatest bending moment occurs in the spring at B which is at a maximum distance from the application of W.

Bending moment at B,

$$M_B = M_{max} = W \times 2y = 2W.y = 2M \text{--}(3.55)$$

Maximum bending stress induced in the spring material,

$$\sigma_b = \frac{M_{max}}{Z} = \frac{2W \times y}{bt^2/6} = \frac{12.W.Y}{bt^2} = \frac{12M}{bt^2} ------------------(3.56)$$

$$\sigma_b = \frac{12 \times 4553745}{44 \times 2.25} = 55196.91\, N/mm^2$$

Assuming that both ends of the spring are clamped, the angular deflection (in radian) of the spring is given by

$$\theta = \frac{M.l}{E.I} = \frac{12M.l}{Ebt^3} ------------------------------(3.57)$$

$$= \frac{12 \times 4553745 l}{208 \times 10^3 \times 44 \times (1.5)^3} = 0.18l$$

$$\delta = \theta \times y = \frac{M.l.y}{E.I} ----------------------------(3.58)$$

$$\delta = 0.18l \times 155mm = 27.9lmm$$

The strain energy stored in the spring

$$ES = \frac{\sigma_b^2}{24E} \times b.t.l = \frac{\sigma_b^2}{24E} \times volume ------------------(3.59)$$

$$ES = \frac{(55196.91)^2}{24 \times 208000} \times 44.1.5.l$$

$$E_S = 40280.87l$$

Where

D = Outside diameter of spring (m)

M = Moment/torque on spring = F.D / 2(Nm)

L = Length of strip (m)

G = Modulus of Rigidity (N/m^2)

I = Second moment of inertia of spring strip (m4)

w = Force to deflect spring(N)

b = Width of spring strip (m)

d = Inside diameter of spring (m)

t = thickness of spring strip (m)

n = Number of turns of spring

E = Young's Modulus (N/m^2)

θ = Deflection (radians)

y = distance from neutral axis to outer fiber of wire/strip = y/2 (m)

CHAPTER FOUR

RESULT AND DISCUSSION

This chapter consists of introduction, traction force, Energy absorbed by the brake, Power absorbed by the brake, Rate of fuel consumption, Energy stored on Flat spiral Spring, Solid-work simulation of parts.

4.1. Introduction

The Kinetic Energy Regenerative System designed here incorporates flat spiral spring, planetary gear mechanism, and planer carrier. The System is so designed that it inverts the energy, stored during the braking, in a manner that maximizes the savings in energy and fuel. The system incorporates various mechanical features to store, convert and invert the energy. The torque that is generated by the KERS has an important place in the feasibility of the device and the torque should be maintained for a reasonable time. The KERS device is capable of storing sufficient energy to power the vehicle during starting of the vehicle from rest after a braking event.

4.2. Traction force(Ft)

Traction force is a force which helps the vehicle to move forward by opposing different resistance forces. Traction between two surfaces depends on several factors:

- Material composition of each surface.
- Macroscopic and microscopic shape (**texture**; **macro texture** and **micro texture**) **Normal force** pressing contact surfaces together. Contaminants at the material boundary including lubricants and adhesives.
- The relative motion of tractive surfaces - a sliding object (one in kinetic friction) has less traction than a non-sliding object (one in static friction).
- The direction of traction relative to some coordinate system - e.g., the available traction of a tire often differs between cornering, accelerating, and braking.
- For low-friction surfaces, such as off-road or ice, traction can be increased by using traction devices that partially penetrate the surface; these devices use the shear

strength of the underlying surface rather than relying solely on dry friction (e.g., aggressive off-road tread or snow chains)[28]

$F_t = F_i + F_a + F_s + F_r$ = from equation (3.11)

Resistance from road load is given by equation (3.26)

$Fg = mv.gsin\phi = 3150x9.81sin\phi = 30901.5sin\phi$ – Gradient resistance

Table 4.1. Slope angle vs grade resistance

Slope angle	0	2	4	6	8	10
Resistance(N)	0	834.34	1667.67	2498.96	3327.21	4151.40

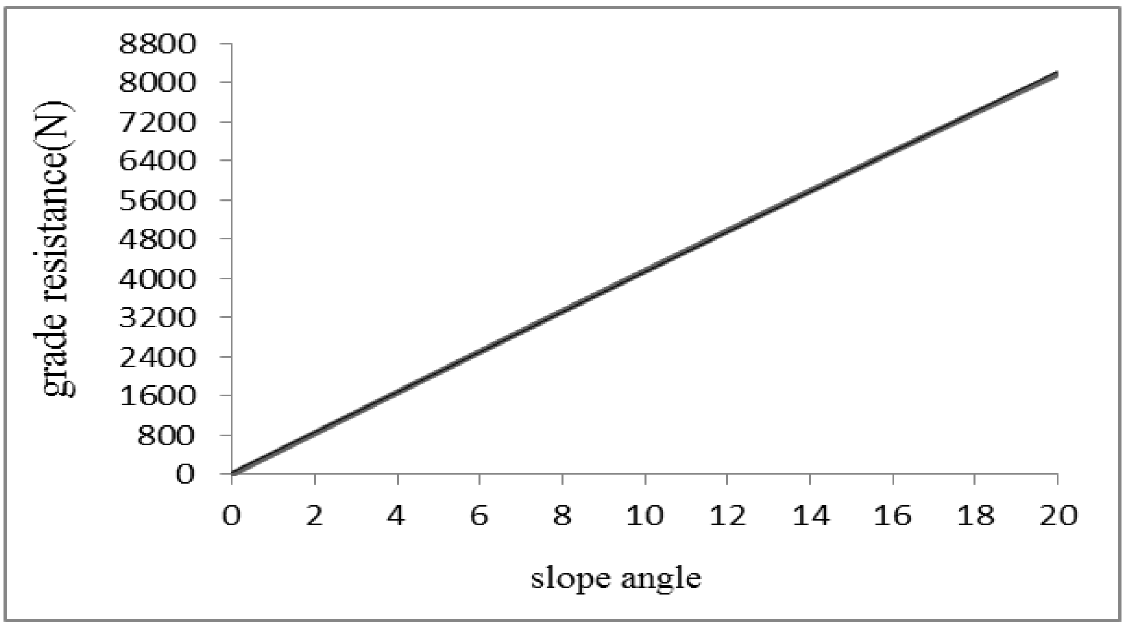


Figure 4.1 Slope angle vs grade resistance

On the figure the result will show as the direct relation of grade resistance load and slope angle. This illustrate as when the vehicle is moving on the higher grade it results to resist the forward motion of the vehicle so the vehicle must have enough resisting force.

Rolling resistance of the vehicle is given by equation (3.28) and (3.29)

$F_r = Pf_r = m_v g$

$$F_r = \frac{T_r}{r_w} = \frac{Pa}{r_w}$$

$$F_r = m_v \times g \times (0.01 + V)N = 3150 \times 9.81 \times (0.01 + V)$$

$$f_r = 0.01\left(1 + \frac{V}{100}\right)$$

$$f_r = 0.01\left(1 + \frac{V}{100}\right) = 0.01 + V$$

F_r = 309.015+30901.5V

Aerodynamic resistance on vehicle is given by equation (3.31)

is the density of the local air in 'kg/m^3'.

$C_D \approx 0.3$ to 0.6 is the drag coefficient.

$A_{FP} = SF \times W_2 \times H$

is the Projected Frontal area in 'm^2'.

where, $SF \approx 0.75$ to 0.85 is the Shape Factor

$$F_a = \frac{1}{2} \times \rho_a \times C_D \times A_{FP} \times v^2$$

$$F_a = \frac{1}{2} \times 1.05 \times 0.394 \times 2.69 \times (V^2)$$

$$F_a = 0.556V^2 N$$

So the traction force is resulted on

$$F_t = F_i + F_g + F_r + F_a$$

$= 18900N + 30901.5\sin\phi\ N + 309.015 + 30901.5V\ N + 0.556V^2N$

Table 4.2 resistance when vehicle moving up slope

up slope	Grade R esistance(N)	Velocity(m/sec)	Rolling Resistance(N)	Aerodynamic Resistance(N)	Total Resistance(N)
0	0	27.8	859370.7	429.7	878700.4
2	1077.9	25.02	772993.8	348.1	793319.8
4	2154.5	22.24	685885.2	275.0	707214.7
6	3228.4	19.46	598359.6	210.5	620698.6
8	4298.5	16.68	510731.9	154.7	534085.1
10	5363.3	13.9	423316.2	107.4	447686.9
12	6421.6	11.12	336425.5	68.7	361815.8
14	7472.0	8.34	250370.7	38.7	276781.4
16	8513.4	5.56	165460.4	17.2	192891
18	9544.4	2.78	81999.8	4.3	110448.5
20	10563.8	0	290.4	0	29754.2

Total resistance force is the sum of resistance force like aerodynamic, rolling and grade force.

So $Rt = RR + Ra + Rg$

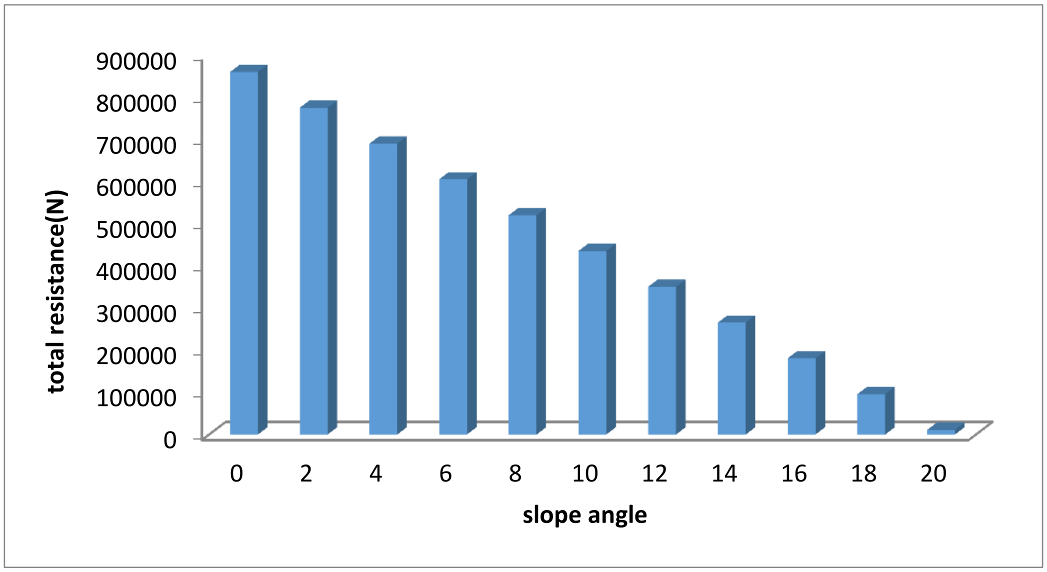


Figure 4.2. Total resistance load on up slope

When the vehicle moving up slope the velocity of the vehicle is decreasing but the gradient resistance will increase.

When the vehicle moving down the slope, the resistance forces are shown on the table below.

Table 4.3. Resistance load when vehicle moving down the slope

down slope	Grade resistance(N)	Velocity(m/sec)	Rolling Resistance(N)	Aerodynamic Resistance(N)	Total Resistance(N)
-20	-10781.2	0	290.4	0	8409.2
-18	-9703.1	2.78	81999.8	4.3	91201
-16	-8624.9	5.56	165460.4	17.2	175752.6
-14	-7546.8	8.34	250370.7	38.7	261762.6
-12	-6468.7	11.12	336425.5	68.7	348925.5
-10	-5390.6	13.9	423316.2	107.4	436933.1
-8	-4312.5	16.68	510731.9	154.7	525474.1
-6	-3234.4	19.46	598359.6	210.5	614235.8
-4	-2156.2	22.24	685885.2	275.0	702904
-2	-1078.1	25.02	772993.8	348.1	791163.8
0	0	27.8	859370.7	429.7	878700.4

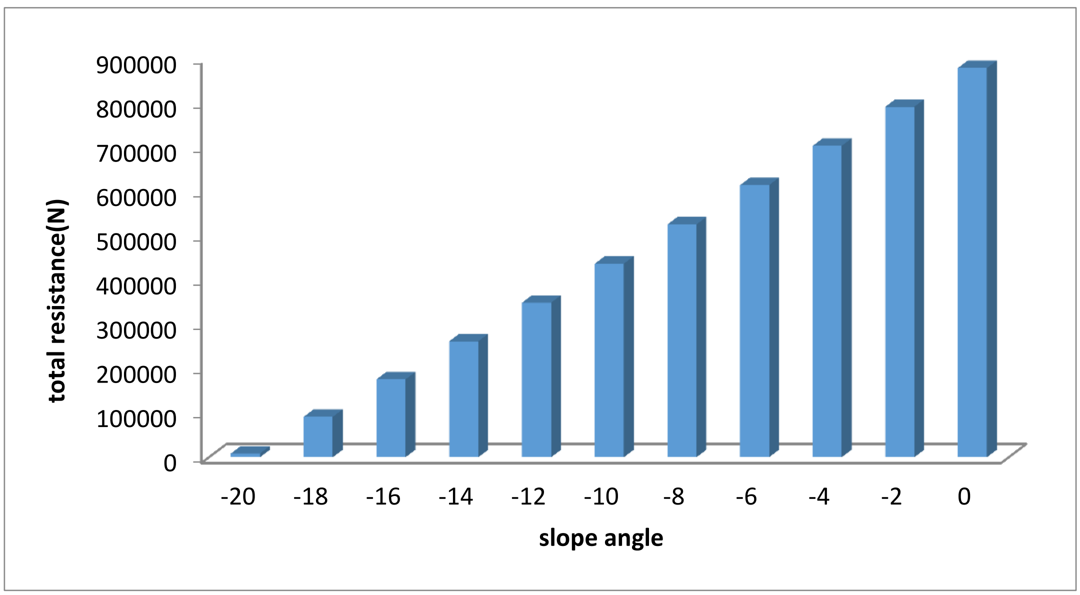


Figure 4.3. Vehicle moving down slope

4.3. Energy absorbed by the brake

The energy absorbed by a brake depends upon the type of motion of the moving body. The motion of a body may be either pure translation or pure rotation or a combination of both translation and rotation. The energy corresponding to these motions is kinetic energy. Let consider these motions as follows:

When the motion of the body is pure translation, consider a body of mass (m) moving with a velocity U m / s. Let its velocity is reduced to V m / s by applying the brake. Therefore, the change in kinetic energy of the translating body or kinetic energy of translation, on equation (3.37)

$$KE = (1/2)\, m\, [(u)^2 - (v)^2]$$

Gross vehicle mass = 3150 from car specification

Let assume vehicle speed ranges from (0-100Km/hr)

This energy must be absorbed by the brake. When the vehicle is stopped after applying the brakes, then the final velocity (V) = 0, and from equation(3.38)

$$KE = (1/2)\, m\, (U)^2$$

Table 4.4. KE loss up to final velocity equals zero

U(m/sec)	0	2.78	5.56	8.34	11.12	13.9	16.68	19.46	22.24	25.02	27.8
KE(KJ)	0	12.2	48.7	109.6	194.8	304.3	438.2	596.4	779.0	985.9	1217.2

