MSc Group Dissertation

Title: Turbocharger Rotor and Generator-Based KERS

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Supervisor: Dr J F Dunne

Abstract

The concept of Hybrid Electric Vehicles (HEV) have been around since the late 1800s but did not initially gain popularity due to the relatively low power output when compared to its gasoline powered counterpart. In 2007 the European union passed legislation to reduce the production of greenhouse gas emission, fuel consumption and energy efficiency. This accelerated research- that was already underway in the HEV industry- on the road to meet these targets. Advances in HEV systems such as regenerative braking and improvements in power output have seen sales in HEV exceed 6.5million in March 2013.

Although technological advances in many area of HEVs have been achieved, the efficiency of energy storage in a battery is still highly inefficient. For example the regenerative braking efficiency of the Toyota Prius, which is the best-selling HEV, is 30%.

This paper addresses the issue of recovered energy storage by exploring alternative methods to improve the efficiency of this process. This is achieved by modifying four existing HEV to store energy mechanically in components that are already present in HEVs powertrains, such as the rotors of a turbocharger and motor/generator. This paper theoretically calculates the improvements in efficiency and fuel consumption by comparing the efficiency of the existing regenerative braking system and that of the modified powertrain.

Executive Summary

This paper was carried out as a part of an MSc group project in Mechanical Engineering at the University of Sussex. It was carried out by four members; Suleman Handuleh, Cihan Kaboglu, Heng Lou and Guong Hu under the supervision of Dr Julian Dunne.

The aim of this project was to investigate the design issues and possible improvements in both efficiency and fuel consumption of hybrid electric vehicles, by developing an alternative method of storing recovered energy during braking. The method for achieving this aim was to carry out extensive research into current methods of energy recovery and storage to identify sources key sources of inefficiency. This was found to be the usage of batteries as the sole component of energy storage. By introducing mechanical energy storage systems, this inefficiency could be circumvented as mechanical storage system were found to far more efficient. The next step was to identify mechanical components that could be used to store this energy and it was found that there were a total of three possible component that could be used, these were; Motor/Generator, Turbocharger and Flywheel. Then theoretical calculations were carried out find the storage capacity of these components. It was found that the available energy to store was greater than the capacity of all three of these components so it was decided that the energy left over could be stored in the battery. This situation did not arise very often and only occurred in very high energy braking above 50mph.

To quantify and analyse the enhancement made to regenerative braking four HEVs were selected with different powertrains in the compact vehicle segment. They

were the Toyota Prius, Chevrolet Volt, Volkswagen Jetta and Honda CRZ. Their current efficiencies were theoretically calculated and modification to their powertrain were carried to incorporate the new concept of storing energy mechanically. The efficiency of the new system were calculated and by applying them to a urban duty cycle an improvement for each vehicle could be found to be 34.7%, 20.4%, 18.5% and 20.6% in regenerative braking efficiency for the Prius, Volt, Jetta and CRZ respectively. Also a fuel consumption improvement of 22.0%, 12.9%, 11.7% and 12.8% in the same respective order of vehicles.

Each of the project objectives were met and a section for Further Work was included in the report to show how to enhance research in this field, which describes an experiment to be carried out to further investigate the half-life of rotational speed of a turbocharger placed in a vacuum to reduced aerodynamic losses.

The management and delegation of task have also been comprised in this paper and are covered by the chapter name Project Scope. Project management is shown a Gantt Chart in **Appendix F.**

Contents

List of Figures

List of Tables

1.Introduction

Energy resources and environmental pollution are the two most pressing issues in the automobile industry today more than ever. There has always been an ethical debate on environmental and about the pollutants given off by Internal Combustion engines. Car manufacturers have attempted to reduce this to some degree, however recent changes to the urgency of this issue have seen governments from around the world, especially those in Europe and the US, pass legislation to reduce CO_2 emissions by 20% in the EU, and 17% in the US both by 2020 .[1]

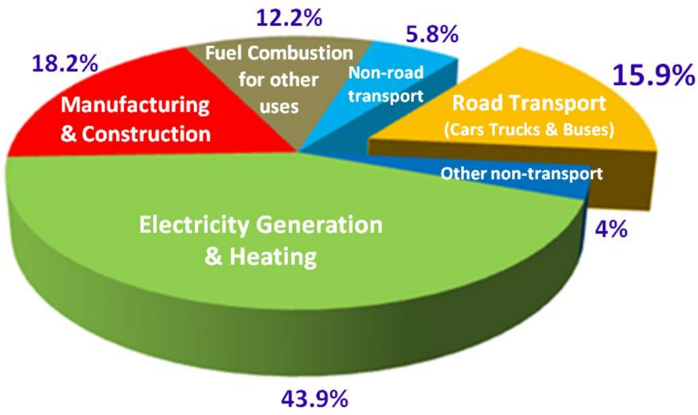

Figure 6.1: Global CO_2 emsisions sector[2]

The Automobile industry has come under much scrutiny on the road to achieve the 2020 target. This is due to the fact illustrated by Figure 1, that motor vehicles directly contribute 15.9% of global CO_2 emissions.[2]

One of the methods taken by these governments is to deter consumers from vehicles which produce high levels of emission by taxing vehicles depending on certain criteria. A statement on the website for The Department of Energy and

Climate change explained how “vehicle tax rates now depend on engine size, fuel type and CO_2 emissions”.[1]

To overcome the problem of CO_2 emissions and the inevitable depletion of fossil fuels, engineers have researched and explored many methods to reduce both overall emissions and fuel consumption while striving to improve vehicle performance. A major step has, in recent years, been taken in the electric car and hybrid vehicle technologies which could potentially solve both of the aforementioned issues by reducing the fuel consumption and therefore pollutants dramatically using a hybrid or completely using an electric vehicle.

Electric car technology has been in commercial development since the early 20th century, starting with vehicles such as the electric New York taxis from 1897 and the Detroit Electric car (1904).The first hybrid car was built in the year 1899 by engineer Ferdinand Porsche called the System Lohner-Porsche Mixte. Both of these designs did not gain popularity as a result of relatively low power outputs compared to their gasoline counterpart .[2]

Recent advances in research on Hybrid Electric Vehicles (HEV) have completely redesigned the automobile powertrain and introduced new sources of energy, as well as innovating methods of recovering energy that is wasted during braking. The combination of the energy from an IC engine with other forms of energy can be the answer to reducing both fuel consumption and CO_2 emissions.

There are many types of Hybrid vehicles and a number of regenerative breaking systems that considerably improve efficiencies and lower emission; these will be further discussed in the Literature Review. One such system has become very popular in the last few years called KERS (Kinetic Energy Recovery System). This system recovers energy from braking that would otherwise be lost as heat energy and stores it in an energy storage devise such as flywheel or battery. When the vehicle accelerates this energy is used to propel the vehicle. This system was introduced to Formula One vehicles in 2009 to add a new dimension to races. There were a number of guidelines that followed this introduction which dictated the amount of energy allowed to be used and at which point during the race the driver could use this extra energy.

KERS have since been applied to a very small number of commercial vehicles and are usually limited to larger vehicles such as trucks and lorries. There is great potential for these systems to be incorporated into a larger section of the market.

This thesis aims to explore the design issues surrounding the improvement in the performance and fuel consumption of a hybrid electric vehicle by taking the idea of KERS and expanding the idea to as many rotating components on an existing design which has the possibility to be converted to an energy storage device.

1.1 Background

In this study, Hybrid Electric Vehicles (HEV) will be limited to Parallel Hybrid Electric Vehicles (PHEV), Series Hybrid Electric Vehicles (SHEV) and Plug-in Hybrid Electric Vehicles. This literature review will aim to investigate the powertrain of each type of vehicle, different methods for capturing energy and explore some of the main issues surrounding regenerative braking to further understand how to combine these systems.

1.1.1 Hybrid Electric Vehicles

The definition of a hybrid vehicle is a vehicle that uses at least two different types of energy for the purpose of vehicle motion. This term has come to mean hybrid electric vehicles in recent years which refer to a combination of mechanical energy provided by an IC engine and Electrical Energy from a battery or from recovered energy from braking. The method of when and how to use these different energy sources depend on the type of hybrid vehicle, as well the method of charging and storing Electrical energy varies with different hybrid configuration.

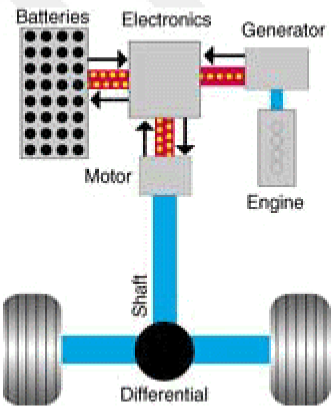

Figure 1.7: SHEV

Series Hybrid Electrical Vehicle (SHEV)

For series hybrids, only the electric motor is connected to the wheels meaning the transmission to the drive motor must always be electrical. In SHEV the battery is the main source of energy although the engine can be called upon. Usually, the SHEV is equipped with an electric generator connecting an engine which supplies electricity for the battery as shown in Fig 2. The main use of the engine/generator set is to keep the battery charged between 40-80% [3]. When the battery reaches the lower limit, the engine starts. Similarly, when the battery reaches the upper limit, the engine will shut off. However, in some SHEVs, electric power to the motor can come from both the batteries and the engine/generator set to increase power in cases such as driving up a hill. When the electric motors are connected to the wheels, the engine will run at optimum performance greatly reducing emissions.

SHEV operation modes:

1. Pure electric traction mode: The engine is turned off and the vehicle is propelled only from the batteries.

2. Pure engine traction mode: The vehicle traction power comes only from the engine - generator, while the batteries neither supply nor accept any power from the drive train. The electric machines serve as an electric transmission from the engine to the driven wheels.

3. Hybrid traction mode: The traction powers are drawn from both the engine - generator and the batteries, merging together in the electrical coupler.

4. Engine traction with battery charging mode: he engine - generator supplies power to charge the batteries and to propel the vehicle simultaneously. The engine - generator power is split in the electric coupler.

5. Regenerative braking mode: The engine - generator is turned off and the traction motor is operated as a generator powered by the vehicle kinetic or potential energy. The power generated is charged to the batteries and reused in later propelling.

6. Battery charging mode: The traction motor receives no power and the engine - generator is operated only to charge the batteries.

7. Hybrid battery charging mode: Both the engine - generator and the traction motor operate as generators in braking to charge the batteries.[4]

Parallel Hybrid Electric Vehicle

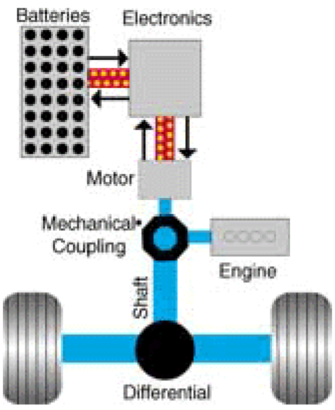

Figure 1.8: PHEV Powertrain

Parallel Hybrids have the same components as a series hybrid but they differ in power transmission operation. The Electric motor and the gasoline engine are both connected to the drive shaft via a mechanical coupling as show in figure#. This allows for either the Engine or motor to be engaged independent of each other to increase overall efficiency by changing the mode of operation [5]. Also by combining the engine and motor, the power output of the vehicle can be dramatically increased which is exemplified by the VW Jetta which currently hold the top speed for a compact hybrid.

PHEV operation modes:

1. Hybrid traction mode: : The traction powers are drawn from both the engine - generator and the batteries, merging together in the mechanical coupler

2. Engine - alone traction mode: Engine supplies the energy to drive wheels and all the energy under this mode is pure mechanical energy.

3. Motor - alone traction mode: Only the electric motor offers its power to the driven wheels.

4. Regenerative braking mode: The electric motor acts as a generator to recover the braking energy.

5. Battery charging from the engine: The engine supplies the power to charge the battery.

1.2 Regenerative Braking

Electric and hybrid electric vehicles typically employ motor-generators that can convert electric current into torque (like a motor) or torque into electric current (like a generator). The latter is commonly used for regenerative braking. When the brakes are applied, the motor-generator provides the resistance necessary to slow the vehicle as it supplies current to the battery to be stored. In the event that the motor-generator cannot slow the vehicle fast enough, a torque coordinator module will apply traditional friction brakes to the extent necessary. The working principle is shown in Figure 4.

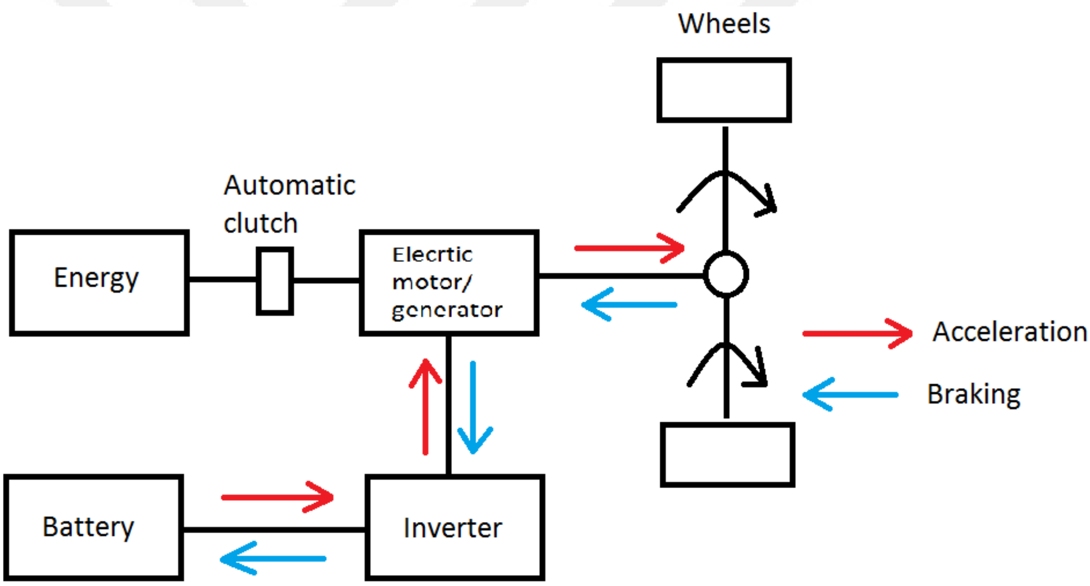

Figure 1.9: Regenerative Braking Mechanism

Although this is the most common regenerative systems, other method of energy storage do exist and are fast growing in popularity such as the method adopted by many formula one team using KERS which use other method of energy storage instead of a battery such as a flywheel or ultra – capacitor.

All regenerative braking systems slow a vehicle down by transferring its kinetic energy into energy storage devices, which can be either used immediately or stored until needed. Gressler, B found that regenerative braking can decrease fuel consumption of vehicles by 10 to 25% depending on their size and Drive Cycle[6] and reduce the CO_2 emission between 406.08 and 1269 kg per year [7].

1.3 KERS

KERS as previously stated is an acronym that stands for Kinetic Energy Recovery System and is another method of regenerative braking. The mechanism by which the energy is recovered is very similar to the one previously stated as it stores energy that would be otherwise wasted during breaking or when there is excess power produced by the engine. This mechanical energy is then used to either turn an electrical engine set in generator mode and generate electricity to be stored or it can be mechanically connected to a mechanical energy storage device such as a flywheel.

The main difference between a KERS and standard regenerative braking systems is that KERS store energy in a peak power source and only for a relatively short period of time, this energy is then recalled on command to give additional power. This differs from the standard system which use recovered energy only to charge a battery .

These systems can use a completely mechanical transmission which have the advantage of potentially being far more efficient. The disadvantage is that the flywheel will eventually decrease in momentum and hence energy. Although advances have seen improvements in bearing and air resistance losses with methods such as vacuum sealing the flywheel, the battery is still more suitable for long term energy storage. There are a number of peak power sources in practice with varying performance and properties suited to different engineering tasks, the most suitable are shown in Figure1.5.

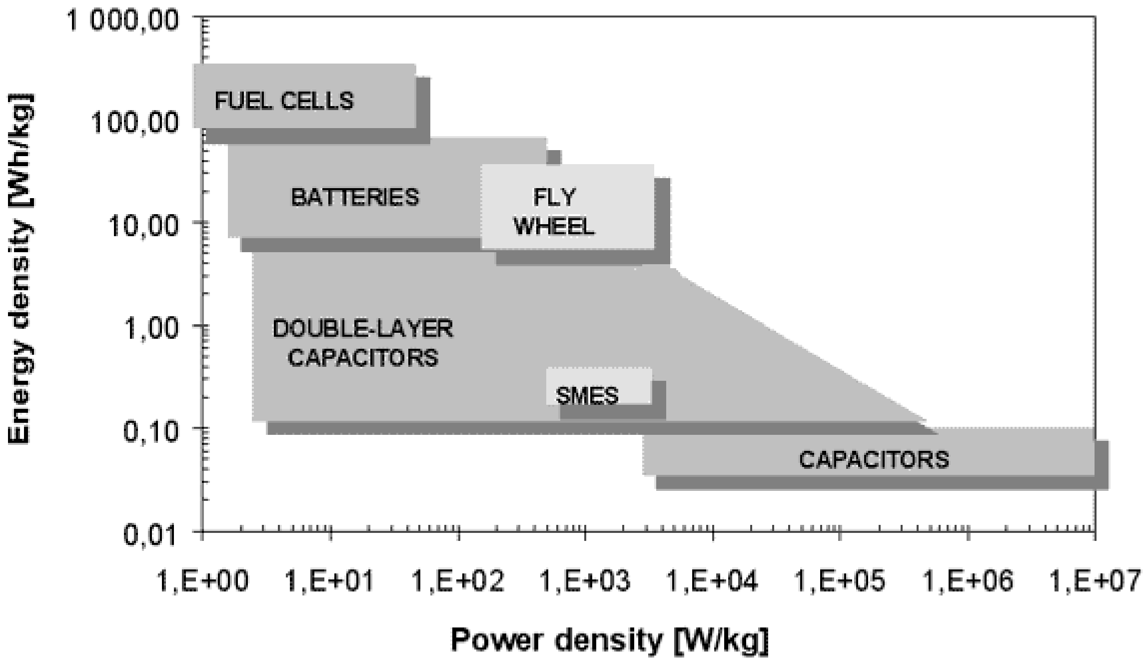

Figure 1.10: Peak Power Sources Performances

To calculate the recaptured energy, there are some ways. One of them is using the mathematical modelling and numerical simulation. For example Corneliu Cristescu et al found based on the calculation, the percentage of braking energy can be captured up to 65% which is figured out by mathematical modelling and numerical simulation. It is shown in Figure 6.[8]

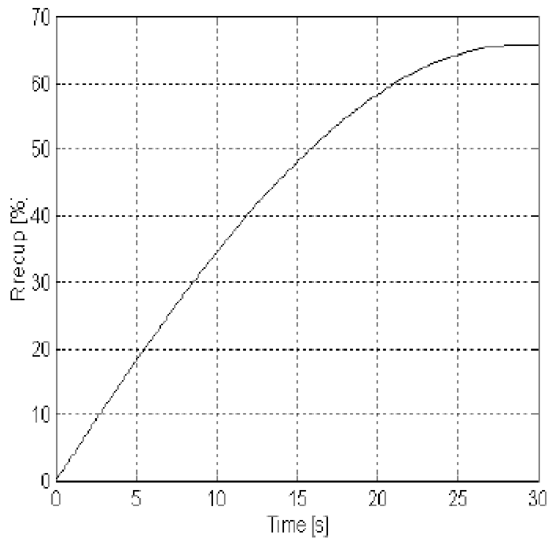

Figure 1.6: Variation of braking energy recovery coefficient[8]

1.3.1 KERS with Fly Wheel

The first type of the system is equipped with flywheel. Typically a lightweight, low-friction flywheel is integrated into the transmission or in the trunk. When the car brakes or even when it is running at constant speed, the extra energy is transmitted to the flywheel pack and spins up a flywheel until it reaches as much as 60,000 rpm. When power is required to step away smartly from a stop light or accelerate onto the highway, the energy that was stored is used to accelerate the vehicle from stop. This is usually when the vehicle requires the most fuel so by using the flywheel to initiate movement the vehicle consumes less energy and emits less CO_2 than normal vehicle. Based on the research, the system can capture 70-80% of waste braking energy [9].