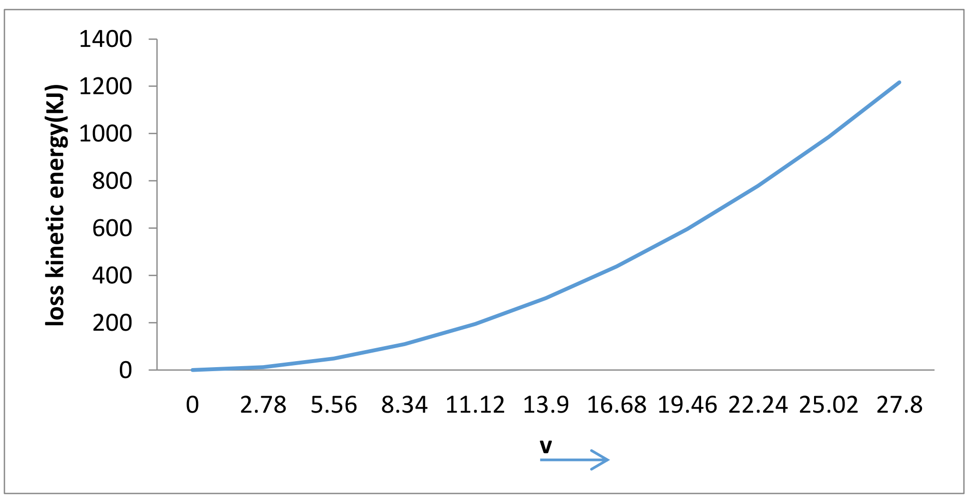


Figure 4.4. Kinetic energy loss up to final velocity equals zero

When the motion of the body is pure rotation, consider a body of mass moment of inertia I (about a given axis) is rotating about that axis with an angular velocity ω_1 rad/s. Let its angular velocity is reduced to ω_2 rad / s after applying the brake. Therefore, the change in kinetic energy of the rotating body or kinetic energy of rotation,

$$KE_2 = (1/2)\, I\, [(\omega_1)^2 - (\omega_2)^2]$$

$$I = mr^2$$

$$KE_2 = 3150 \times (0.34)^2 = 364.14 Kg.m^2$$

$$\omega = V/r = from(0\text{-}27.778 m/s)/0.34m$$

Where

m = mass of the vehicle r = effective radius of the wheel

Table 4.5 kinetic energy in relation to angular rotation

ω(rad/sec)	0	8.18	16.36	24.54	32.72	40.9	49.08	57.26	65.44	73.62	81.8
KE(KJ)	0	12.2	48.7	109.6	194.9	304.7	438.6	596.9	779.7	986.8	1218.3

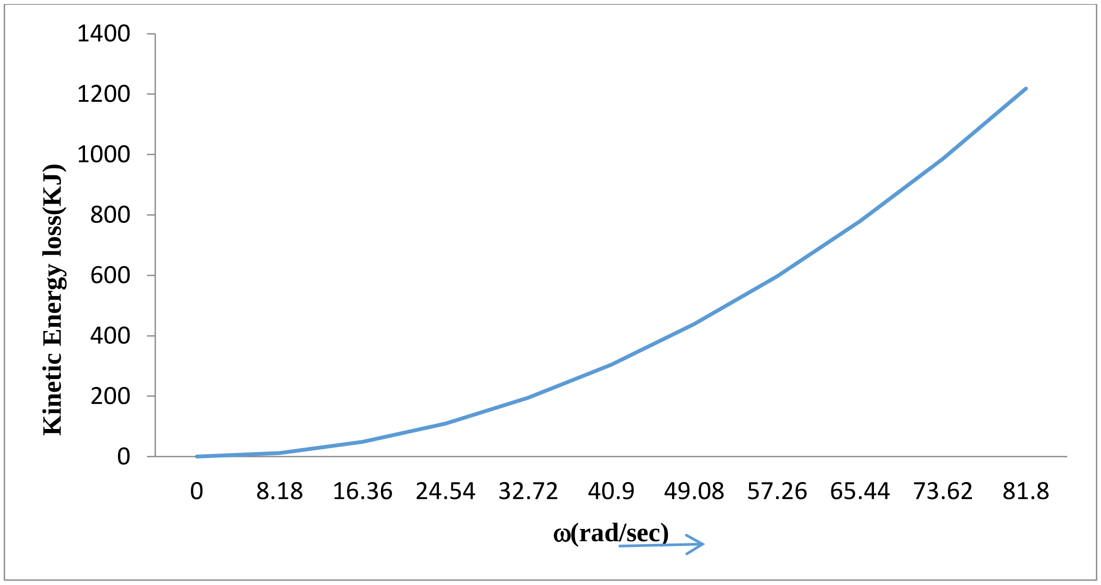


Figure 4.5. Kinetic energy in relation to angular rotation.

Total kinetic energy absorbed by the brake

When the motion of the body is a combination of translation and rotation, considering a body having both linear and angular motions,

$$KE_T = KE_1 + KE_2$$

Table 4.6. Total kinetic energy due to final velocity equals zero and angular velocity

velocity	kinetic energy 1(KJ)	kinetic energy 2(KJ)	total kinetic energy(KJ)
0	0	0	0
2.78	12.15	12.15	24.30
5.56	48.62	48.60	97.22
8.34	109.40	109.37	218.77
11.12	194.48	194.44	388.92
13.89	303.87	303.82	607.69
16.67	437.57	437.50	875.07
19.45	595.58	595.48	1191.06
22.23	777.90	777.77	1555.67
25	984.53	984.37	1968.90
27.78	1215.47	1215.27	2430.74

Kinetic energy of the vehicle when there are about five passengers with average mass of 75kg

Total mass = mass of vehicle + mass of passenger + extra load added

Let say extra load added = 200kg

m = 3150 + 375 +200 = 3725kg

KE = 1/2(3725)V^2

Table 4.7. KE loss when vehicle loaded

V(m/sec)	0	2.78	5.56	8.34	11.12	13.9	16.68	19.46	22.24	25.02	27.8
KE(KJ)	0	14.4	57.6	129.5	230.3	359.8	518.2	705.3	921.2	1165.9	1439.4

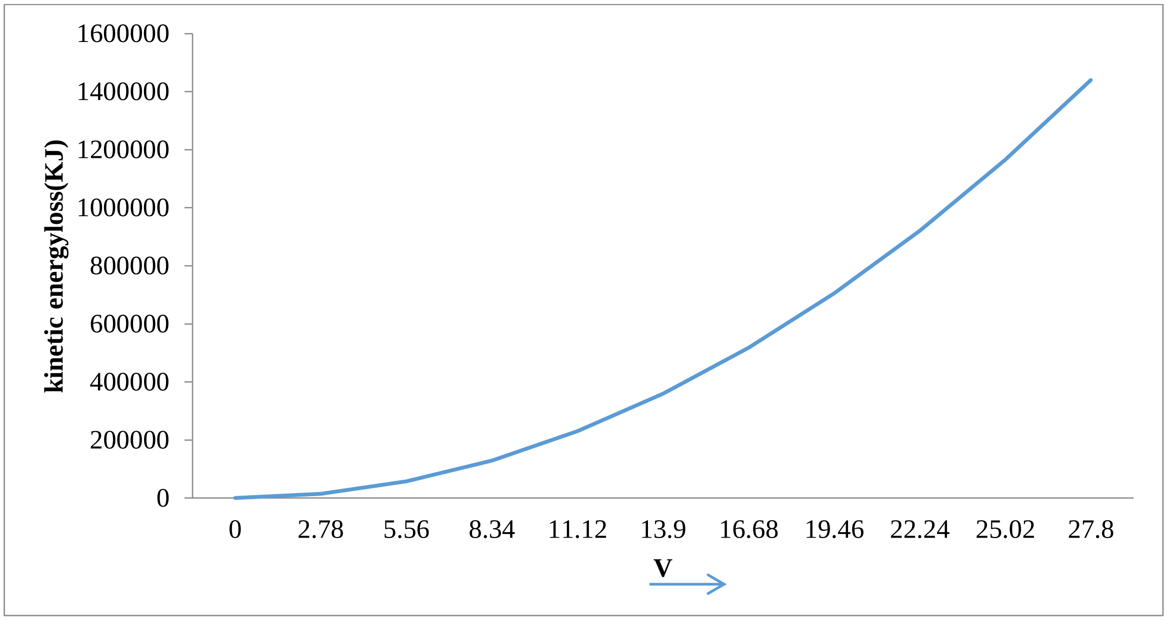


Figure 4.6. Kinetic energy loss when vehicle is loaded

Kinetic energy absorbed by the vehicle when the vehicle has additional mass

Table 4.8. KE of vehicle with additional mass and vehicle mass only is related

velocity(m/s)	kinetic energy B	kinetic energy A	KE.B - KE.A
0	0	0	0
2.78	14.37	12.15	2.22
5.56	57.49	48.62	8.87
8.34	129.36	109.40	19.97
11.11	229.97	194.48	35.50
13.89	359.34	303.87	55.47
16.67	517.44	437.57	79.87
19.45	704.30	595.58	108.72
22.22	919.90	777.90	142.0
25.00	1164.25	984.53	179.72
27.78	1437.34	1215.47	221.87

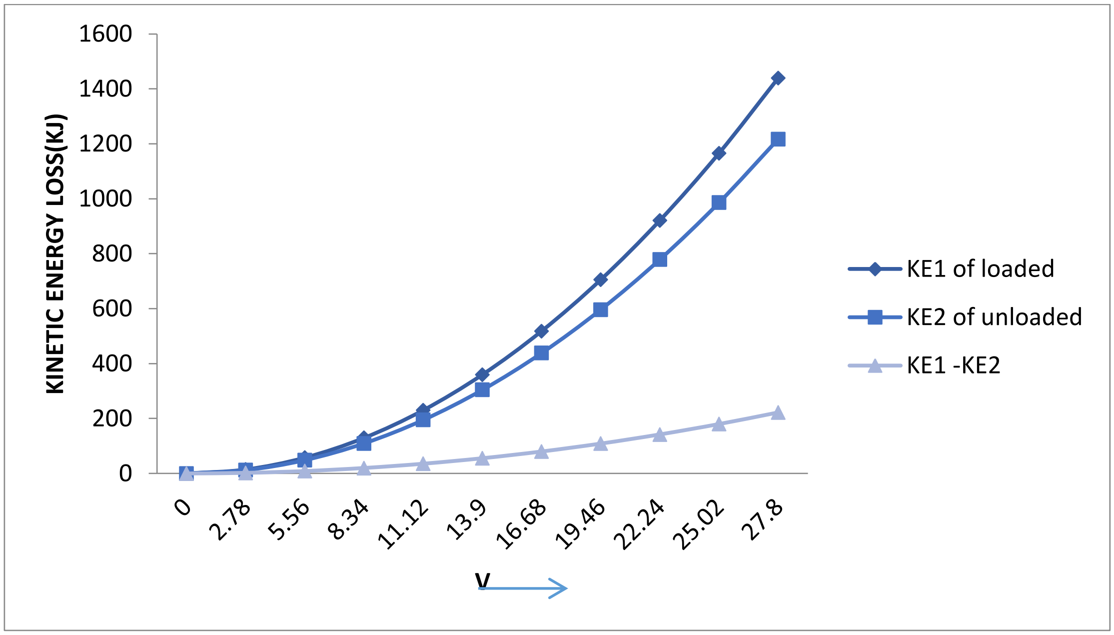


Figure 4.7. Kinetic energy vs velocity of the car

Total energy absorbed by brake has direct relation with the velocity of the vehicle as shown on the figure 4.8 and table 4.7, so by braking the vehicle that is in high velocity has high absorbable energy due to this kinetic energy recovery system must be there to save the loosing energy while braking.

For vehicle moving with a velocity of 27.78m/sec the kinetic energy loss of Toyota hilux 4x4 is about 2430.74KJ but the calorific value of Diesel is approximately 44800 kJ/kg [30]. This means 2430.74/44800 = 0.0543 kg or 54.3 gms of Diesel equivalent energy was lost as heat.

While for some, these might be insignificant values, however they become huge numbers over the lifetime of the car. Therefore regenerative braking feature is an important to evolve for having sustainable transport.

4.4. Energy stored on Flat spiral spring

The spiral spring is subjected to a torque applied in such a way that the relative shaft–housing rotation causes bending of the turns of the spiral strip. It is assumed that the spring housing is fixed using a driver controlled lever and the inner shaft is loaded by a torque (during vehicle braking) about the spring axis, the spiral spring will thus deform and stores the kinetic energy of the vehicle as elastic potential energy. This stored energy can then be utilized to provide an instant boost to the vehicle.

$$E_S = \frac{(\sigma b)^2}{24E} \times b.t.l = \frac{(\sigma b)^2}{24E} \times volume$$

$$E_S = \frac{(55196.91)^2}{24 \times 208000} \times 44 * 1.5 * 4000$$

$$E_S = 40280.87 * 4000 = 161.1KJ$$

Angular deflection with variation of length of the spring

$$\theta = \frac{M.l}{E.I} = 0.81l$$

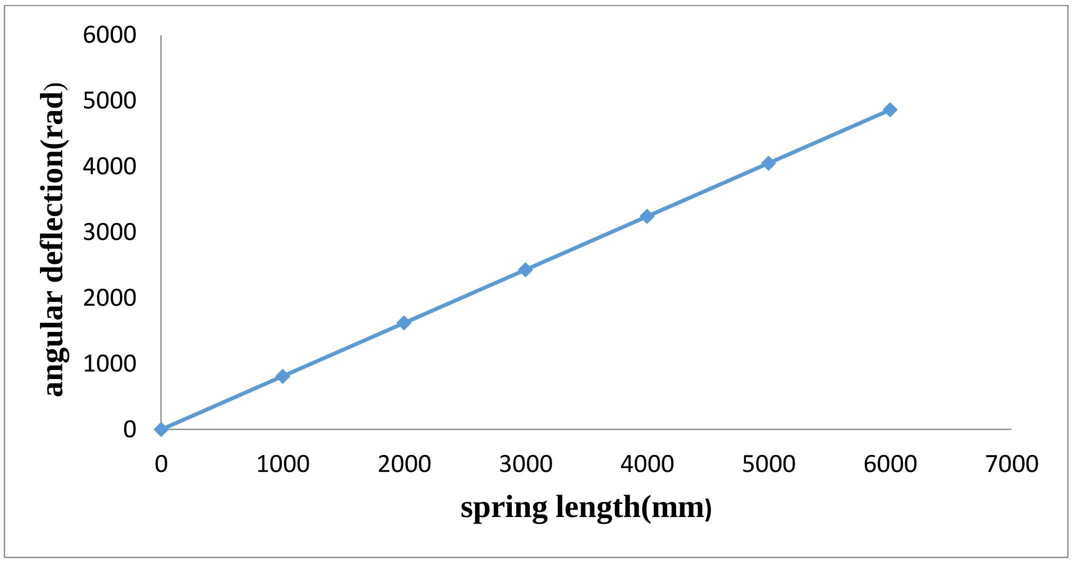


Figure 4.8. Angular deflection with varying spring length

Spring length designed to 5000mm because at this length the KE recovery is more efficient than spring length that is less than 5000mm and due to space on the vehicle the length of the spring should not be more than 5000mm.

The efficiency of braking is given by equation

$$\eta_b = \frac{E_s}{KE} \times 100\%$$

Table 4.9. Kinetic Energy, Energy stored and Efficiency

No	V (m/sec)	KE $_1$ (KJ)	KE $_2$ (KJ)	KE_T (KJ)	Energy Stored (KJ)	η%
1	8.34	109.5	109.5	219	201.4	91.9
2	11.12	194.8	194.8	389.5	201.4	51.7
3	13.89	304.3	304.3	608.6	201.4	33.1
4	16.68	438.2	438.2	876.4	201.4	23.0
5	19.46	596.4	596.4	1192.9	201.4	16.9
6	22.24	779.0	779.0	1558.0	201.4	12.9
7	25.02	985.9	985.9	1971.9	201.4	10.2
8	27.8	1217.2	1217.2	2434.4	201.4	8.3

The result shown on the table 4.9 is illustrating the vehicle with flat spiral spring kinetic energy recovery and vehicle without flat spiral kinetic energy recovery. By taking the velocity of the vehicle from 8.34m/sec to 27.8 the kinetic energy loss of the vehicle is increasing with the increase of velocity but efficiency of the kinetic energy recovery system will decrease. Braking the Vehicle with velocity of 8.34m/sec has 219KJ of kinetic energy loss and energy stored by flat spiral spring is 201.4KJ and the system is 91.9%.

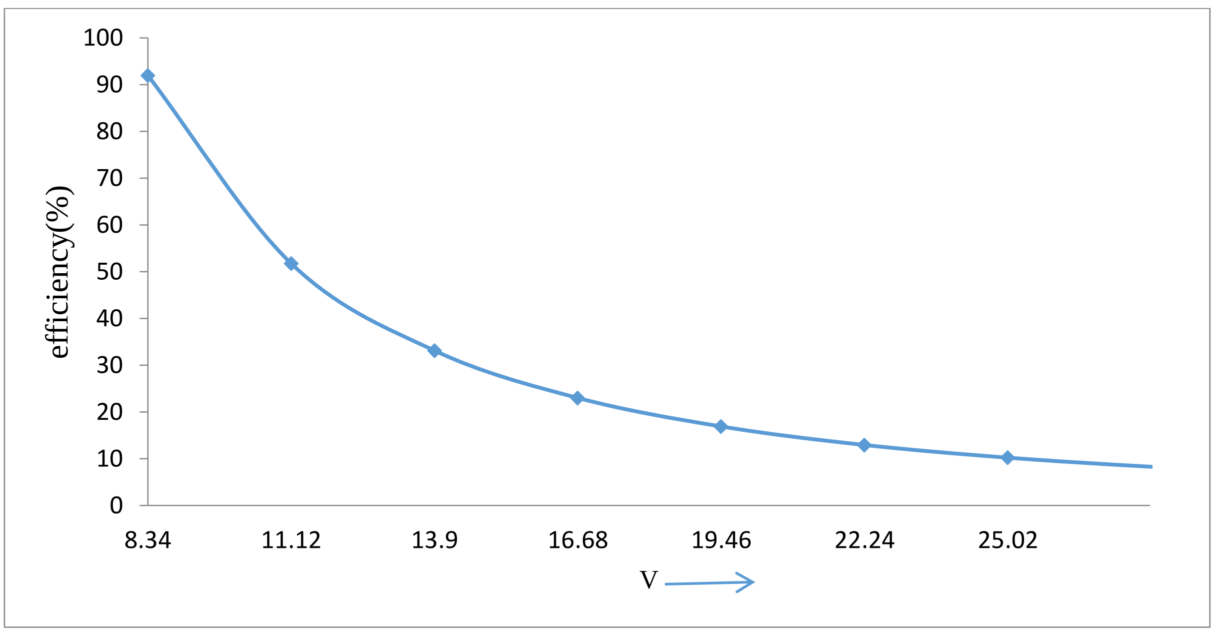


Figure 4.9. Efficiency of Kinetic energy recovery system with varying vehicle velocity

4.5. Solid-work simulation of parts

4.5.1. Carrier

Carrier is one part of the kinetic energy recovery system which is design to hold the carrier pin with the planet gear. On solid work the simulation of carrier is done and the results are shown below on tables.

Material Properties carrier

Table 4.10. Material property of carrier

Name:	AISI 1020
Model type:	Linear Elastic Isotropic
Default failure criterion:	Max von Mises Stress
Yield strength:	3.51571e+008 N/m^2
Tensile strength:	4.20507e+008 N/m^2
Elastic modulus:	2e+011 N/m^2
Poisson's ratio:	0.29
Mass density:	7900 kg/m^3
Shear modulus:	7.7e+010 N/m^2
Thermal expansion coefficient:	1.5e-005 /Kelvin

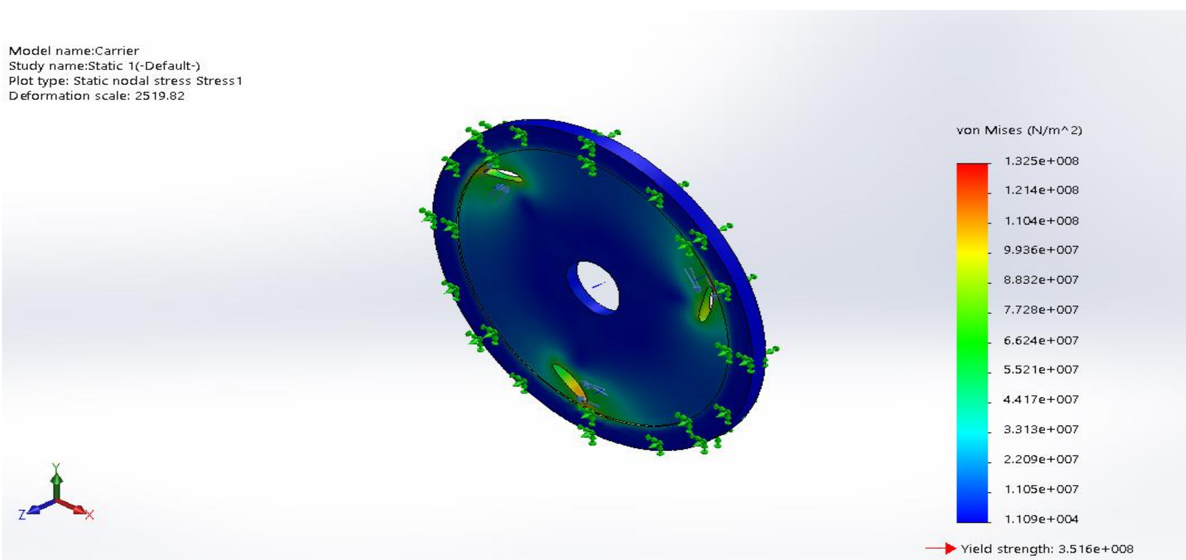


Figure 4.10. Carrier-Static 1-Stress-Stress1

Figure 4.10 shows simulation result of von mises stress for carrier which has minimum value $1.109*10^4$ N/m^2 and maximum value $1.325*10^8$ N/m^2 and selected material yield strength is $3.516*10^8$ N/m^2. This shows the carrier is safe for application because yield strength is greater than the von mises stress.

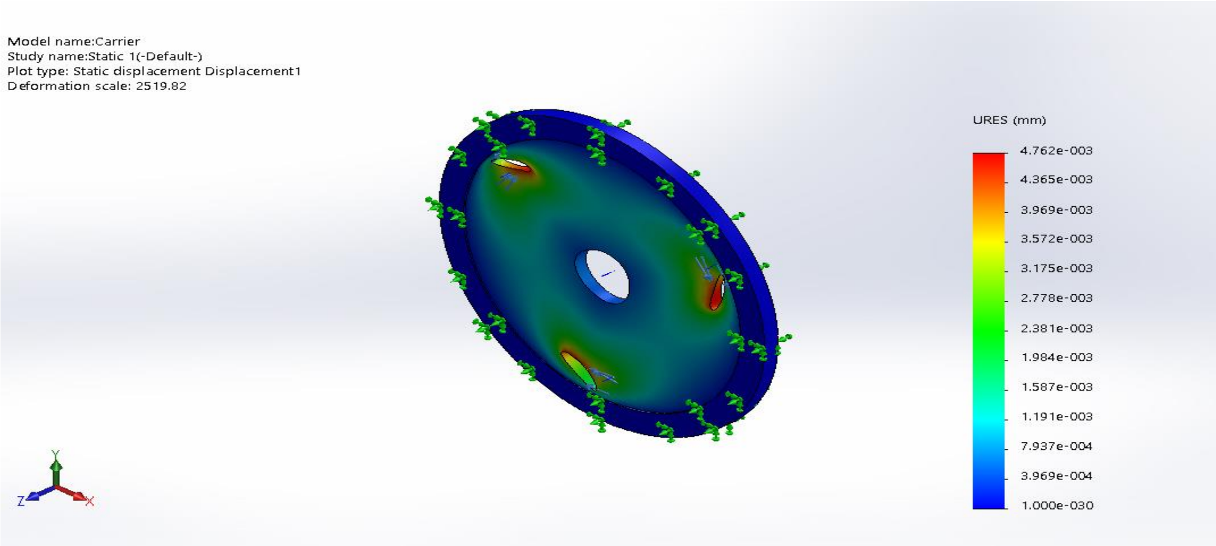


Figure 4.11. Carrier-Static 1-Displacement-Displacement1

The deformation scale is 2519.82 which indicate the carrier is too far to deform with the applied torque.

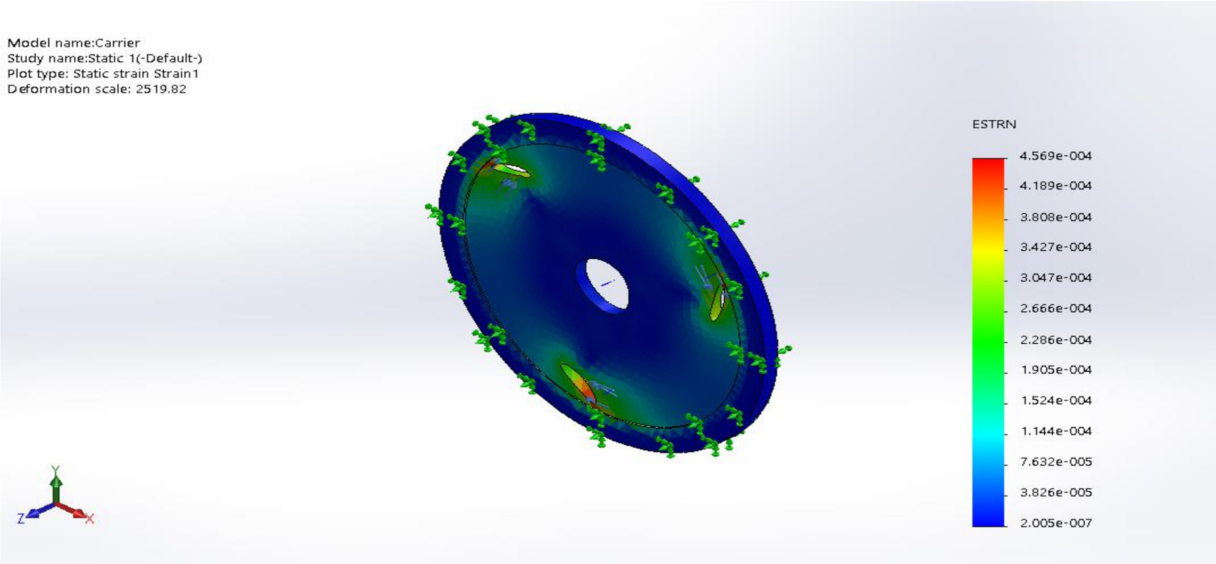


Figure 4.12. Carrier-Static 1-Strain-Strain1

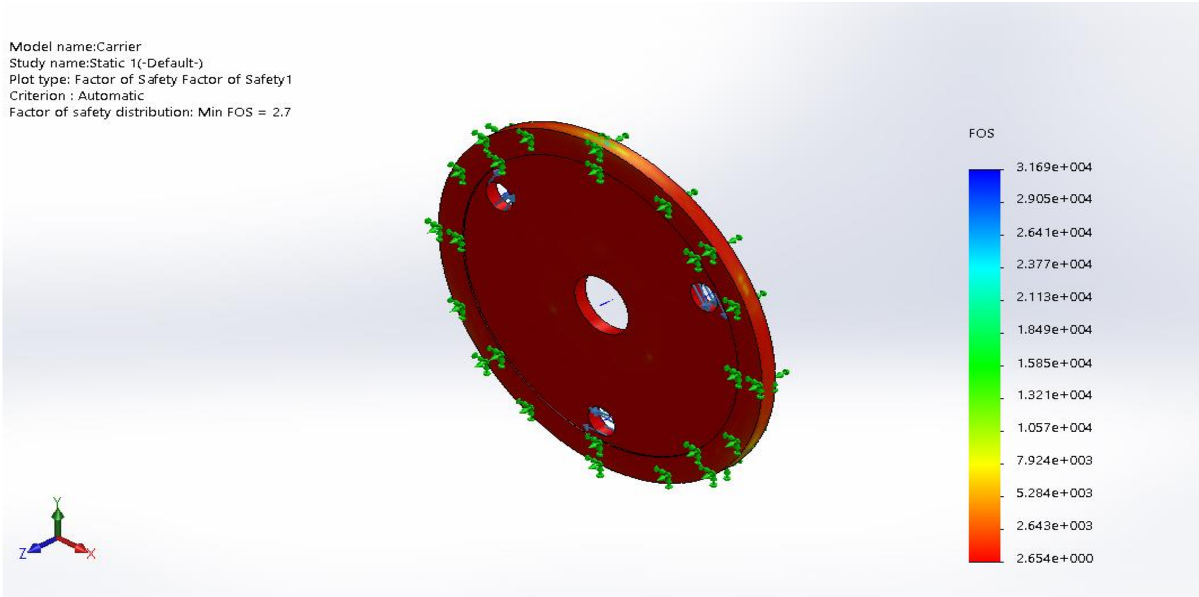


Figure 4.13. Carrier-Static 1-Factor of Safety-Factor of Safety1

4.5.2. Carrier pin

Carrier pin(shaft) is used to connect the carrier(arm) with the planet pears.