The system consists of a flywheel connected by a continuously variable transmission (CVT) to the drivetrain. Drivetrain includes some output gear trains and transports to the rear driveshaft to the rear wheels, see Figure 7 and 8. The CVT towards a gear ratio is moved that would speed the flywheel up, enables it to store energy.

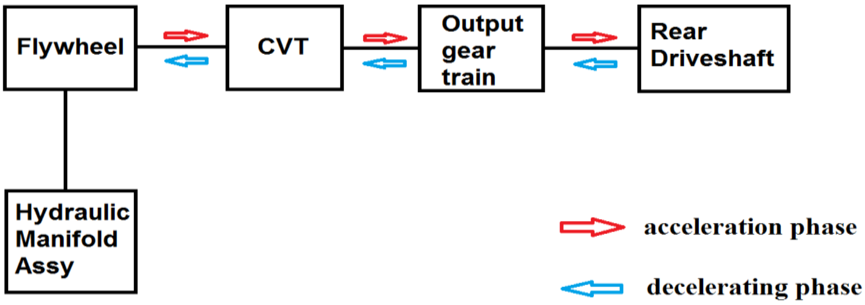

Figure 1.7: KERS Flywheel arrangement

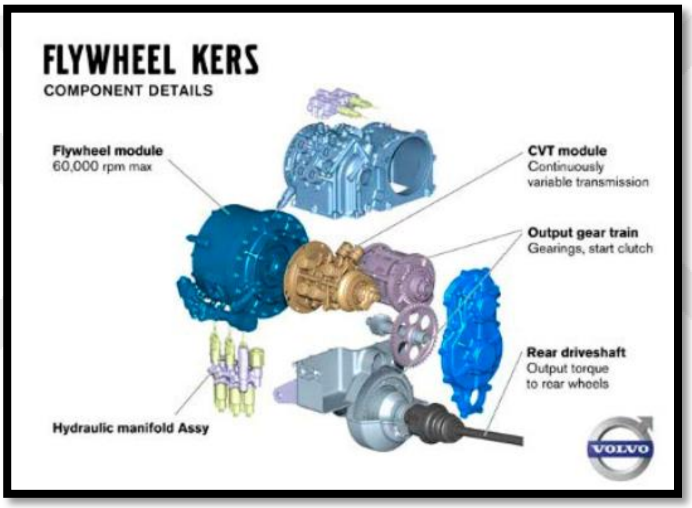

Figure 1.8: KERS Flywheel Volvo design [10]

The system with flywheel has several advantages. For example, the structure is simple and mechanical; it can provide high efficiency and also the total weight is lighter than others. However, because it needs very high rotating speed, it requires very large gear rate, hence, the system needs more space and may cause the unbalanced problem. Besides, the output torque is not very strong and the ability of storing energy is limited.

1.3.2 KERS with Battery

As previously stated the mechanism of a battery storage device differs slight than that of a mechanical storage and is shown by Figure 1.9. This system is the same for a battery or an ultra-capacitor.

This system as previously mentioned is not as efficient as mechanical options for instance Mackay, SGJ found the efficiency of a battery KERS capture and return is between 50-60% [9].

Figure 9 shows the mechanism of energy recovery. As shown there is more complication in energy storage in this system. For example the motor/ generator produces AC current while the battery requires DC current to store this energy. This means that a component must be added to carry out this task which causes further losses.

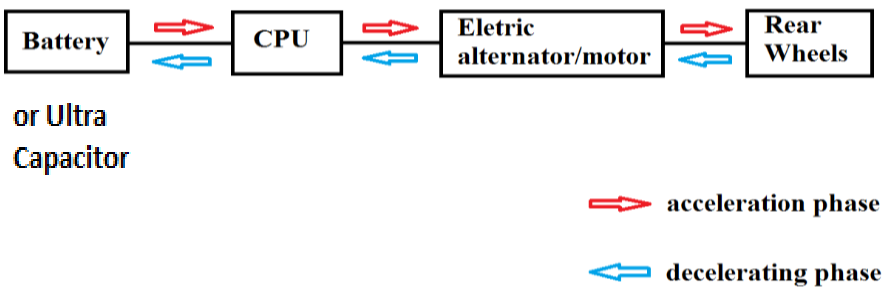

Figure 1.9: KERS Battery Arrangement

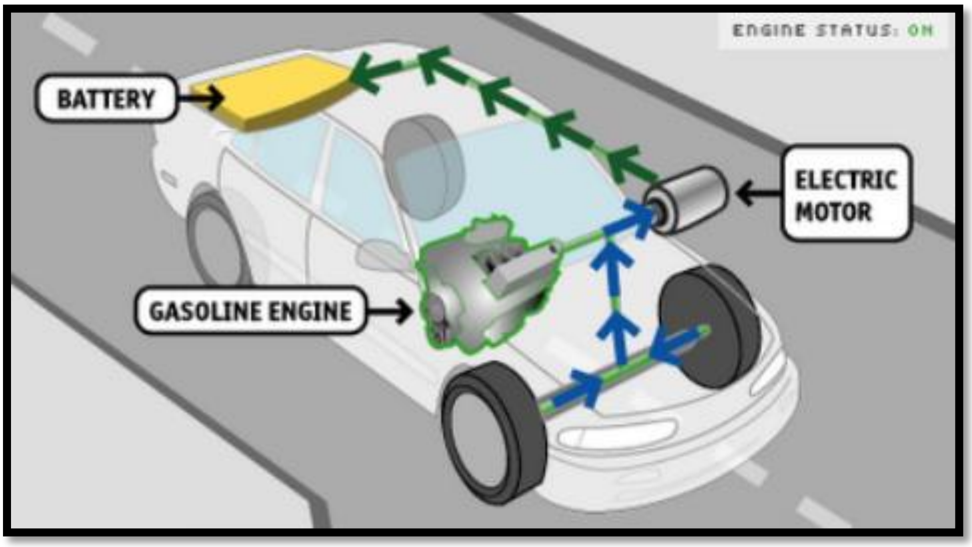

Figure 1.10: KERS Battery model [10]

1.4 Duty Cycle

Duty cycle is the ratio of time that mechanism is active and inactive. It is calculated by using the equation 1.1:

$$D = \frac{\mathcal{T}}{T} \qquad (1.1)$$

Where:

D - Duty cycle

$\mathcal{T}$ - Total time spent recovering energy

T - Total time spent driving

Duty cycle is very important for regenerative braking. For example duty cycle of regenerative braking is high, it means regenerative braking system is active very frequently. Duty cycle provides a driver with information regarding how often a vehicle starts and stop along a journey. For example when automotive companies quote savings in fuel consumption of 30% or 30mpg (miles per gallon), this figure is usual followed by a comment on the operating conditions i.e. urban or highway travel. Urban travel will mean a significant increase in the duty cycle compared with highway travel as the vehicle starts and stops more often, this is desirable when recovering energy via regenerative braking. Drive cycles have been standardized to give a means of comparison for different vehicles with different fuel consumption [11]. These standards are devised by carrying out in depth study into driving conditions in a urban area, rural and motor way. In this thesis the European Stationary Cycle will be used exclusively.

2. Project Scope

This chapter will outline the boundaries of this project and explain the activities to be carried out. This is achieved by first stating the overall aim of the project and listing the objectives to be achieved and explaining their importance to this project. This is intended to give the reader a better sense of what to expect from this project. Finally a breakdown of the delegation of tasks is carried out to show each member of the groups contribution to the project.

2.1 Aim

To improve the regenerative braking efficiency of hybrid electric vehicles by exploring the design issues surrounding Kinetic Energy Recovery Systems and Extended Range Electric Vehicle.

2.2 Objectives

To consider the following:

1. Background study into existing energy recovery systems

2. Explore the energy storage potential of components in existing HEVs
3. Method of power transmission and decoupling for existing HEVs
4. Outline switching options to improve efficiency and fuel consumption
5. Design of experiment to study measurement issues surrounding half-life measurements

2.3 Methodology

To achieve the objectives stated previously, the members of the group researched HEV vehicles and the technologies used to power and recover these vehicles. Once a clear understanding was obtained, the group looked at all potential energy storage devices by starting with all parts of the vehicle that rotate. A list of all rotating parts was created and a judgment was made on the feasibility of it storing energy. The component were then shortlisted to 4 potential energy storage device which were; the drive motor, turbocharger, flywheel and battery. An energy source was delegated to each member of the group to increase productiveness. Once the energy storage devices were identified, design issues were explored with the aim of minimal modification to the existing powertrain when transferring energy to and from these devices. While exploring the method of power transmission, each member of the group was assigned a HEV to modify. The member had to gain an understanding of that vehicle and know the complete driveline, power output and efficiency. The group then consulted with each other and applied the modification to existing vehicle and compared the theoretical data of existing design to that of the modified design. Decisions were made about switching option of different energy storage sources to obtain the most efficient strategy of power management. The outcome of the modification were recorded on a table and discussed. Finally conclusions were made about the potential improvements made to the vehicle efficiency and fuel consumption.

2.4 Group members and Delegation of tasks

Throughout this group project, asks were delegated to each member of the group to insure an equal contribution. The first step was to assign a Chair a secretary for the group meeting which are stated below. The next step was to divide the initial stages of the project, such as Introduction, Background research and Literature review, the task were delegated at the weekly group meetings depending on what information was needed. This allocation were recorded in the minute for each meeting and can be seen in Appendix A.

Once these sections were complete the net task was to divide the energy storage devices to be investigated. This entailed finding out the working principle of each device and to produce a method storing energy without determent to its main function.

The next delegation was to assign each member with a HEV. The task was to gain a full understanding of the workings of each vehicle powertrain so the group could apply the modifications to each vehicle.

Finally, calculations were carried out to analyse the improvements made to each vehicle. Fuel saving and CO_2 emission improvements were given and this task was shared by all member of the group.

Task	**Delegated To**
Chair of meetings	CK
Secretary of meeting	SH
Introduction	All
Turbocharger	SH
Drive Motor	HL
Flywheel	GH
Battery	CK
Chevrolet Volt	HL
VW Jetta	SH
Toyota Prius	CK
Honda CRZ	GH
Calculations and Table	All
Discussion and Conclusion	All
Project Management	All
Collating report and editing	SH

Table 2.1: Task of delegation

3. Potential for Energy Storage – Turbocharger

3.1 Turbocharging an Engine

Turbochargers are used to improve the power output of an engine. This is achieved by passing exhaust gases through an axial turbine as the gases are expelled from the combustion chamber. This causes the turbine to rotate at thousands of revolution per minute. The turbine is connected to a compressor by a shaft, which takes in fresh air and compresses it before mixing with fuel. As the air is compressed more fuel can be added during combustion resulting in more engine produced by the engine.

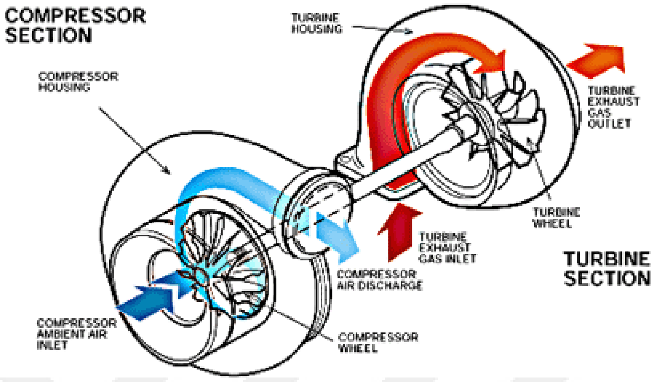

Figure 3.1: Turbocharger diagram[12]

A turbocharger can improve the CO_2 emissions by a considerable amount as the increase in available air during combustion facilitate s a more complete combustion. This is overshadowed by the fact that more fuel is used in a turbocharged engine meaning the millage of a naturally aspirated engine of the same size is actually better. [13]

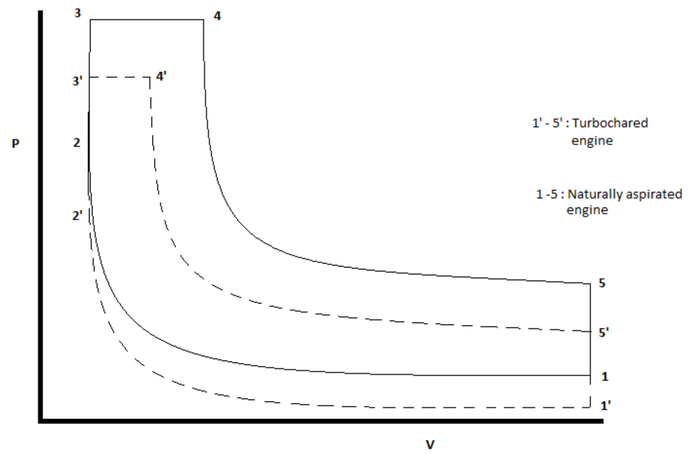

Figure 3.2: The pressure/volume graph of a naturally aspirated engine

Figure 3.2 shows the pressure/volume graph of a naturally aspirated engine compared to the same engine but turbocharged. The graph does not show the exhaust and intake. The following equation shows how work and volume are related with work, while the rate of work done is power:

$$w = \int p \, dv \qquad (3.1)$$

This equation means that the area outlined by 1-5 is equal the work done by the engine. In the case of a 4-stroke engine useful work is done every other revolution so to calculate power the one must multiply the area within the p/V graph by half of the engine speed. Because of the increase in pressure and amount of air/fuel mixture at the beginning of the cycle, far more work is down during combustion shown at 2-3. [14]

3.2 Method of Energy Storage

The turbocharger is located just after the exhaust manifold and is not directly connected to the vehicles powertrain. All turbochargers have a minimum engine speed before it is beneficial for it to be engaged, also during braking the turbocharger is not used as the additional power is not required. These periods of time give possibility for the turbocharger to be used to store mechanical energy either from the regenerative braking or from the engine exhaust. This system is designed on the principle of a KERS, so the existing driveline would have to be modified in order to transfer energy between the wheels and the turbocharger. The bearing properties of turbochargers are ideal for this application, although aerodynamic and bearing losses caused by rotation of the axial turbines would have to be addressed.

It was decided that the modifications to the existing power transmission would have to be minimal to allow for retro fitting and keep installation cost down and allow for the possibility of a payback period from improved fuel economy. The method of power transmission is to extend the shaft on the turbocharger and is connected mechanically to a CVT by a clutch. The clutch allows for engagement when the turbocharger is to be used as a flywheel and when disengaged can continue working ordinarily to boost the engine. The CVT is required to transfer the rotational energy from the turbocharger to the driveline at the correct rpm and torque.

3.2.1 Energy Storage Calculation

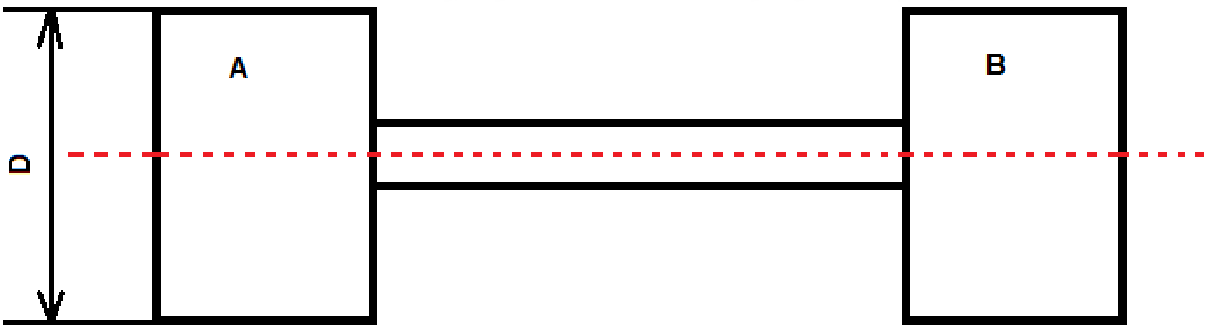

Figure 3.3: Structure of turbocharger's rotor

For the turbocharger's rotor, there are total two wheels, wheel A and B, and their weight is 0.3 kg. The diameter is 0.06m, the maximum rotating speed is 280000rpm which equals to 29306.67rad/s. The inertia of rotor is ,

$$I = \frac{1}{2}mr^2 \qquad (3.2)$$

And the rotating energy is,

$$E = \frac{1}{2} I \omega^2 \qquad (3.3)$$

So the inertia of the rotor is,

$$I = \frac{1}{2} \times 0.12 \times 0.03^2 = 5.4 \times 10^{-5} kg \cdot m^2$$

And the rotating energy is,

$$E = \frac{1}{2} \times 5.4 \times 10^{-5} \times 29306.67^2 = 23.2 kJ \qquad [15]$$

3.2.2 Turbocharged Parallel Hybrid

Generally speaking parallel hybrids are fitted with a bigger engine than a series hybrid, this is due to modes of operation of each type of vehicle. This means that the turbocharger on a parallel hybrid will also be bigger and hence can store more energy. However parallel hybrid engines are in use more often than in series hybrids so the turbocharger will be required for turbocharging the engine and would be unavailable for energy storage.

The powertrain of a parallel hybrid allows for power to be drawn from either the drive motor or the ICE via a coupling, the CVT of the turbocharger would also be coupled on to the differential as a third source of energy. This method avoids losses by using a completely mechanical transmission and not changing to electrical energy, also it allows for quick storage and discharge of energy. [5]

3.2.3 Turbocharged Series Hybrid

In series hybrids the tractive force comes from an electric motor and the engine is only used to recharger a battery once it drops below a certain level, typically 35%. This means that the mechanical energy stored in the turbocharger also requires transferring into electrical energy before it can be used by the electric motor. To overcome this issue the turbocharger CVT is couple to the engine and so both their output energy can be converted into electrical energy by the generator.

One benefit of the series configuration is that the engine is not use for long periods of time, during these periods excess recovered energy from braking could be stored in the turbocharger, in a similar way as a flywheel in a KERS, and be discharged when needed for acceleration. This is provided that the generator also be used as a motor to transfer the regenerated energy to the turbocharger.[3]

3.2.4 Difficulties in Application

There are a number of design issues that need to be considered when attempting to turn a turbocharger in to a KERS. The first issue considers the efficiency of energy storage in a turbocharger and whether the bearing losses would be too significant to successfully store energy for the required duration. To answer this question a lab experiment must be carried out to determine the effects of bearing losses on half-life of turbocharger rotational speed. A test rig is required which can imitate the conditions that exist during clutch engagement and recapturing the energy either to turn a generator or to be coupled with the driveshaft, refer to **12 Further work – Design of Experiment.**

3.3 Evacuating Turbocharger Flow Chambers

One method of improving the half-life of the rotational speed of the turbocharger is to evacuate both flow chambers using a vacuum pump or by temporarily sealing one end of the chamber and allowing the impeller to evacuate the air and exhaust gases. This would improve the efficiency of the bearings as there would be less air to cause drag.

This design idea also carries another issue, turbochargers are designed to have a pressure gradient in one direction. They are designed for the pressure in the chamber to be as much as five time higher than atmospheric and are made in a way to support the incredible forces which would otherwise cause the turbocharger to explode, hence why the housing of is made from a strong metals such as stainless steel. By evacuating the chambers of a turbocharger the pressure gradient is reversed, now the pressure on the outside is considerably larger than the inside and can make the turbocharger implode. Initial calculations are shown to estimate the forces that would be experienced by the turbocharger:

To investigate whether the existing design is strong enough to overcome these forces a lab experiment needs to be carried out refer to: **12 Further Work – Design for Experiment.**

3.4 Regenerative efficiency of a Turbocharger

The efficiency of energy regeneration for a turbocharger as an energy storage device is dependent on two aspects; the method of energy transmission to and from the turbocharger and the losses in the turbocharger during storage. As previously stated, the losses in the turbocharger during energy storage requires experimentation in order to quantify. For this reason the efficiency used in calculation will be assumed to be the same as a flywheel which is quoted at 95% plus a 5% predicted loss due to aerodynamic drag which depends on the shape of the rotor. The method of transmission to and from the turbocharger varies with each vehicle so the overall efficiency of the storage system will also vary depending on the efficiency of each component in the powertrain.[16]

It was decided that the most efficient method of transmission would have to be completely mechanical. This would also satisfy the previous decision to keep the modification minimal and allow for retrofitting. To achieve this, the following transmission was designed:

Figure 3.4: Turbocharger Powertrain

Each of the aforementioned components have their own associated efficiencies and the addition of these value give the overall regenerative efficiency of this energy storage system. The efficiency of these components will be further explored in later chapters.