Material Properties of carrier pin is a shaft which is used in

Table 4.11. Material Properties of carrier pin

Name:	AISI 1020	Volumetric property
Model type:	Linear Elastic Isotropic	Mass:0.0198549 kg Volume:2.51327e-006 m^3 Density:7900 kg/m^3 Weight:0.194578 N
Default failure criterion:	Max von Mises Stress	
Yield strength:	3.51571e+008 N/m^2	
Tensile strength:	4.20507e+008 N/m^2	
Elastic modulus:	2e+011 N/m^2	
Poisson's ratio:	0.29	
Mass density:	7900 kg/m^3	
Shear modulus:	7.7e+010 N/m^2	
Thermal expansion coefficient:	1.5e-005 /Kelvin	

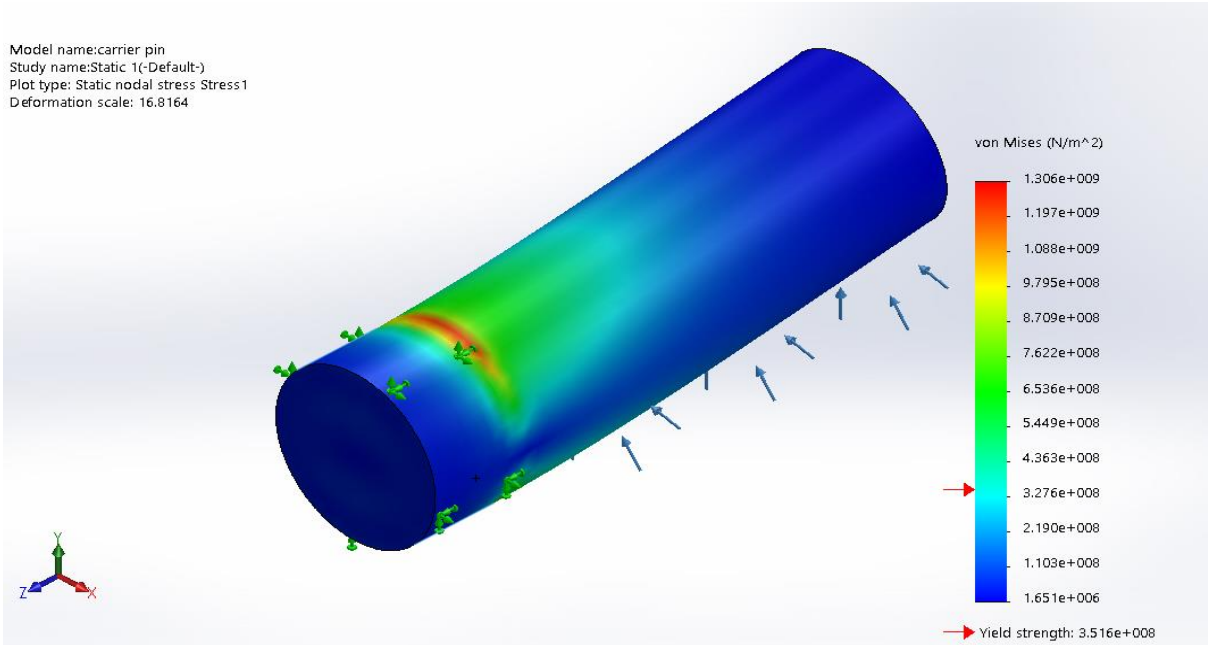


Figure 4.14. Carrier pin-Static 1-Stress-Stress1

Figure 4.14 shows simulation result of von mises stress for carrier which has minimum value $1.601*10^6$ N/m^2 and maximum value $1.306*10^9$ N/m^2 and selected material yield strength is $3.516*10^8$ N/m^2 but carrier pin stress is $3.276*10^8$ which is less than the yield strength so carrier pin is safe for application.

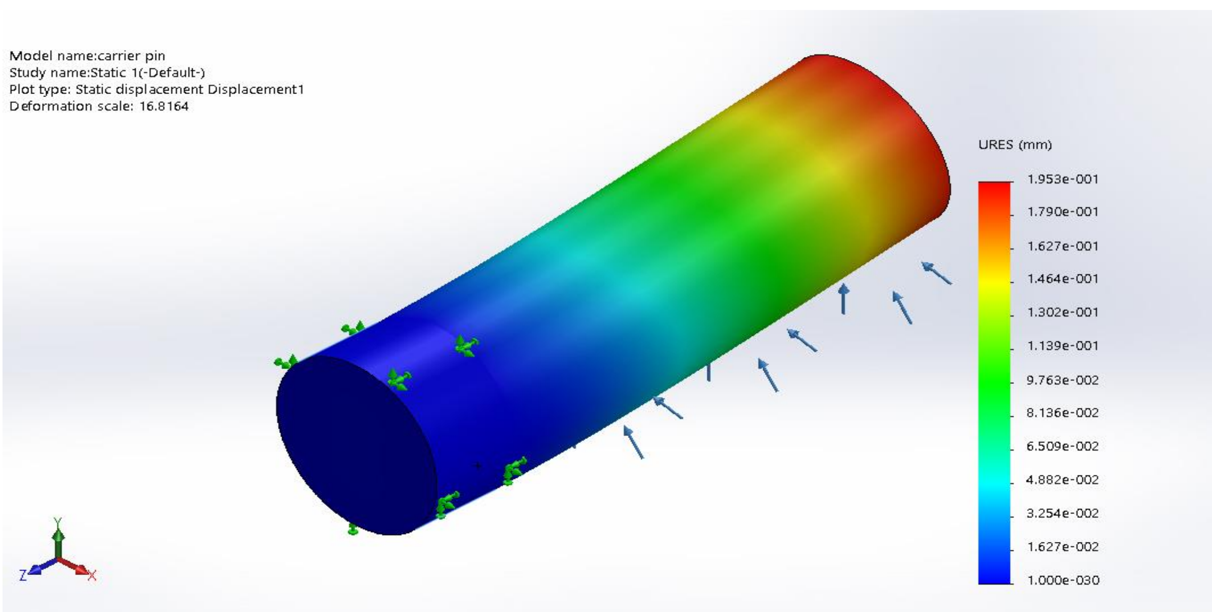


Figure 4.15.Carrier pin-Static 1-Displacement-Displacement1

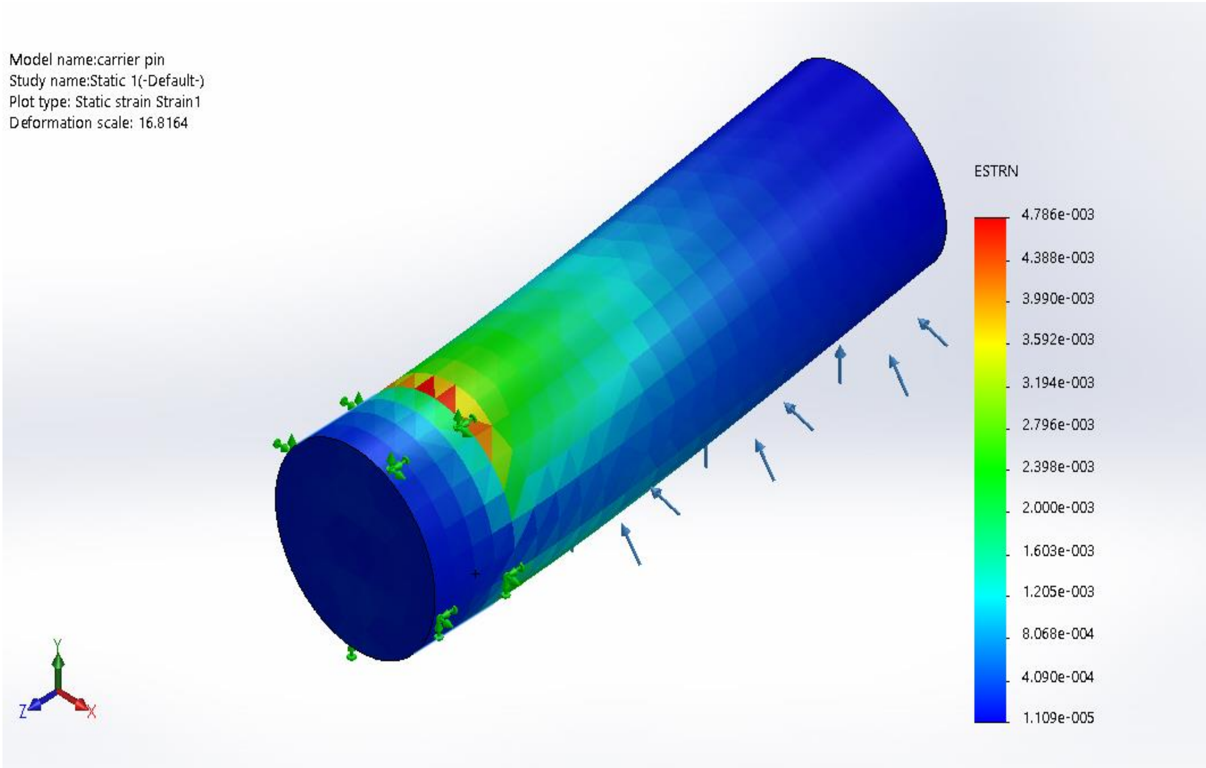


Figure 4.16. Carrier pin-Static 1-Strain-Strain1

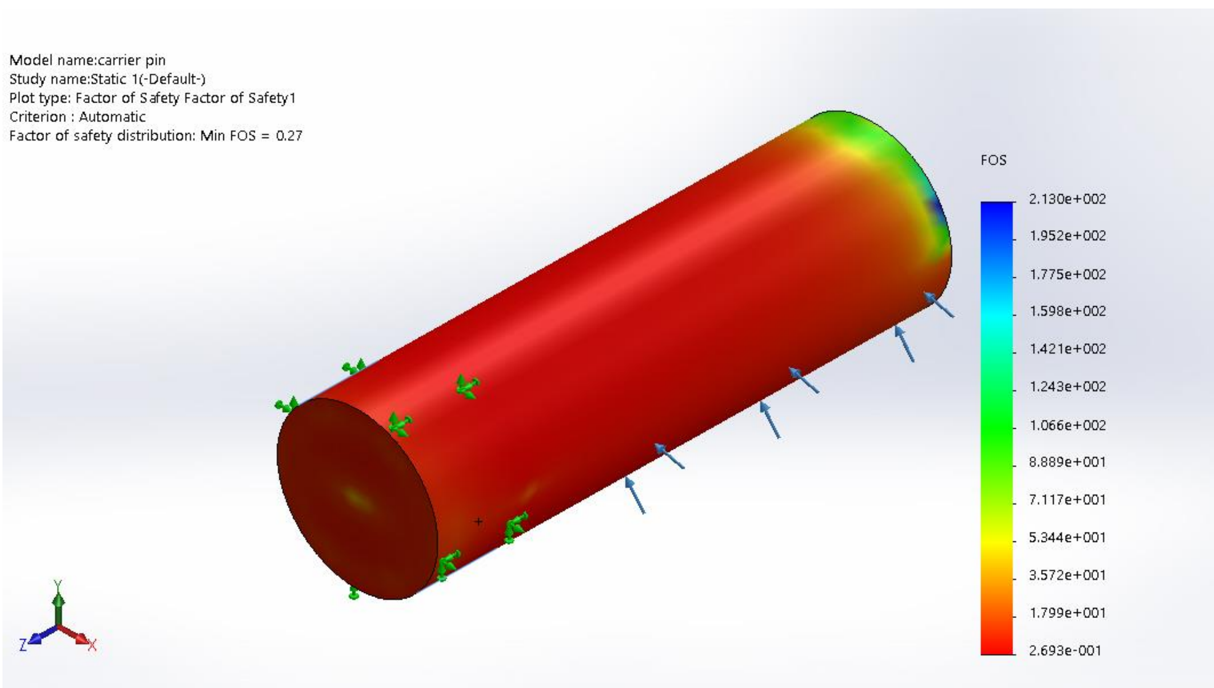


Figure 4.17. Carrier pin-Static 1-Factor of Safety-Factor of Safety1

4.5.3. Ratchet

The one-way clutch is a ratcheting device onto which the drum is mounted. The one-way clutch ensures that the motion or energy is not transmitted to the drum during idling or braking.

Table 4.12. Material Properties of the ratchet

Name:	AISI 1020	Volumetric Properties
Model type:	Linear Elastic Isotropic	Mass:0.0026572 kg
Default failure criterion:	Max von Mises Stress	Volume:3.36354e-007 m^3
Yield strength:	3.51571e+008 N/m^2	Density:7800 kg/m^3
Tensile strength:	4.20507e+008 N/m^2	Weight:0.0260406 N
Elastic modulus:	2e+011 N/m^2	
Poisson's ratio:	0.29	
Mass density:	7900 kg/m^3	
Shear modulus:	7.7e+010 N/m^2	
Thermal expansion coefficient:	1.5e-005 /Kelvin	

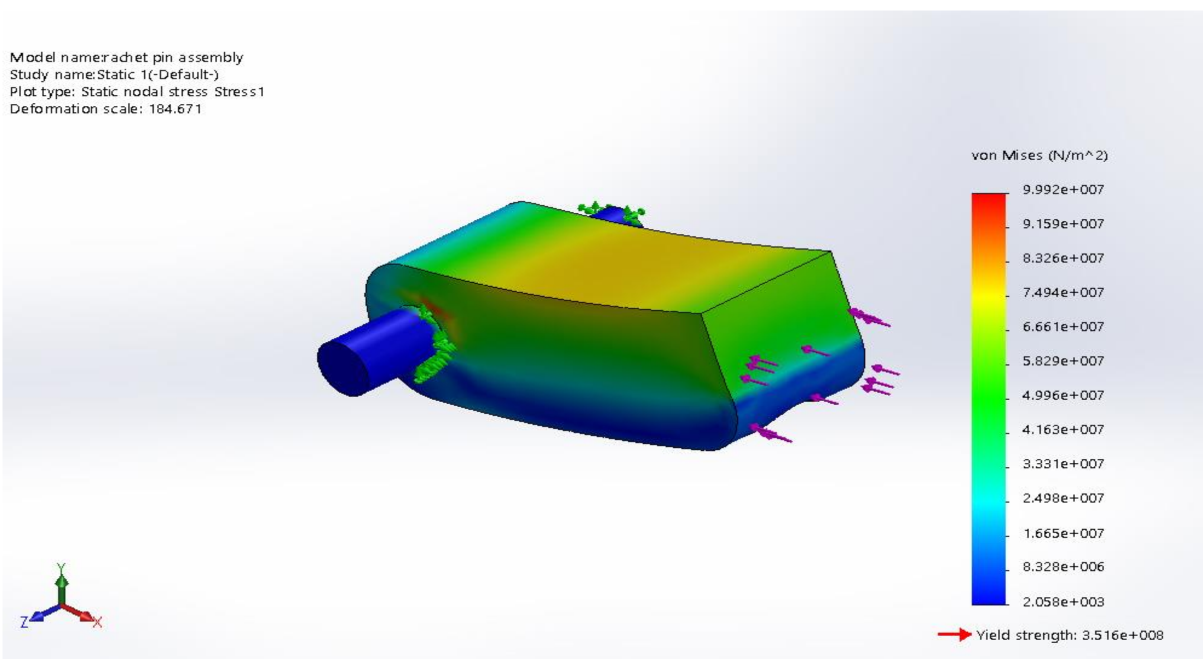


Figure 4.18. Ratchet pin assembly-Static 1-Stress-Stress1

Figure 4.18 shows simulation result of von mises stress for carrier which has minimum value $2.058*10^3$ N/m^2 and maximum value $9.992*10^7$ N/m^2 and selected material yield strength is $3.516*10^8$ N/m^2. This shows the carrier is safe for application because yield strength is greater than the von mises stress.