4. Potential for Energy Storage – Drive Motor

4.1 Background of Electric Motor

The principle of current magnetics is the basic theory of electric motor. This link between electricity, magnetism, and movement was originally discovered in 1820 by French physicist André-Marie Ampère (1775–1867) .[17] In terms of its working principle, suppose we bend our wire into a U-shaped loop, so there they effectively two parallel wires running through the magnetic field. One of them takes the electric current away from us through the wire and the other one brings the current back again. Because the current flows in opposite directions in the wires, Fleming's Left-Hand Rule tells us the two wires will move in opposite directions. In other words, when we switch on the electricity, one of the wires will move upward and the other will move downward. It is how the motor work in theory, however, there are still some problems during that period. For example, the wires will quickly tangle up, not only that, but if the coil reached the vertical position, it would flip over, so the electric current would be flowing through it the opposite way, hence, the forces on each side of the coil would reverse.

In fact, there are two ways to overcome this problem. One is to use a kind of electric current that periodically reverses direction, which is known as an alternating current (AC). In the kind of small, battery-powered motors, a better solution is to add a component called a commutator to the ends of the coil. In this situation, the commutator is a metal ring divided into two separate halves and its job is to reverse the electric current in the coil each time the coil rotates through half a turn. One end of the coil is attached to each half of the commutator. The electric current from the battery connects to the motor's electric terminals. These feed electric power into the commutator through a pair of loose connectors called brushes, made either from pieces of graphite or thin lengths of springy metal, which the brush against the commutator. With the commutator in place, when electricity flows through the circuit, the coil will rotate continually in the same direction. It can see Figure 4.1,

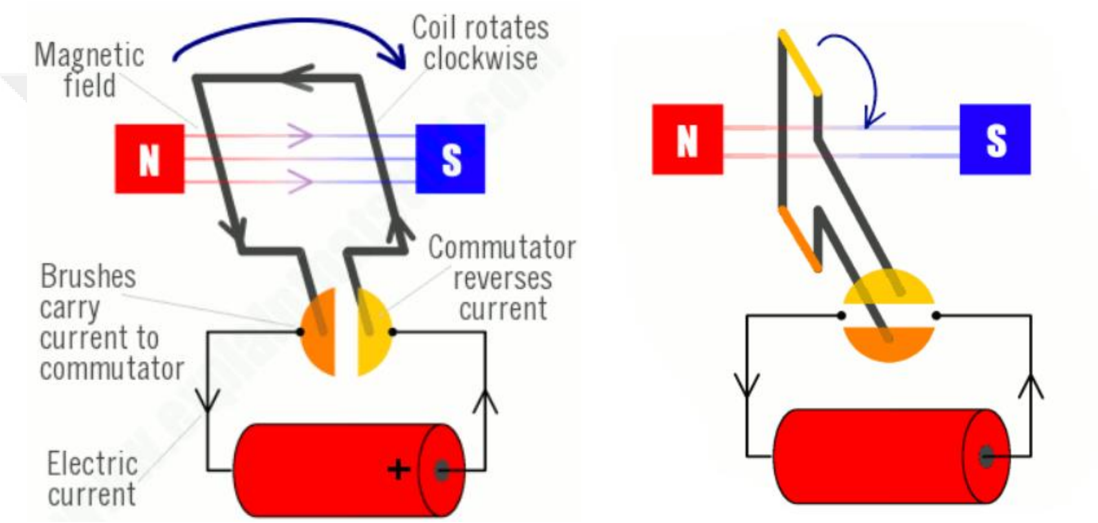

Figure 4.1: Motor working principle [17]

In normal motoring mode, most electric motors operate through the interaction between an electric motor's magnetic field and winding currents to generate force within the motor. In electric and hybrid vehicle, traction motor and generator usually play a significant role which produces and transmits power to drive shaft. In the other side, one advantage of using them is that specific types can regenerate energy (i.e. act as a regenerative brake) - providing braking as well as increasing overall efficiency. Generally, EV/ HEV motors require frequent start/ stop, high rate of acceleration/ deceleration, high – torque low – speed hill climbing, low – torque high – speed cruising and very wide – speed rang of operation.[18] Moreover, there are some types of electric motor often applied in EV/ HEV, see Table 4.1

Motor type	Weight (lb.)	Average Efficiency
DC commutator	218	0.85
AC induction	100	0.935
AC PM disc	75	0.96
AC PM	100	0.935
AC inductor	Heavy	0.80
AC rotating field synchronous	121	0.93

Table 4.1: Different motors in EV/ HEV [19]

4.2.Method of energy storage

Normally, electric motor is based on the principle of current magnetics, but when it turns into energy storage place, the electromagnet can be uncharged, hence there is no magnetic field in M/G. This should be achieved by adding an extra clutch or the relative equipment to make the motor rotor spin individually. In addition, the magnet in electric motor should be replaced by electromagnet, so when the motor acts as a storage place, no electricity through the electromagnet which means there is no torque or friction caused by magnet. Therefore, the motor's rotor can just act as a flywheel. By using the existing transmission used to transfer power to the motor and then decoupling once the required rotational speed is met, the motor can be used to store energy . It is worth mentioning that, if the gear ratio can satisfy the requirement when the car driving, when reversed, this ratio should also be suitable for the motor to store the waste energy when the car breaking. In addition, unlike the battery which need to convert kinetic energy to electric to store, the “M/G flywheel” uses pure kinetic energy which can significantly decrease the losses in energy conversion, hence increase the efficiency of energy storage and also can offer good performance of the frequent energy charging and releasing.

4.3 Mechanism

Motor/ Generator stores the energy recovered from wheels, and the braking energy losses occur in three places – differential, reduction gear box and bearing friction in the M/G. All of their losses are relatively low (the efficiencies will be discussed in the next section), therefore, there is great potential for the "M/G flywheel" to be used to store energy. The mechanism of M/G storage see Figure 4.2.

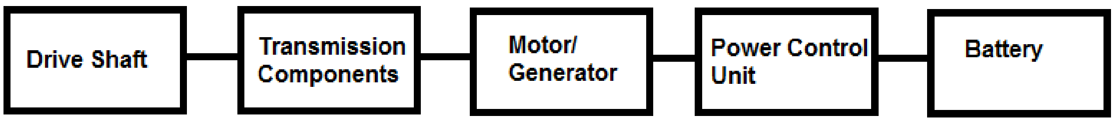

Figure 4.2: Mechanism of M/G storage

4.3.1 Different powertrain

Traditionally, Hybrid Electric Vehicle (HEV) were classified into two basic kinds – series and parallel. Recently, with the introduction of some HEVs offering the features of both the series and parallel hybrids, the classification has been extended to three kinds – series, parallel and series – parallel. In the year 2000, it is interesting to note that some newly HEVs cannot be classified into those kinds. So these HEVs are named as complex hybrid.[18] In this report, the “M/G flywheel” is only applied in two simple kinds of HEVs which are series and parallel. The example of series vehicle is Chevrolet Volt and parallel one is Honda CRZ.

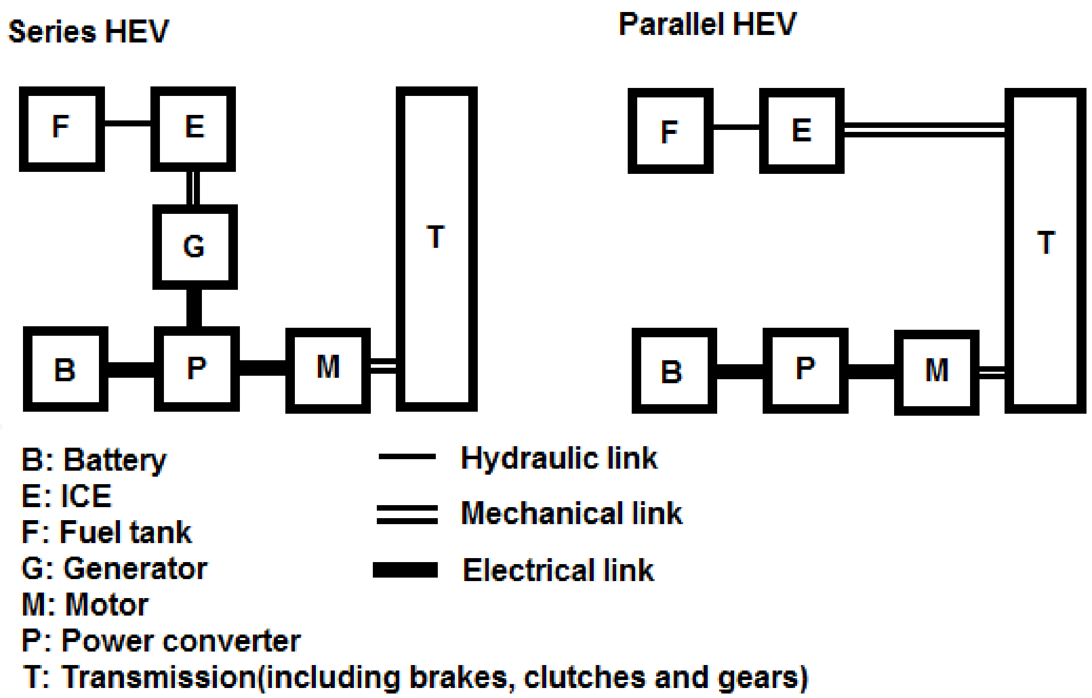

Figure 4.3: Classification of HEVs [3,5]

For those two types of HEV, the general corresponding functional block diagram can see Figure 4.3, in which the electrical link is bidirectional, the hydraulic link is unidirectional and the mechanical link is also bidirectional. It can be found that the key feature of the series HEV is to couple the ICE with the generator to produce electricity for pure electric propulsion. Moreover, the key feature of the parallel HEV is to combine both the ICE and electric motor with the transmission via the same drive shaft to propel the wheel. In other word, electric motor provides main power to the drive shaft. In turns of parallel one, the electric motor more tend to be an assistance systems or a range extender when vehicle accelerates, rounds a curve or out of battery. Hence, the power of traction motor and generator of series HEV are more powerful than the parallel one, which means if the M/G act as a storage place, the storage capacity of series HEV is larger and more efficient than parallel one.

4.4Regenerative Efficiency of a Drive Motor

Normally, the power from M/G to wheel has to through some connecting parts, such as transmission, which include reduction gears and gear box or CVT or planetary gears, differential, and wheel. The general powertrain of M/G see Figure 4.4.

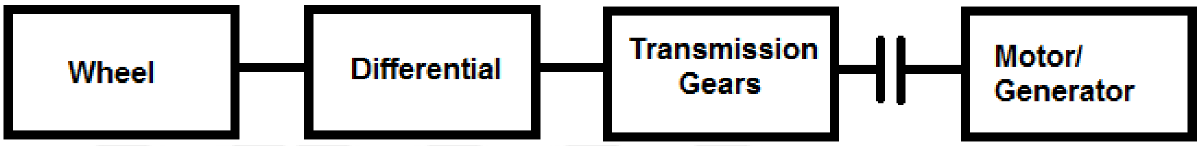

Figure 4.4: General Powertrain of M/G

The differential is designed to drive a pair of wheels while allowing them to rotate at different speeds mainly when vehicle turning corner. If a vehicle is not equipped with differential, the result is the inner wheel spinning and/or the outer wheel dragging, and this results in difficult and unpredictable handling, damage to tires and roads, and strain on (or possible failure of) the entire drivetrain. It is consisted of couples of gears, which can see Figure 4.5.

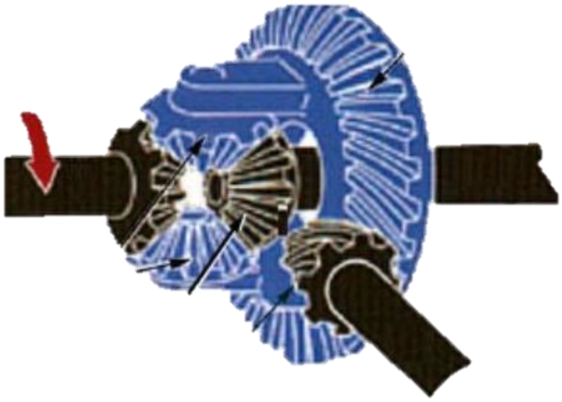

Figure 4.5: 3D mode of differential[20]

When car breaks, the energy goes through wheel, half shaft, differential and later to transmission. Considering about that, there are totally two pairs of gears working during that period and the efficiency of gears friction can be estimated. Therefore, the efficiency of differential can be found out.

As last section mentioned before, when traction motor and generator act as a storage place or like a flywheel, the friction loss is very low. Usually, the type of motor applied in HEV is called AC PM Motor which can be brush or brushless. In order to minimise the friction, the motor can be chosen as brushless. In that situation, the friction of M/G is just caused by the bearings, and the storage efficiency is relative high. Moreover, the category of motor bearing is the same as engines - deep groove ball bearing which has great durability, low coefficient of friction and high limiting speed.

When M/G is turned to be the “M/G Flywheel”, an additional equipment is needed whose function is similar to a clutch. Usually, clutches are designed to engage and disengage the transmission system from the engine when a vehicle is being driven away from a standstill and when the gearbox gear changes are necessary. However, here the function of this equipment focuses on decoupling transmission with motor and generator, hence, motor and generator can rotate individually with high storage efficiency.

5. Potential for Energy Storage – Flywheel

5.1 Background of flywheel

Flywheels have been used to store and stabilise energy for hundred years. In the earliest examples, the principle of flywheel is found in the Neolithic spindle, potter's wheel and spinning wheels. Recently, by using in bearing technology, power electronics and vacuum enclosures it has improved the performance characteristics of flywheels. The first modern flywheel systems were large stationary installations used to provide uninterruptible power supply and the production of very large pulses of electricity for scientific or industrial use. Only in the last two decades flywheel technology has been considered for use in mobile applications. It was held back by prohibitive weight and unwanted precession forces. In this case, the specific tensile strength is the key characteristics. Based on this demand, carbon fibre composite technology has been used in flywheels leading to the development of light, high-speed flywheel systems. And in the particularly vehicles, mechanical flywheel systems with a continuously variable transmission (CVT) has been produced to transfer power to and from flywheel. At present, formula one racing cars has used this technology to improve their cars.

The next evolution was electrically-driven flywheels which do not require a CVT system thus avoiding added weight and reduced efficiency. The flywheel produced by Williams Hybrid Power is electrically driven which can avoid the difficulty in sealing part in mechanical flywheel systems.

Common uses of a flywheel include:

Providing continuous energy when the energy source is discontinuous. For example, flywheels are used in reciprocating engines because the energy source, torque from the engine, is intermittent.

Delivering energy at rates beyond the ability of a continuous energy source. This is achieved by collecting energy in the flywheel over time and then releasing the energy quickly, at rates that exceed the abilities of the energy source.

Controlling the orientation of a mechanical system. In such applications, the angular momentum of a flywheel is purposely transferred to a load when energy is transferred to or from the flywheel.[21]

Flywheels are typically made of steel and rotate on conventional bearings; these are generally limited to a revolution rate of a few thousand RPM.[22] Some modern flywheels are made of carbon fiber materials and employ magnetic bearings, enabling them to revolve at speeds up to 60000 RPM.[23]

5.2 Method of energy storage

For a mechanical flywheel systems, flywheel is a rotating mechanical device that is used to store rotational energy. Flywheels have a significant moment of inertia and thus resist changes in rotational speed. The amount of energy stored in a flywheel is proportional to square of its rotational speed. Energy is transferred to a flywheel by applying torque to it, thereby increasing its rotational speed, and hence its stored energy. Conversely, a flywheel releases stored energy by applying torque to a mechanical load, thereby decreasing its rotational speed.

A flywheel is a spinning wheel or disc with a fixed axle so that rotation is only about one axis. Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

$$E_k = \frac{1}{2} I \omega^2 \qquad (5.1)$$

Where:

ω is the angular velocity

I is the moment of inertia of the mass about the center of rotation.

The moment of inertia is the measure of resistance to torque applied on a spinning object (i.e. the higher moment of inertia, the slower it will spin when a given force is applied)

The moment of inertia for a solid cylinder is

$$I = \frac{1}{2} m r^2 \qquad (5.2)$$

For a thin-walled empty cylinder is,

$$I = m r^2 \qquad (5.3)$$

And for a thick-walled empty cylinder is,

$$I = \frac{1}{2} m (r_{external}^2 + r_{internal}^2) \qquad (5.4)$$

Where *m* denotes mass, and *r* denotes a radius.

When calculating with SI units, the standards would be for mass, kilograms; for radius, meters; and for angular velocity, radians per second. The resulting answer would be in joules.

The amount of energy that can safely be stored in the rotor depends on the point at which the rotor will warp or shatter. The hoop stress on the rotor is a major consideration in the design of a flywheel energy storage system.

$$\sigma_t = \rho r^2 \omega^2 \qquad (5.5)$$

Where:

σ_t is the tensile stress on the rim of the cylinder.

ρ is the density of the cylinder.

r is the radius of the cylinder, and

ω is the angular velocity of the cylinder.

This formula can also be simplified using specific tensile strength and tangent velocity:

$$\frac{\sigma_t}{\rho} = \upsilon^2 \qquad (5.6)$$

Where:

$\frac{\sigma_t}{\rho}$ is the specific tensile strength of the material

υ is the tangent velocity of the rim.

Flywheel purpose, type	Geometric Shape Factor(k)	Mass (kg)	Diameter (cm)	Angular velocity (rpm)	Energy stored (MJ)	Energy stored (kWh)
Small battery	0.5	100	60	20,000	9.8	2.7
Regenerative braking in trains	0.5	3000	50	8,000	33.0	9.1
Electric power backup	0.5	600	50	30,000	92.0	26.0

Table 5.1: Energy storage traits[24]

High-energy materials

For a given flywheel design, the kinetic energy is proportional to the ratio of the hoop stress to the material density and to the mass:

$$E_k \propto \frac{\sigma_t}{\rho} m \qquad (5.7)$$

$\frac{\sigma_t}{\rho}$ could be called the specific tensile strength. The flywheel material with the highest specific tensile strength will yield the highest energy storage per unit mass. This is one reason why carbon fiber is a material of interest.

For a given design the stored energy is proportional to the hoop stress and the volume:

$$E_k \propto \sigma_t V \qquad (5.8)$$

5.3 Mechanism

when the vehicle brake, the mechanical energy from the wheel first go through the powertrain to the drive motor, then the rest of the energy goes through the powertrain which is shown below in figure 5.1 to store the energy in the flywheel. All these steps are all mechanical energy transfer, do not have conversion.

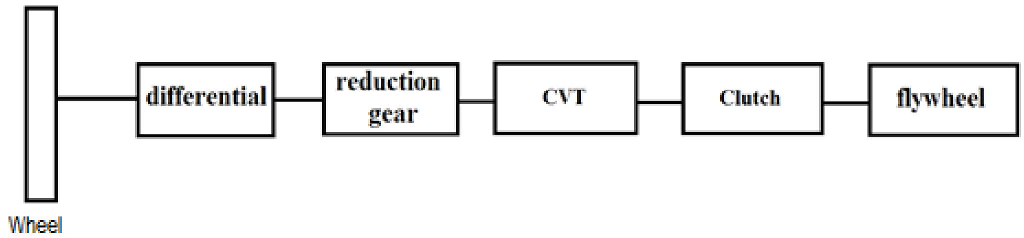

Figure 5.1: The schematic structure of energy flow process for battery

5.4 Regenerative Efficiency of a flywheel

By using flywheel to store the energy, first we should know the efficiency of flywheel cannot be 100%, on the other hand, we choose flywheel as the storage part is also means the flywheel has a high and reliable efficiency. There are two kinds of flywheels, one is totally mechanical one, all the energy transfer as kinetic energy, don't have energy conversion, and the other one is like Williams flywheel, it has a motor generator to transfer the kinetic energy to the electric energy, so during the conversion time, it has another unwanted energy lose. As a result, in our report, we choose the mechanical one to store braking energy, in the following part, we will talk about which part and where does the flywheel have the energy and how can we do to improve the efficiency of flywheel.