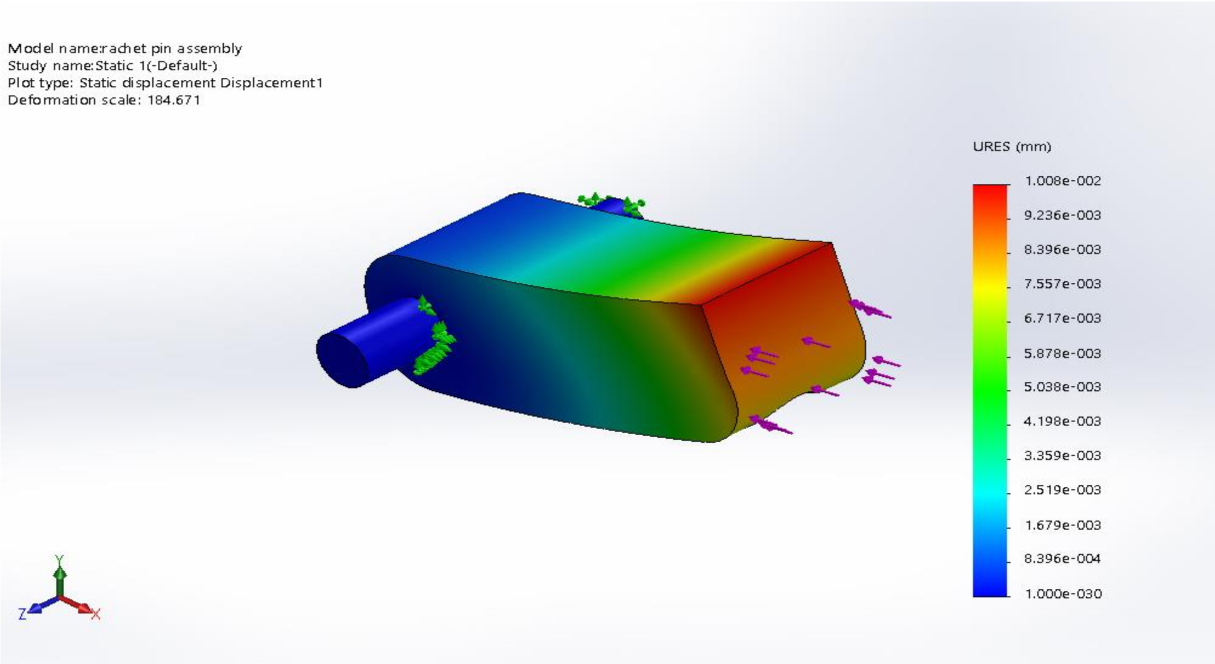


Figure 4.19. Ratchet pin assembly-Static 1-Displacement-Displacement1

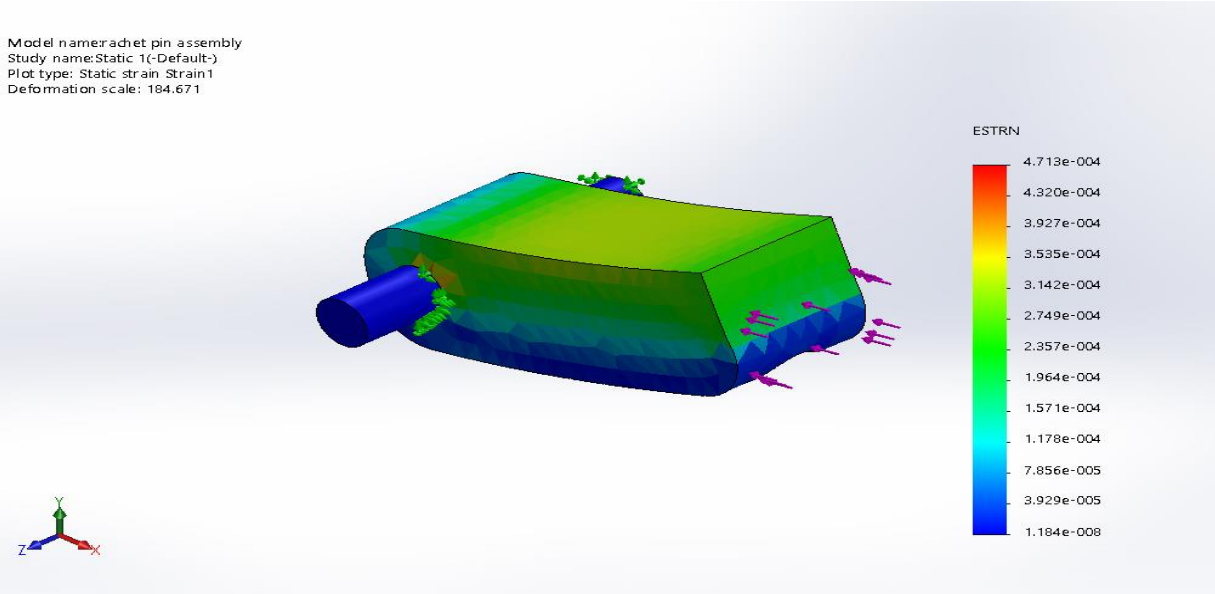


Figure 4.20. Ratchet pin assembly-Static 1-Strain-Strain1

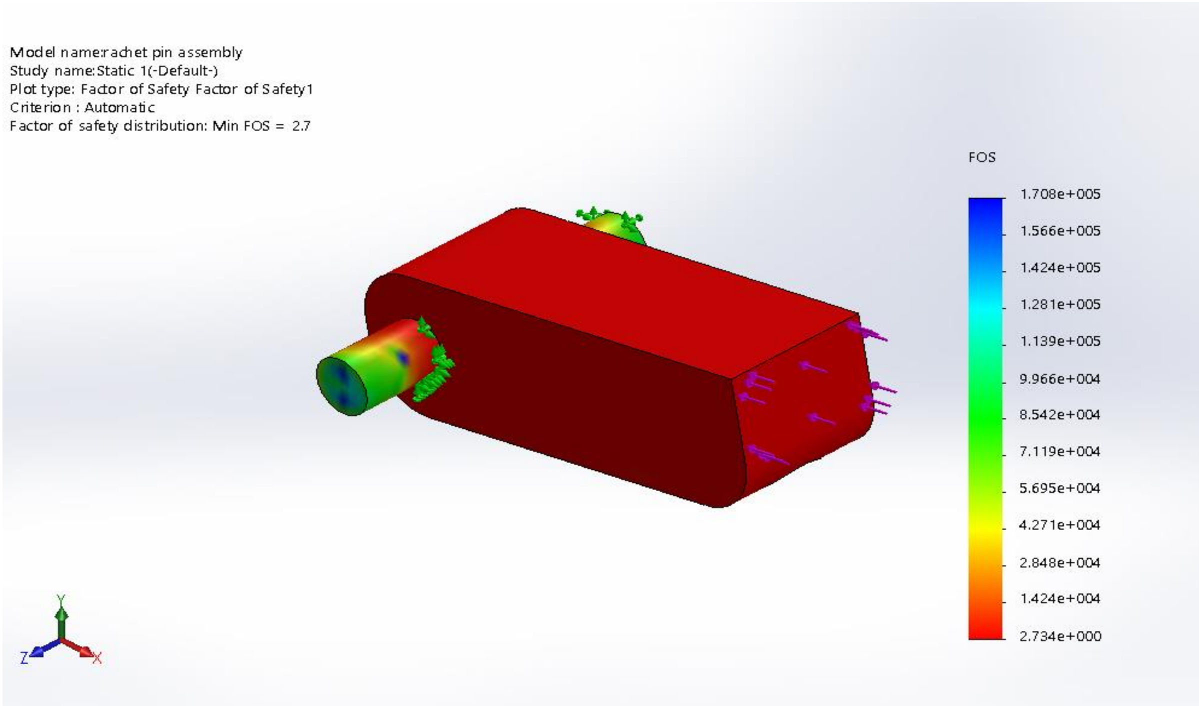


Figure 4.21. Ratchet pin assembly-Static 1-Factor of Safety-Factor of Safety1

4.5.4. Drum

Table 4.13. Material Properties of the drum

Name:	AISI 1020	Volumetric Properties
Model type:	Linear Elastic Isotropic	Mass:0.364595 kg Volume:4.61512e-005 m^3 Density:7900 kg/m^3 Weight:3.57303 N
Default failure criterion:	Max von Mises Stress	
Yield strength:	3.51571e+008 N/m^2	
Tensile strength:	4.20507e+008 N/m^2	
Elastic modulus:	2e+011 N/m^2	
Poisson's ratio:	0.29	
Mass density:	7900 kg/m^3	
Shear modulus:	7.7e+010 N/m^2	
Thermal expansion coefficient:	1.5e-005 /Kelvin	

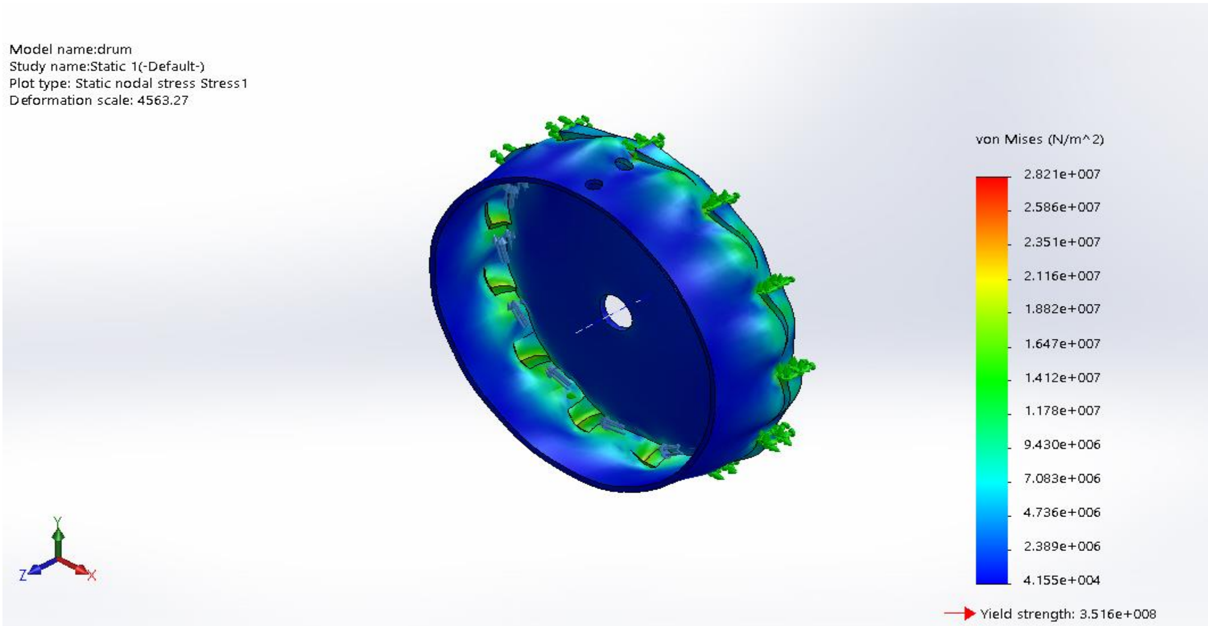


Figure 4.22. Drum-Static 1-Stress-Stress1

Figure 4.22. Shows simulation result of von mises stress for drum which has minimum value $4.155*10^4$ N/m^2 and maximum value $2.821*10^7$ N/m^2 and selected material yield strength is $3.516*10^8$ N/m^2. This shows the carrier is safe for application because yield strength is greater than the von mises stress