6. Potential for Energy Storage – Battery

6.1 Background of Battery

An electric battery is a device which has one or more electrochemical cells that convert stored chemical energy into electrical energy. Batteries provide a means for storing energy and have become a vital entity in modern life. They are used for powering a many of devices, both large and small. Battery technology has been known for two centuries. Volta demonstrated the "voltaic pile". This consists of an electrochemical cell which contains two different metal electrodes. These metal are used to provide an electrochemical potential. This experiment demonstrated current and showed that he magnitude is dependent on area of electrodes. When area of electrodes is made bigger, it gives higher current. [25]

6.2 Working Principle of Battery

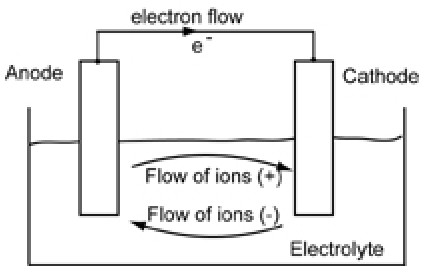

Figure 6.1: Electrochemical cell [26]

A cell consists of a negative electrode; an electrolyte, which conducts ions; a separator, also an ion conductor; and positive electrode. It is shown Figure 6.1. There are two type of electrode which are aqueous, composed water and the other is non-aqueous. When the cell is connected to an external load, or device to be powered, a current of electrons flow through the load or external device from negative electrode to positive electrode. When the external load is removed the electrochemical reaction finishes. [27]

There are two main types of batteries, primary battery, which convert its chemical energy into electricity only once and then must be discarded. The other one is secondary battery. It has electrodes that can be reconstituted by passing electricity back through it which allows for reuse; also called a storage or rechargeable battery.

Voltage requirement is different for each application f a battery. So electrochemical cells are connected in series to meet the voltage requirements. The voltage supplied by each cell is determined by its electrochemical reaction. The open circuit voltage of an electrochemical can be calculated from the energy of the reaction

$$\Delta G = -n\ F\ E_o \qquad (6.1)$$

Where ΔG: the energy of reaction in Joules per mole (The free energy of spontaneous reaction is negative by convention)

n: the number of moles per reaction

F: The Faraday, 96,500 coulombs per equivalent

E_o: The cell voltage when the electrolyte concentration is 1 litre at standard temperature and pressure.

Temperature and the concentration of the electrolyte play an important role in calculating the energy of reaction. This relationship can be calculated using the Nerst equation:

$$E = E_o + R\ T\ \ln F \times \ln (([a-]\ [b+]) / [gh]) \qquad (6.2)$$

Where E : The cell voltage at ambient temperature and present electrolyte concentration

T : Temperature in °K

R : The ideal gas constant, 8.3145 Joule/mole/ °K

[a-]: The concentration of negative ions in the electrolyte

[b+]: The concentration of positive ions in the electrolyte

[gh]: The concentration of electrolyte solvent [29]

Batteries have become important in the transition from fossil fuels to alternative energy. Batteries are the most important and expensive component for hybrid and pure electric vehicle because for hybrid and electric vehicle main energy storage is the battery. There are three types of batteries for hybrid and electric vehicle. These are lead-acid, nickel based batteries such as nickel/ iron, nickel/cadmium and nickel- metal hydride(Ni-MH) batteries. Lithium based batteries, such as lithium-polymer (Li-P) and lithium- ion(Li- I) batteries. Each battery has different chemical reaction which shown Table 6.1. [30]

Battery chemistry	Chemical reaction
Lead- acid	$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$
Nickel – cadmium	$2Ni(OOH) + Cd + 2H_2O \rightarrow$ $2Ni(OH)_2 + Cd(OH)_2$
Nickel- metal hydride	$MH + Ni(OOH) \rightarrow M + Ni(OH)_2$
Lithium- ion	$Li_xC + Li_{1-x}O_2 \rightarrow LiMO_2 + C$

Table 6.1: Chemical reaction for different kind of battery chemistry [29]

For hybrid and electric vehicle the most popular batteries are nickel- metal hydride and lithium ion because of the performance shown in Table 6.2. In the project four different hybrid cars are examined. These vehicles use lithium- ion and nickel – metal hydride batteries. So these two is explained as following.

Battery type	Specific energy storage (Wh/kg)	Specific power (for 30 s at 80% capacity) W/kg	Specific cost ($/kwh)	Cycle life (Charges and discharges to 80% of capacity)
Lead- acid	35	200	125	450
Nickel –Cadmium (Ni-Cd)	40	175	600	1250
Nickel- metal hydride (Ni- MH)	70	150	540	1500
Lithium- Ion (Li-Ion)	120	300	600	1200

Table 6.2: Performance of various battery types [30]

6.2.1 Nickel- metal hydride (Ni- MH) battery

Nickel- metal hydride (Ni- MH) batteries are used in computers, medical equipment and other mobile applications nowadays because they have greater specific energy and specific power capability than lead- acid and nickel- cadmium batteries. However they have some disadvantageous. One of them is the biggest one is more expensive than the others.

The battery`s chemical reaction is shown on table 1. When the battery is discharged, metal hydride in the negative electrode is oxidized to from metal alloy and nickel oxhydroxide in the positive electrode is reduced to nickel hydroxide. During charging the reverse reaction occurs.

This type of batter has the advantage of having the highest specific energy (70- 95 Wh/kg), and highest specific power (200- 300 W/kg) which improves environmental friendliness; a flat discharge profile and rapid charge capability. But the weakest point of the batteries is initial cost as mentioned before. [30]

6.3.2 Lithium- Ion (Li-Ion) battery

The Li-I battery uses a lithiated carbon intercalation material for negative electrode instead of metallic lithium. They also use a lithiated transition metal intercalation oxide for positive electrode and a liquid organic solution or a solid polymer for electrolyte. Lithium ions are swinging through the electrolyte between the positive and negative electrodes during discharge and charge. The general chemical reaction is shown on the table 1. On discharge, lithium ions are released from the negative electrode. The electron flow takes place by using the electrolyte. For charging the battery, the process is reversed.

These type of battery has a specific energy of 120 Wh/ kg, an energy density of 200 Wh/L and specific power of 260 W/kg. Li-ion batteries are also relatively cheap, for these reasons they are the most common type found in HEVs. [31]

6.3.3 Charging and discharging battery

There are two types of methods used for charging batteries of HEV. The first is through regenerative braking which all HEVs and EV use, the second is only used by vehicles which are name plug-in vehicles. Only difference between plug-in and conventional hybrid vehicle is plug-in hybrid vehicles (PHEVs) battery is charged by using external electric power source such as household mains. However all hybrid vehicle's battery is charged power which is produced by internal combustion engine, when the internal combustion engine produce more power than is necessary to drive the vehicle. In addition under braking or when the accelerator is lifted, the kinetic energy of the vehicle, which is called regenerative braking energy, is used for charging the battery by using the electric motor which act as generator. Normally the energy is lost as friction heat. Storing regenerative braking energy into battery is not efficient for the short of time because when the energy is wanted to store into battery, it should be convert to mechanical to electrical; after that when the energy is needed, the process is reversed. Hence efficiency is very low. The efficiency of the battery will be explained in the next topic.

When a battery in a HEV is reaches below 35%, typically, the engine will automatically begin to recharge. In series hybrids the engine is connected to a generator which transfer the mechanical energy to electric and will turn on once the battery reaches a predetermined level. In some parallel hybrids the energy from the engine has to travel a further distance but is still used to recharge the battery.

6.3 Regenerative Efficiency of a Battery

There are a number of energy conversion involved in recovering energy and storing it in a battery. The energy conversion is from chemical to electrical (battery), DC current to AC current (inverter), electrical to mechanical (motor / generator), adjusting to proper rotational speed (transmission gears), torque to force (differential and wheel) when the battery is discharging. When the battery is charging by using the regenerative braking, the process is reverse. Each one of these step incur a loss which combine to give the total regenerative efficiency for a battery. This process demonstrated figure 6.2.

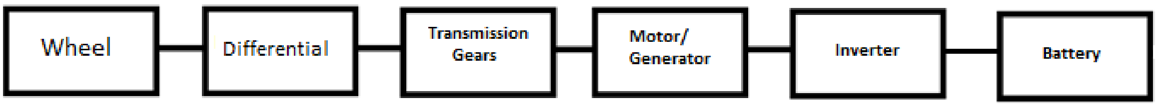

Figure 6.2: The schematic structure of energy flow process for battery

6.3.1 Efficiency of battery

The reason for the energy or power losses during battery discharging and charging is in the form of voltage loss. Thus the efficiency of the battery during discharging and charging can be defined at any operating point as the ratio of the cell operating voltage to the thermodynamic voltage, that is,

During discharging

$$\eta = \frac{V}{V_0} \qquad (6.3)$$

During charging

$$\eta = \frac{V_0}{V} \qquad (6.4)$$

The terminal voltage, as a function of battery current and energy stored in it or state of charge, is lower in discharging and higher in charging than the electrical potential produced by chemical reaction. The efficiency of Li-ion battery is shown figure 6.3 during charging and discharging. Batteries have a high discharging efficiency with a high state of charge and high charging efficiency with low state of charge. The net cycle efficiency has a maximum in the middle range of the state of charge, So the battery operation control unit of a hybrid electric vehicle should control the batteries state of charge in its middle range. This will enhance the operating efficiency and depress the temperature rise caused by the energy loss. High temperature would damage the battery. [31]

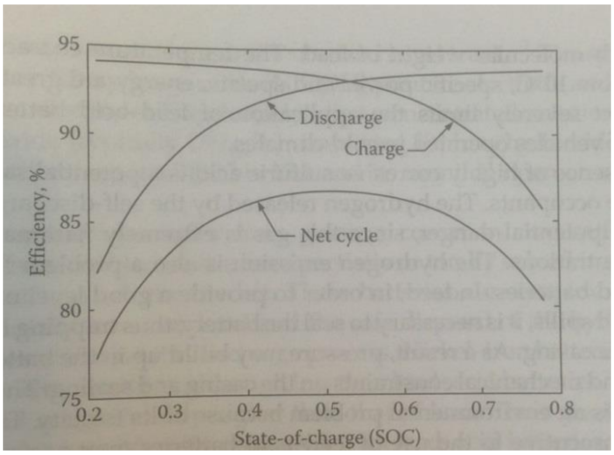

Figure 6.3: Typical Li-ion battery charge and discharge efficiency [31]

So when the wheel to wheel regenerative braking efficiency is calculated, the state of charge is accepted in the middle range and temperature level is optimum.