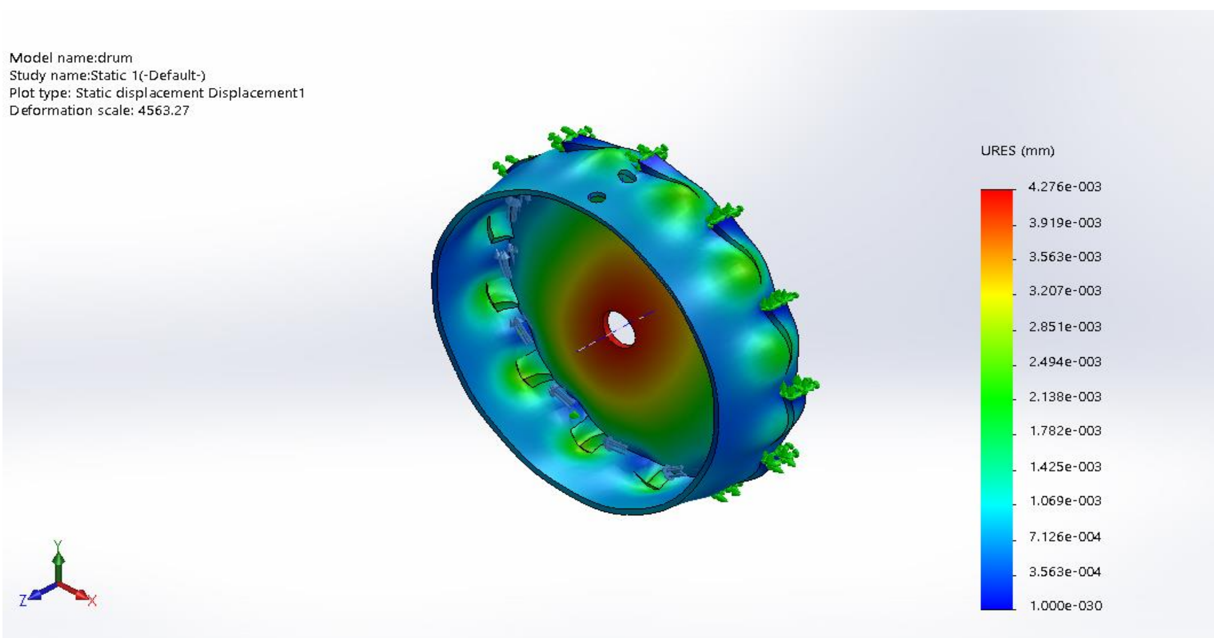


Figure 4.23. Drum-Static 1-Displacement-Displacement1

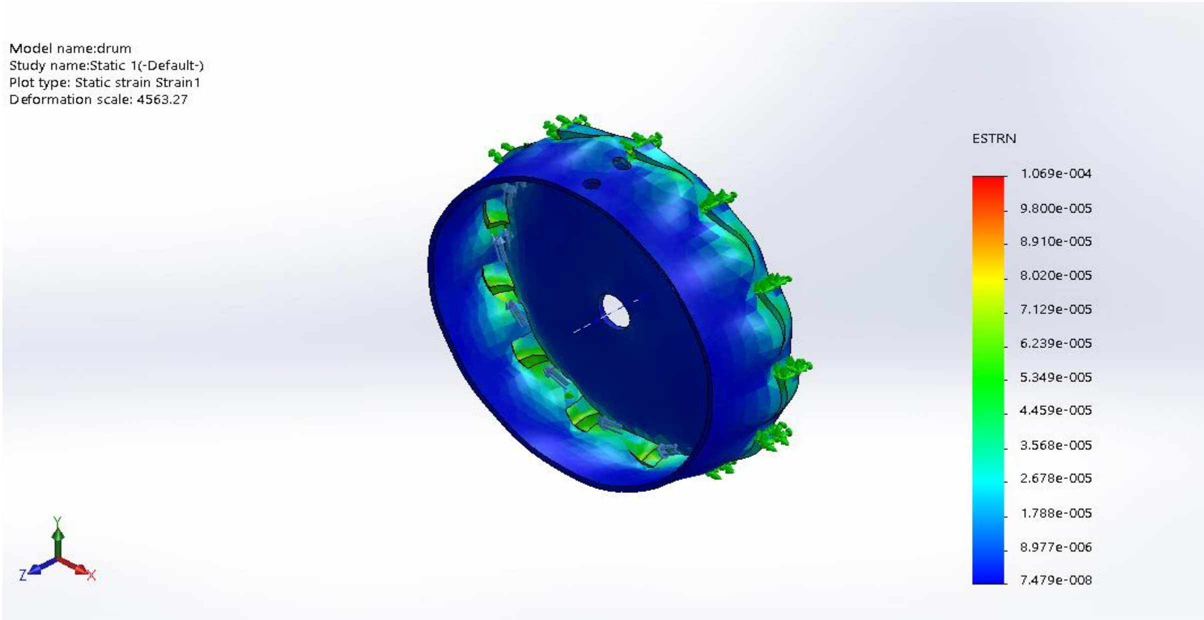


Figure 4.24. Drum-Static 1-Strain-Strain1

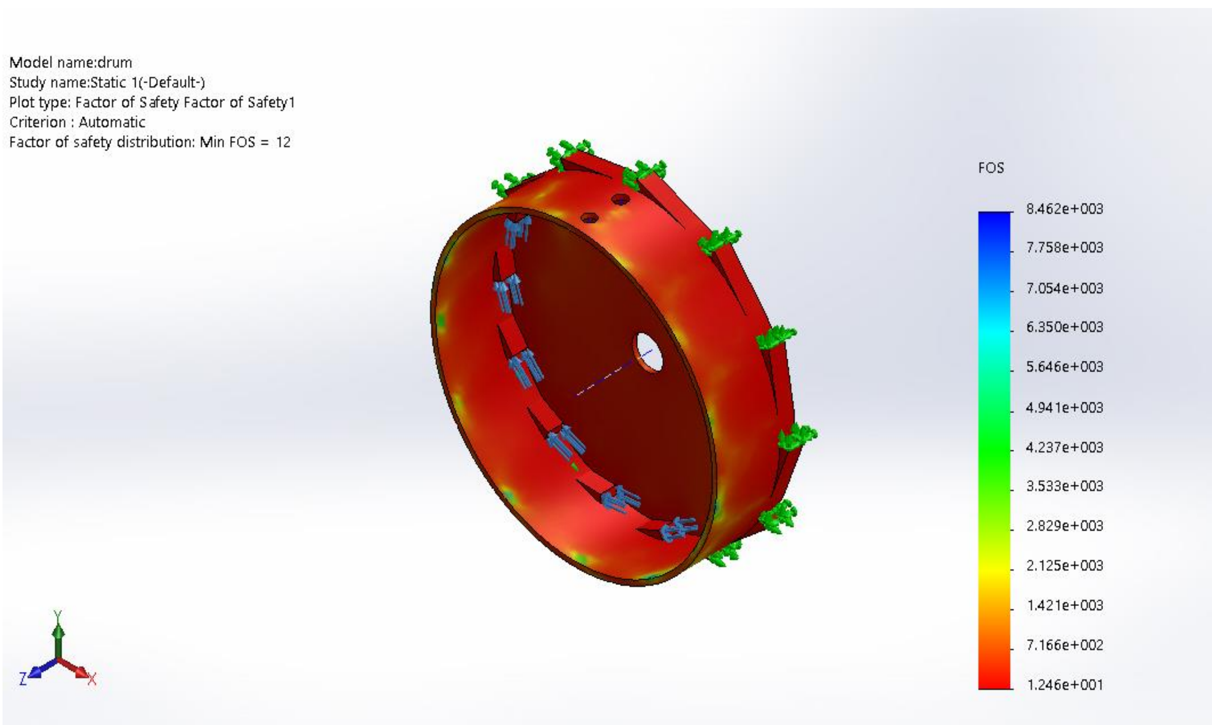


Figure 4.25. Drum-Static 1-Factor of Safety-Factor of Safety1

Table 4.14. Total mass of the KERS

No	Part name	Qunt.	Mass (kg)	Total(Kg)
1	Sun gear	1	0.11	0.11
2	Planet gear	3	0.316	0.948
3	Ring gear	1	0.138	0.138
4	Carrier	1	0.364595	0.365
5	Carrier pin	3	0.0199	0.0199
6	Bearing	6	0.0005	0.03
7	Ratchet	14	0.0026572	0.0372
8	Drum	1	1.35	1.35
9	Spring	1	0.154	1.54
10	Housing	1	1.35	1.35
			Total	5.89

The table show mass of the kinetic energy recovery system that is around 6 Kg. When this mass is related to gross mass of the vehicle which is 3150Kg the load added to the vehicle is negligible

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1. Summary

Flat spiral spring based regenerative braking system is designed to save the lost kinetic energy for Toyota Hilux 4x4. Recovery of the energy is the most interesting and valuable job for designers, manufacturers, and also vehicle companies so design of flat spiral spring for Toyota Hilux 4x4 is compatible with small modification on the vehicle due to different consideration and results that are found.

By taking the velocity of the vehicle from 8.34m/sec to 27.8 the kinetic energy loss of the vehicle is increasing with the increase of velocity but efficiency of the kinetic energy recovery system will decrease. Braking the Vehicle with velocity of 8.34m/sec has 219KJ of kinetic energy loss and energy stored by flat spiral spring is 201.4KJ and the system is 91.9%.

The simulation of parts like carrier, carrier pin, ratchet, and drum is done for von mises stress, displacement, equivalent strain and safety factor with solid work design and the parts are safe for application.

In this mechanism the planetary gears are attached to the planet carrier by using studs and bolts. During normal motion of vehicle, both the planet gear and carrier rotates about the same axis i.e. axis of shaft. Thus no motion is transmitted to the ring gear and is at a standstill position which thereby results in no energy is being transmitted and stored into the spring.

However when the brake is applied to stop the vehicle, the planet carrier stops rotating about the axis of shaft and as a result the gears start rotating about its own axis with the help of flat bearing which are previously bored into the planetary gears. Now the motion is transmitted to the ring gear and ring gear starts rotating in opposite direction as that of the wheel. As the drum and ring gear are coupled together, as soon as the ring gear starts rotating; the drum also starts rotating in the same direction as that of the ring gear. Since the internal end of the spring is brazed with the drum, as the drum rotates spring also starts winding. The winding of spring results in compression of spring and in this way the energy is stored into the spiral spring. In this way the spiral spring plays a vital role in Kinetic Energy Recovery System as main energy storing element. The ratchet restricts reverse motion of spring (i.e. involuntary unwinding of spring) and only allows spring to be winded. Restoring this stored energy is exact opposite of the storing method. When the brake is released and accelerator pedal is pressed, clutch will also open. Due to this the spring is release and starts rotating in the same direction as that of the wheel. This rotation of the spring is transferred to the axle shaft through the planetary gear assembly. Vehicle is accelerated by using the energy stored in the spring in form of compression of spring. In this way KERS utilizes the energy which is otherwise lost during braking in the form of heat energy and increases the fuel efficiency of the vehicle. It does so without affecting the performance or fuel economy of the vehicle.

5.2. Conclusion

A flat spiral spring-based mechanical regenerative braking is able to use the flat spiral spring to slow the vehicle while storing energy as well as accelerate the vehicle while releasing energy from the spring. This concept was designed to be placed on the planetary gear assembly of the vehicle.

The axle only rotates in one direction while the vehicle is in forwarding motion, thus the design allow for this single direction of motion during both the regeneration mode and assist mode. In most strain devices, the deformation and relaxation cycle involves a reversal in direction. The flat spiral spring regenerative system mechanism is intended to function only when the vehicle is moving forward, thus it must account for the reversal of the storage element.

The regenerative braking and assist modes should only be active while the car is accelerating or decelerating, when the vehicle is at a constant speed the device should be inactive. Ideally, the device should produce minimal effects on the vehicle while not in use. Thus, this device must engage and disengage from the axle.

By taking the velocity of the vehicle from 8.34m/sec to 27.8 the kinetic energy loss of the vehicle is increasing with the increase of velocity but efficiency of the kinetic energy recovery system will decrease. Braking the Vehicle with velocity of 8.34m/sec has 219KJ of kinetic energy loss and energy stored by flat spiral spring is 201.4KJ and the system is 91.9% and can save 0.00464L of fuel from 0.005L which will be consumed at 8.34m/sec. But vehicle moving at 27.8m/sec the kinetic energy loss is 2434.4KJ and the stored energy is 201.4KJ and the kinetic energy recovery system is 8.3%. So using of flat spiral spring kinetic energy recovery is effective and recommendable for vehicle which has high stop and go times.

5.3. Recommendations

Today`s world automotive technology is highly organized and very fine to look after the problem that the existing vehicles faced on. Toyota Hilux have a problem of lost energy during braking in a form of heat. A number of scholars has investigate the problem of lost energy for different types of vehicles and design kinetic energy recovery system based on their investigation. But for Toyota Hilux I recommend to use flat spiral spring based energy recovery system. The flat spiral spring energy recovery system is not complicated, easily installed on the vehicle, cheaper than electrical KERS, light weighted than other KERS and the biggest advantage is not much modification in an existing vehicle transmission system.

5.4. Future work

In coming days spring based regenerative system will gain more attention with the advancement in spring design and spring material. The vehicle with start-stop cycle of driving will be affected the most with the introduction of this technology. The kinetic energy recovery using flat spiral spring is effective even though needs more improvement and electronic integration in to the system which is not done hear.

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Appendix – A

Vehicle specification

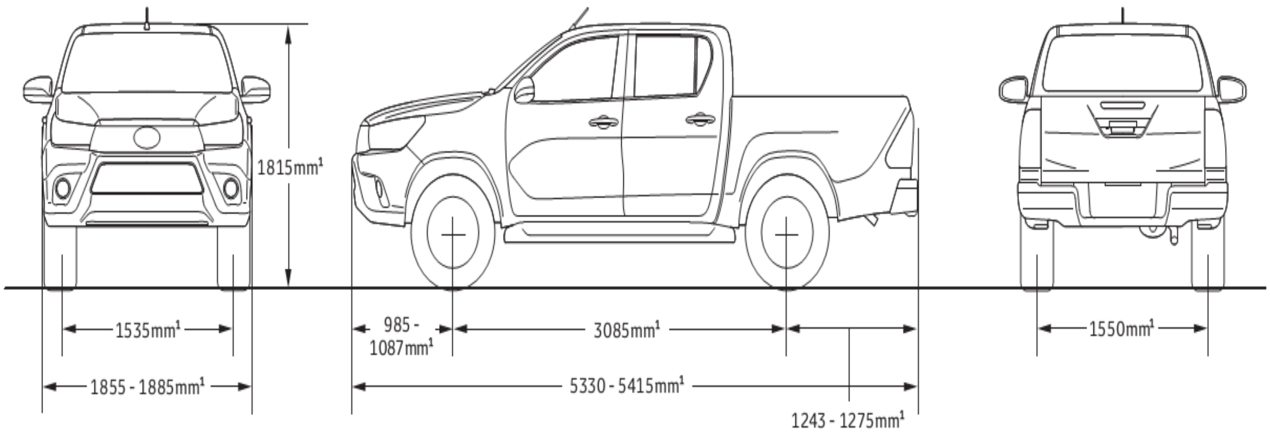
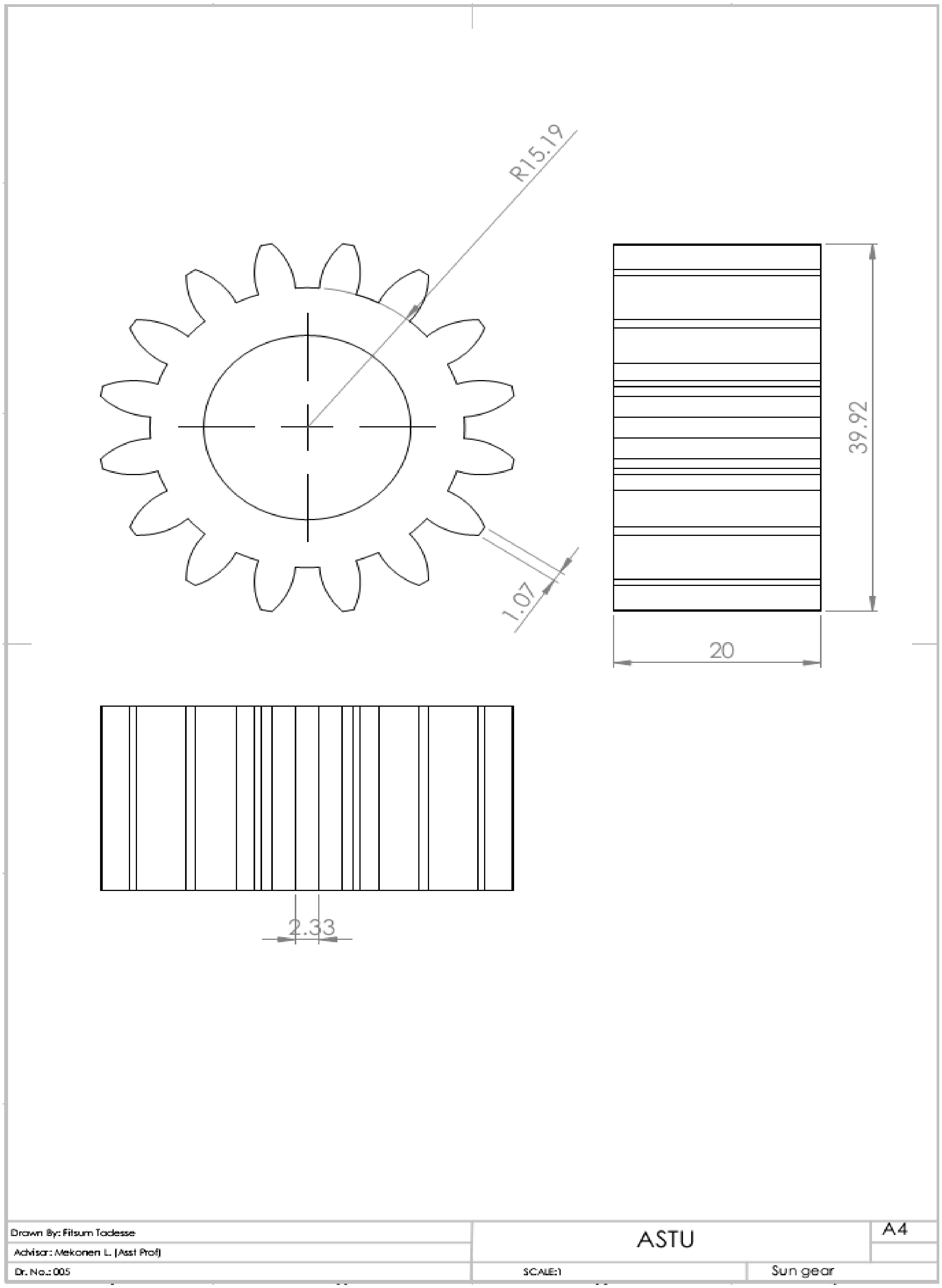
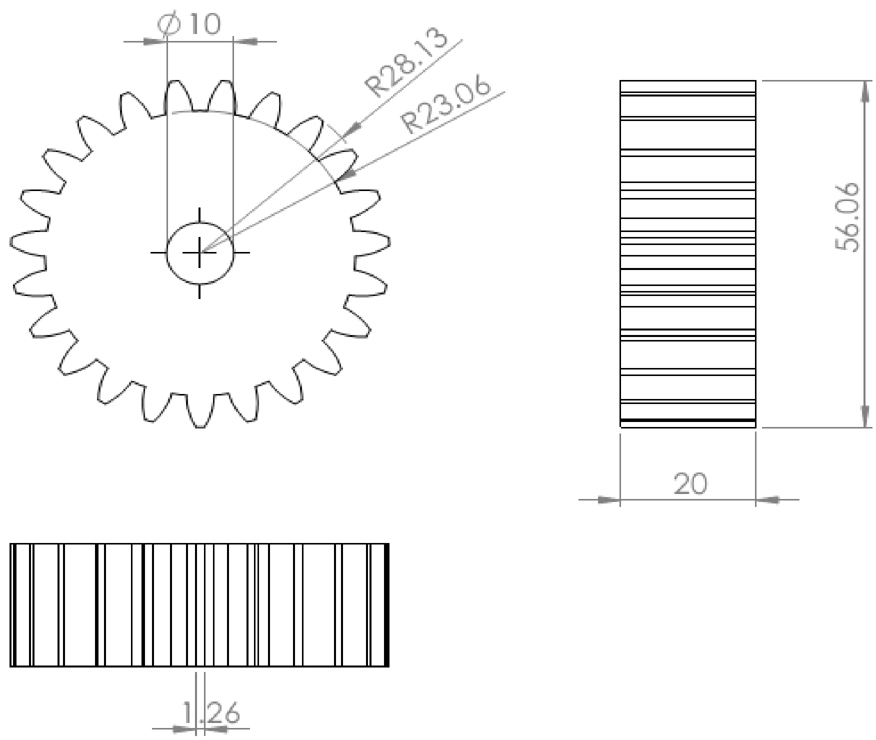


Table 5.1. Toyota Hilux thechnical specification

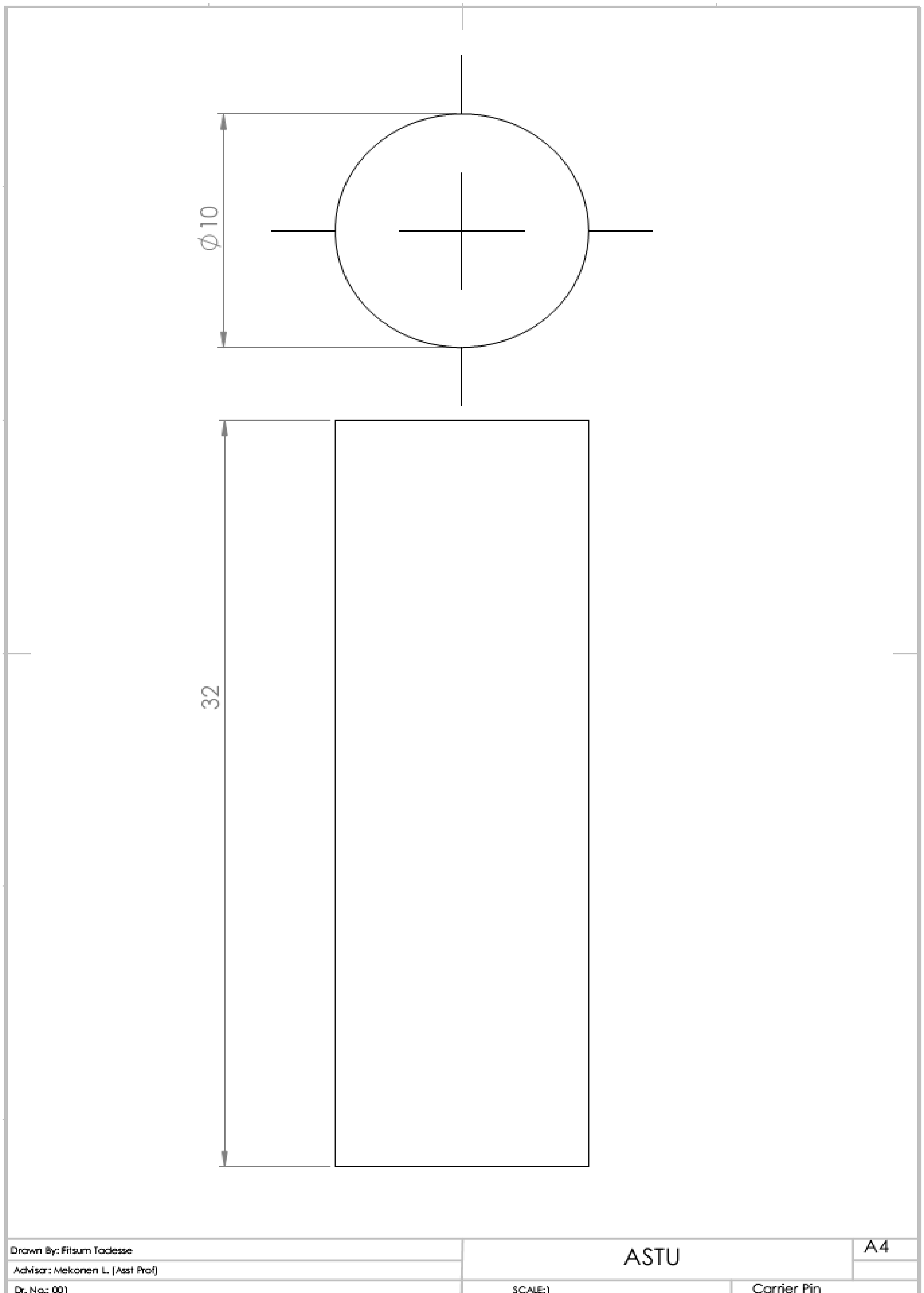
Model	Hilux	Transmission-type	Manual
Power	150 hp/3400 rpm.	Number of ratios	6-speed
Max. Power(bhp/KW@rpm) Max.torque (Nm@rpm) Max.speed(kmph) Acceleration 0 - 62mph (sec) Fuel consumption-combined(mpg)	148/110@3400 400Nm/1600-2000 rpm. 106 13.2 40.4	Ratios	1st 4.784; 2nd 2.423; 3rd 1.443; 4th 1.000; 5th 0.777; 6th 0.643; Rev 4.066
		Differential gear ratio(final drive)	3.583
Position of engine	Front, longitudinal		
Model Engine	2GD-FTV		
Engine displacement	2393 cm3		
Number of cylinders	4		
Gross vehicle weight	3150 kg.		

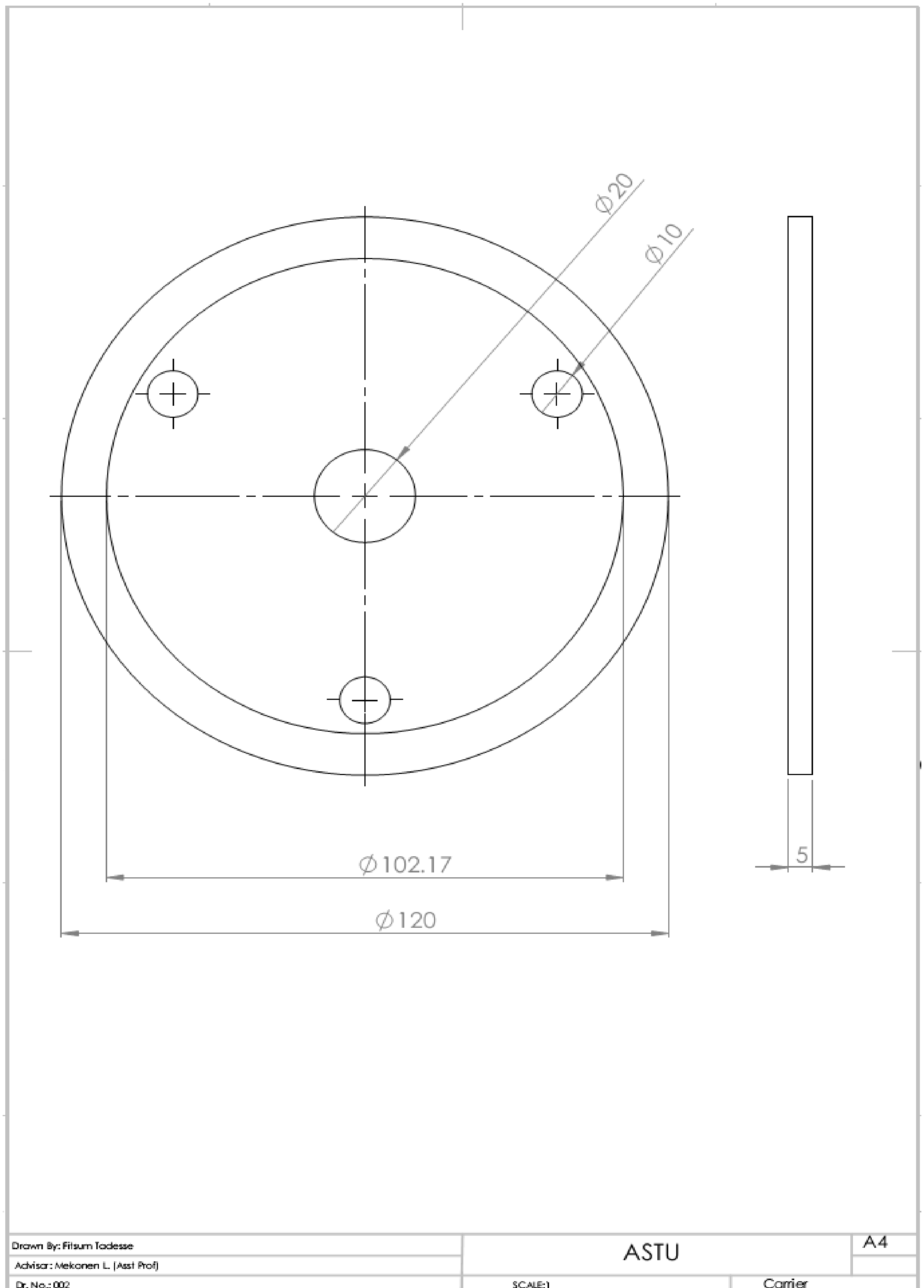
Kerb weight	1915-1965Kg		
Axle(front/rear)	Rated load 1000kg/2150kg		
Fuel tank volume	80 l		
Length	5335 mm.		
Width	1855 mm.		
Height	1815 mm.		
Wheelbase	3085 mm.		
Front track	1535 mm.		
Rear (Back) track	1550 mm.		
Front overhang	1000 mm.		
Rear overhang	1250 mm.		
Ride height	293 mm.		
Drag coefficient (Cd)	0.394		
Minimum turning circle (turning diameter)	13.4 m		
Approach angle	31°		
Departure angle	26°		
Tire size	265/65 R17		
Wheel rims size	7.5J x 17		
Front brakes	Ventilated discs		
Rear brakes	Drum		
ABS	Yes		

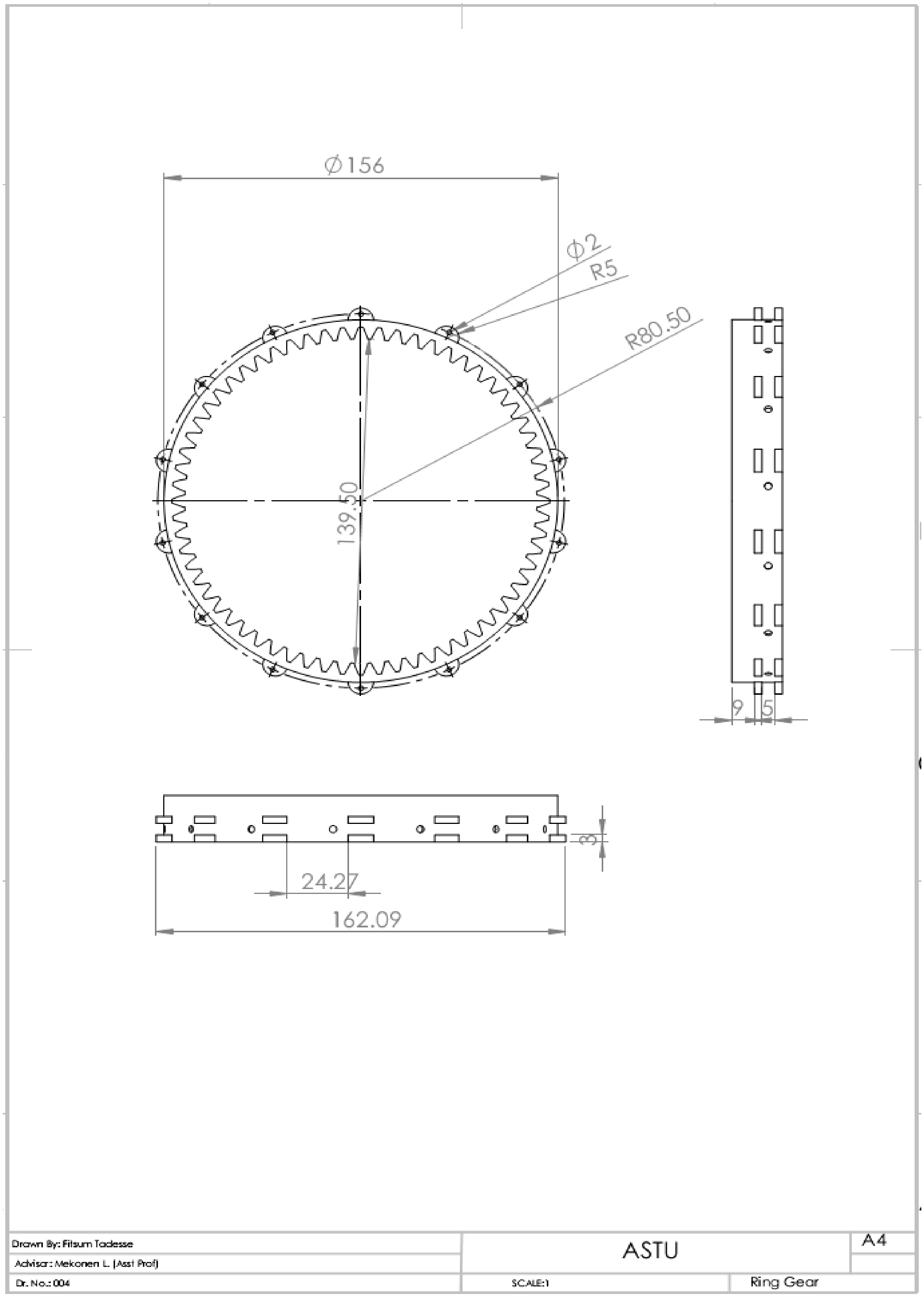

R15.19
1.07
39.92
20
2.33
Drawn By: Fitsum Tadesse
Advisor: Mekonen L. (Asst Prof)
Dr. No.: 005
ASTU
A4
SCALE:1
Sun gear



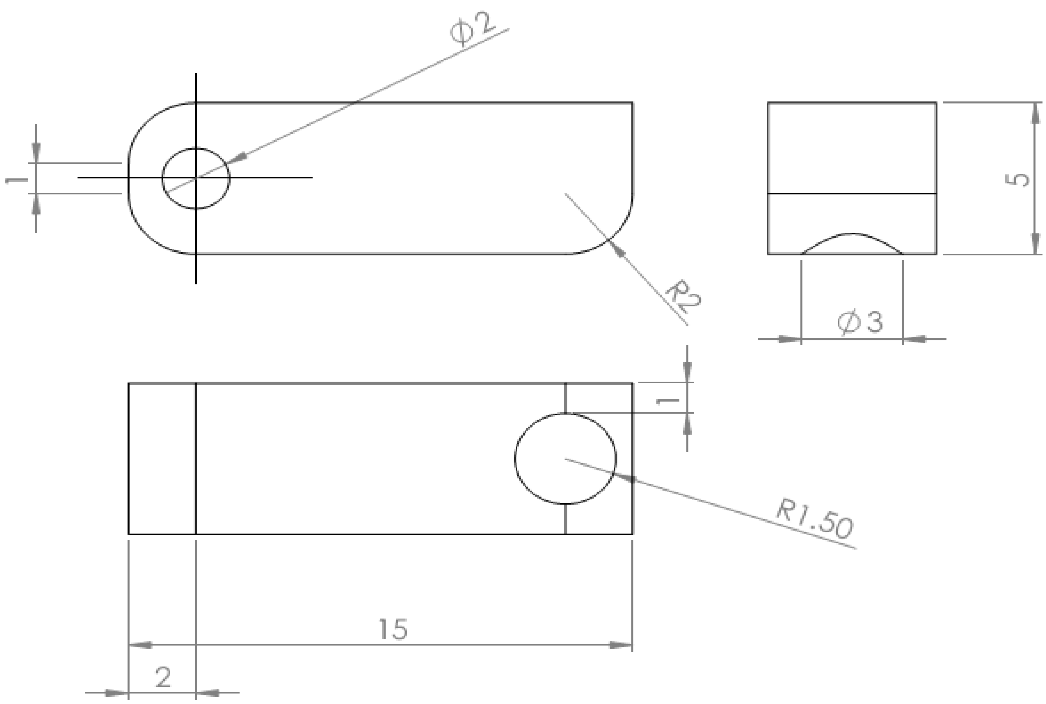
Drawn By: Fitsum Tadesse	ASTU	A4
Advisor: Mekonen L. (Asst Prof)		
Dr. No.: 006	SCALE:1	Panetry gear


⌀10
32
Drawn By: Fitsum Tadesse
Advisor: Mekonen L. (Asst Prof)
Dr. No.: 001
ASTU
A4
SCALE:1
Carrier Pin

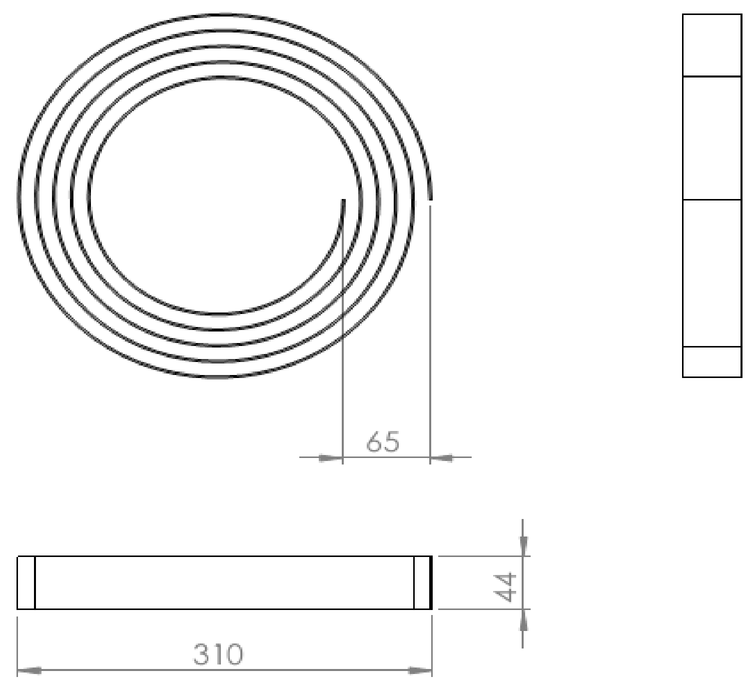

Ø20
Ø10
Ø102.17
Ø120
5
Drawn By: Fitsum Tadesse
Advisor: Mekonen L. (Asst Prof)
Dr. No.: 002
ASTU
A4
SCALE:1
Carrier



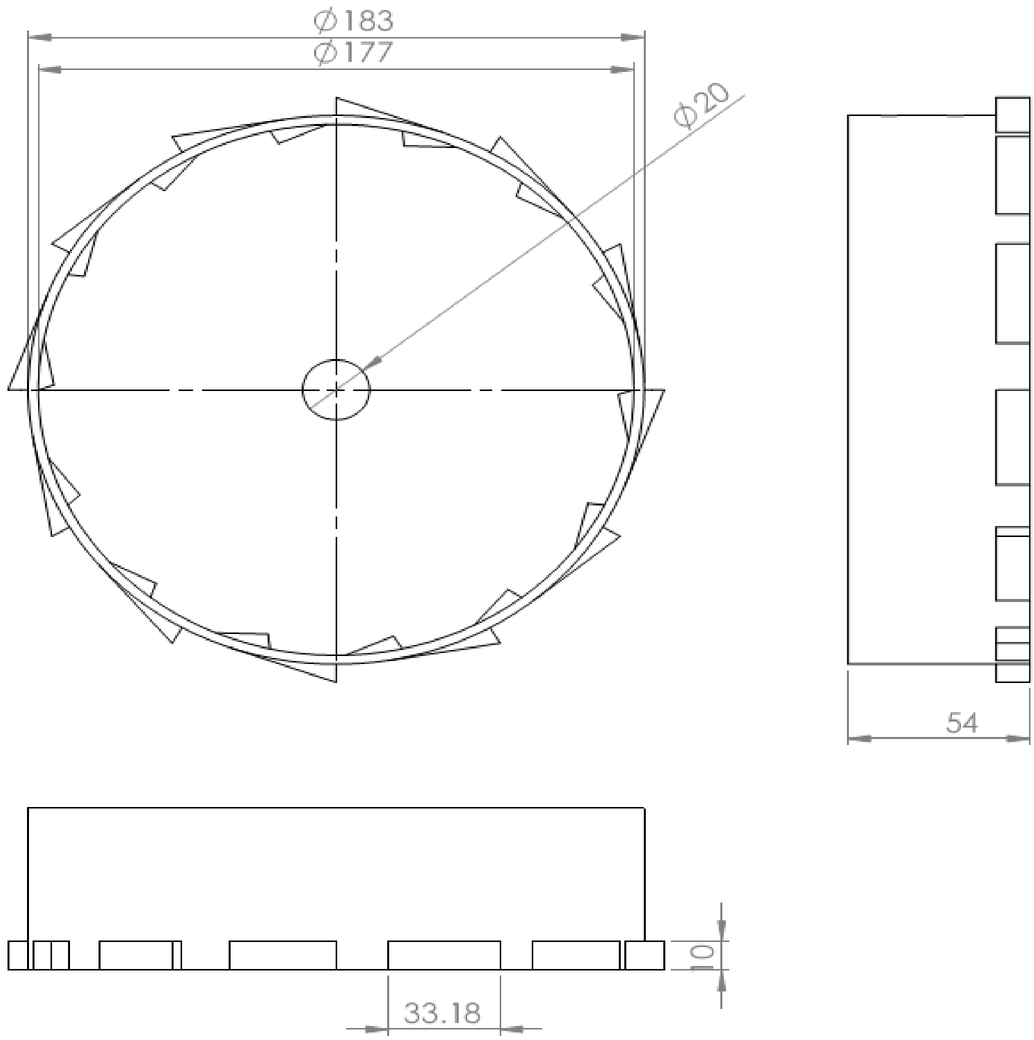
Ø156
Ø2
R5
R80.50
139.50
9
5
3
24.27
162.09
Drawn By: Filsum Tadesse
Advisor: Mekonen L. (Asst Prof)
Dr. No.: 004
ASTU
A4
SCALE:1
Ring Gear



Drawn By: Fitsum Tadesse	ASTU	A4
Advisor: Mekonen L. (Asst Prof)		
Dr. No.: 007	SCALE:1	Rachet

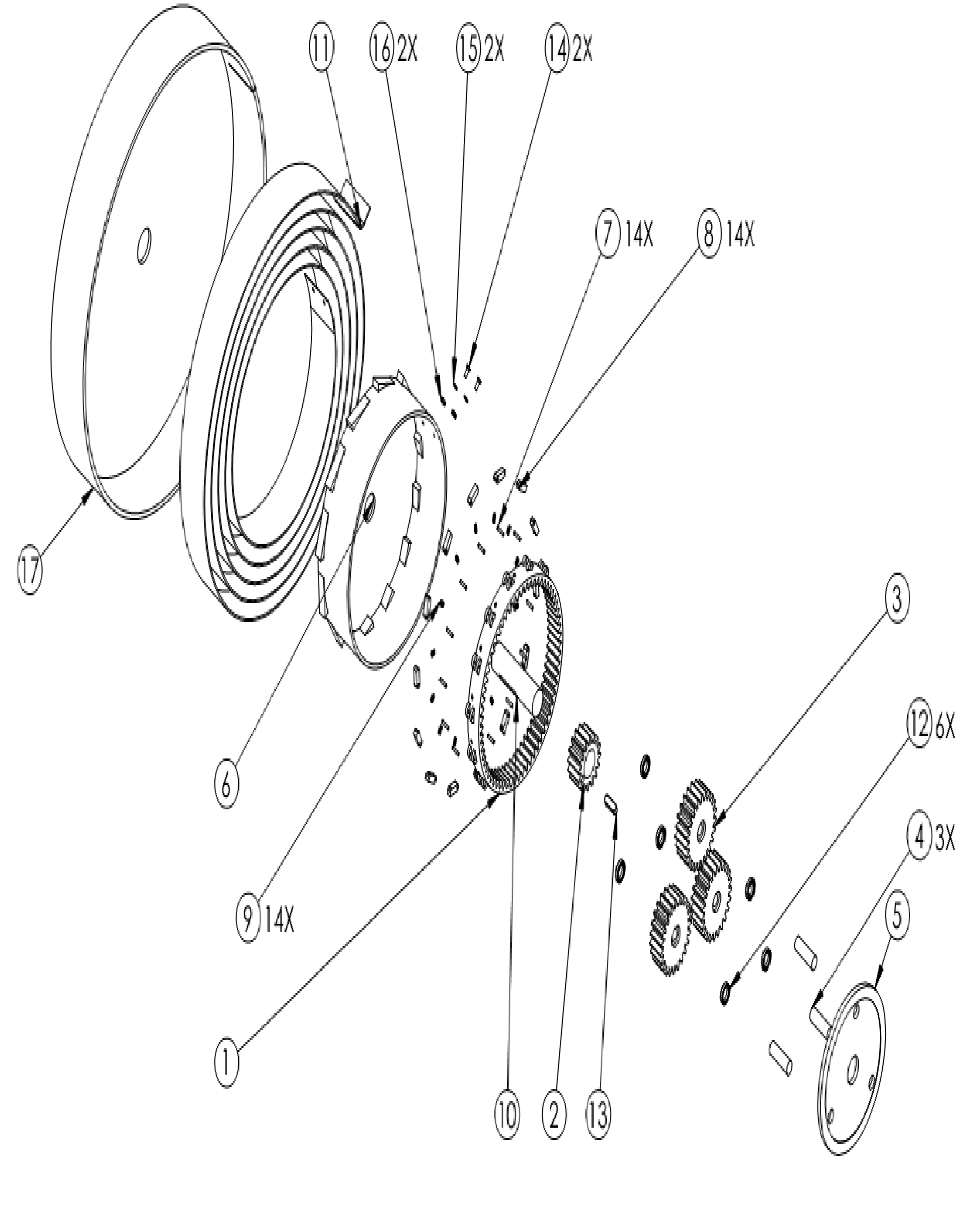


Drawn By: Fitsum Tadesse	ASTU	A4
Advisor: Mekonen L. (Asst Prof)		
Dr. No.: 008	SCALE:1	Spiral Spring



Drawn By: Fitsum Tadesse	ASTU	A4
Advisor: Mekonen L. (Asst Prof)		
Dr. No.: 003	SCALE:1	Drum

ASSEMBLY DRAWING



	NAME	SIGNATURE	DATE	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS	TITLE:
DRAWN	FITSUM TADESSE				**Assembly Explode**
CHK'D					
APPV'D					
MFG				SCALE:1:4	SHEET 5 OF 9

ITEM NO.	PART NAME	DESCRIPTION	SPECIFICATION	MATERIAL	QTY.
1	RING GEAR	ISO - Internal spur gear 2.25M 64T 20PA 20FW ---S64S150OD 1.0AF	2.25M 64T 20PA 20FW	AISI 4340	1
2	Sun Gear	ISO - Spur gear 2.25M 16T 20PA 20FW --- S16A75H50L20.0S1	2.25M 16T 20PA 20FW	AISI 4340	1
3	Planet Gear	ISO - Spur gear 2.25M 23T 20PA 20FW --- S23A75H50L20.0N	2.25M 23T 20PA 20FW	AISI 4340	3
4	carrier pin	-		AISI 1020	3
5	Carrier	-		AISI 1020	1
6	drum	-		AISI 1020	1
7	Rachet pin	ISO 8734 - 2 x 20 - A - St	2 X 20 - A - St	AISI 4140	14
8	rachet	-		AISI 4340	14
9	rachet spring	-		AISI 316 Stainless Steel Sheet	14
10	drive shaft	drive shaft		AISI 1020	1
11	spiral spring	spiral spring		AISI 316 Stainless Steel Sheet	1
12	Planet Gear Bearing	ISO 1224 - 171015 - R,20,DE,AC,20_68	171015		6
13	Key	Key ISO 2491 6x4-20-A	6 X 4 X 20 - A	AISI 4140	1
14	Spring screw	ISO 7046-1 - M3 x 8 - Z - 8N	M3 X 8	AISI 1020	2
15	washer	ISO 8738 - 3	3	AISI 1020	2
16	Nut	ISO - 4035 - M3 - N	M3	AISI 1020	2
17	Housing	Housing		AISI 1020	1

Table: Bill of mMaterials