The efficiency of vehicle batteries and general information about them are kept highly confidential due to industry competitiveness . Adding to this lack of information was the fact that there are many different ways to calculate efficiency, and that there are many factors that can be overlooked. The efficiency of a battery can be calculated as the amount of power discharged by the battery divided by the amount of power delivered to the battery. This takes into account the loss of energy to heat, which warms up the battery. The charge-discharge efficiencies of various batteries are summarized in Table 6.3. Li-ion efficiencies are extremely high, Pb-acid efficiencies have a huge range, NiMH efficiencies are low at 66%.[32-34]

Battery type	Charge/discharge efficiency
Li-ion	80% - 90%
Pb-Acid	50% - 92%
NiMH	66%

Table 6.3: Batteries efficiency [10-12]

6.3.2 Efficiency of inverter

Inverters are electric power converter that convert direct current (DC) to alternating current (AC). Inverter parameters such as the input voltage, the output voltage and frequency depend on the design. Generally a highly efficient inverter which include dc to dc converter to regulate the voltage is used for renewable energy and reversible application. For hybrid electric vehicle high efficient inverter is used. Karl H.E. et.al carried out an experiments to investigate inverter of different output amplitude and different loads. Their finding indicated an average efficiency of 96%. The experimental result is shown in Table 6.4.[35]

Resistance[Ω]	Power input[W]	Power output[W]	Efficiency
1.6	43.8	42.6	97%
0.8	86.7	83.6	96.5%
0.4	136.0	129.5	95%

Table 6.4: Simulated efficiency of inverter for different resistance, power input and power output [35]

7. Application to Existing Vehicles

This chapter explores the improvements that could be made to 4 existing vehicles by modifying the existing drive line and by using the energy storage devices previously explained. This is achieved by outlining the existing powertrain to identify the mechanical and regenerative efficiency currently available. Once this is quantified, modification to the powertrain are carried out with minimal new parts to improve the regenerative efficiency of these vehicles and finally compare the efficiency of the existing vehicle with that of the modified vehicle.

The vehicle were selected to explore as much variety as possible in the compact hybrid market. The vehicles were Chevrolet Volt, Toyota Prius, Volkswagen Jetta and the Honda CRZ.

7.1 Mechanical transmission efficiency

The efficiencies of each component are shown by table 7.1, for instance, the bearing's efficiency is 99%, clutch is 99% and each pair of gears is 95 – 97%.[31] For reduction gears, they are coupled with two gears, one is differential's, the other is on the hub axle of M/G, so the efficiency will be $97\%^2$, which is 94%. As reduction gears consist of two gears that have the same size teeth but are of different diameters and they are used to reduce the rotational speed of the input shaft to a slower rotational speed on the output shaft. The same calculation method is also suitable for planetary gears. When turning to the "M/G Flywheel", based on its structure, the energy loss is just caused by bearings at both ends, hence, the "M/G Flywheel" efficiency is $99\%^2$, which is 98%. In terms of differential, even though its structure is a little complex, during break, there just two small pairs of gears work in the same time, so its efficiency is 98%[31].

The continuously variable transmission(CVT) and gear box both have the purpose of adjusting the gear ratio. However, CVT requires fewer gears than in a gear box. The efficiencies of a CVT and gear box are 92% and 96% respectively[31]. The following table shows the efficiencies of each component,

Wheel bearing	99%
Differential	98%
Reduction gear	94%
Clutch	99%
Planetary gears	94%
Inverter	96%
CVT	92%
Gear box	96%

Table 7.1: Efficiencies of each component

7.2 Chevrolet Volt

The Chevrolet Volt concept car debuted at the January 2007 North American International Auto Show, becoming the first-ever series plug-in hybrid concept car shown by a major car manufacturer.[36]It is a typical series HEV which operates as a purely electric vehicle for the first 25 to 50 miles (40 to 80km) in charge – depleting mode.[37] When the battery capacity drops below a pre – established threshold from full charge, the vehicle enters charge – sustaining mode, and the Volt's control system will select the most optimally efficient drive mode to improve performance and boost high – speed efficiency.

7.2.1 Existing system of Chevrolet Volt

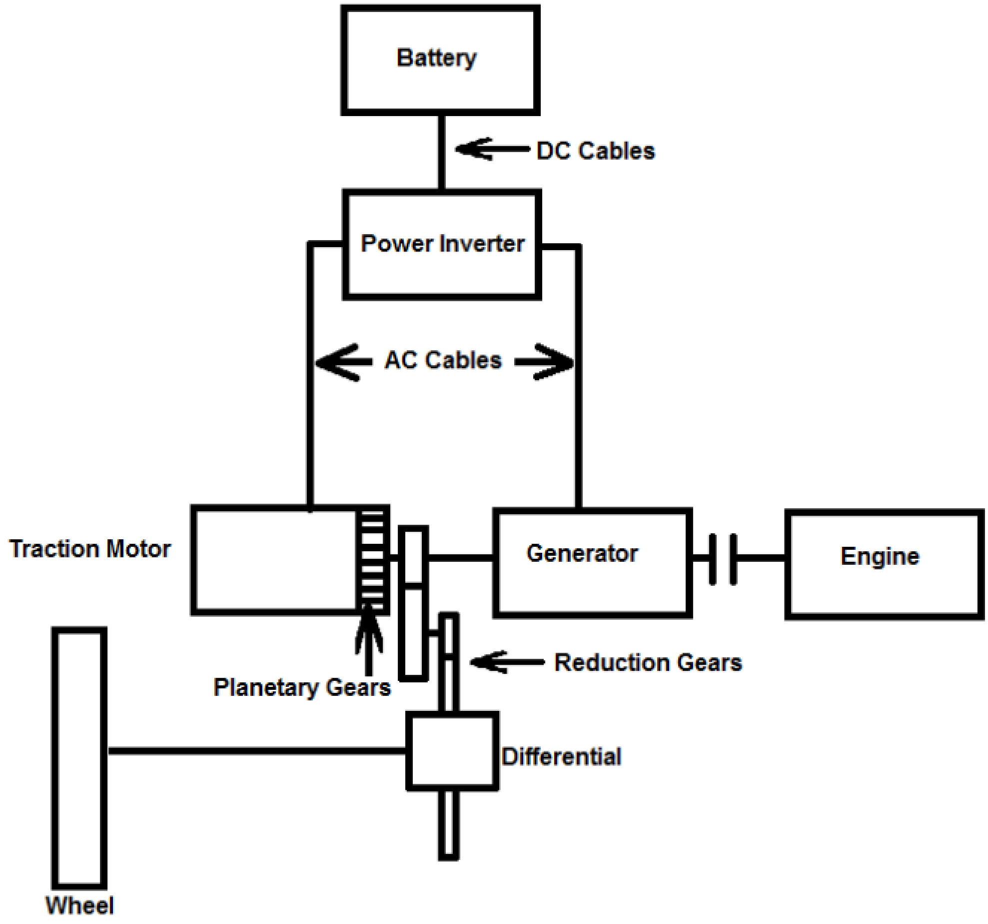

Figure 7.1: The complete diagram of Chevrolet Volt`s powertrain

The 16 kWh battery provides the core energy to the whole car. In this situation, the vehicle’s traction motor and generator are comparatively powerful, which are 111.1 kW and 55kw. The basic powertrain sees the Figure 7.2.

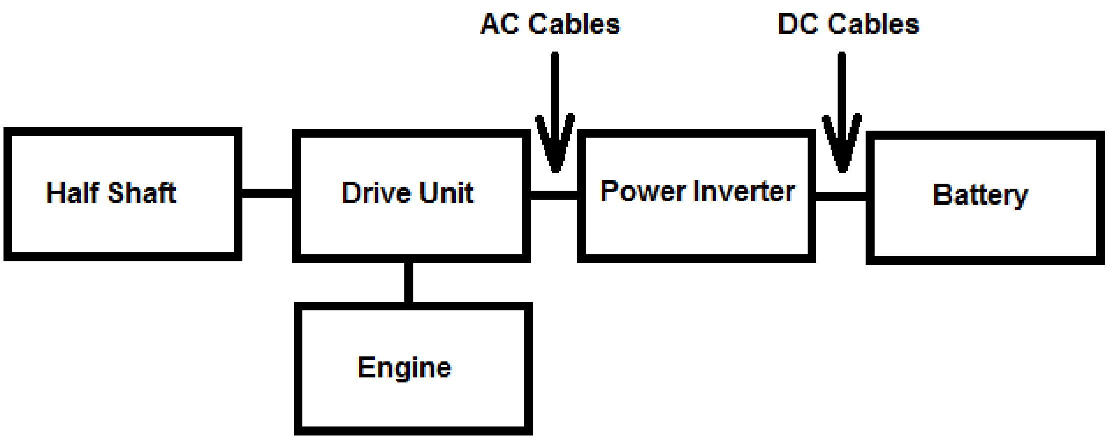

Figure 7.2: Powertrain of Chevrolet Volt

From Figure 7.2, it is easy to notice that no matter energy from battery or engine, it always delivers to drive unit and then to drive shaft, it is exact series HEV. The construction of drive unit can see Figure 7.3,

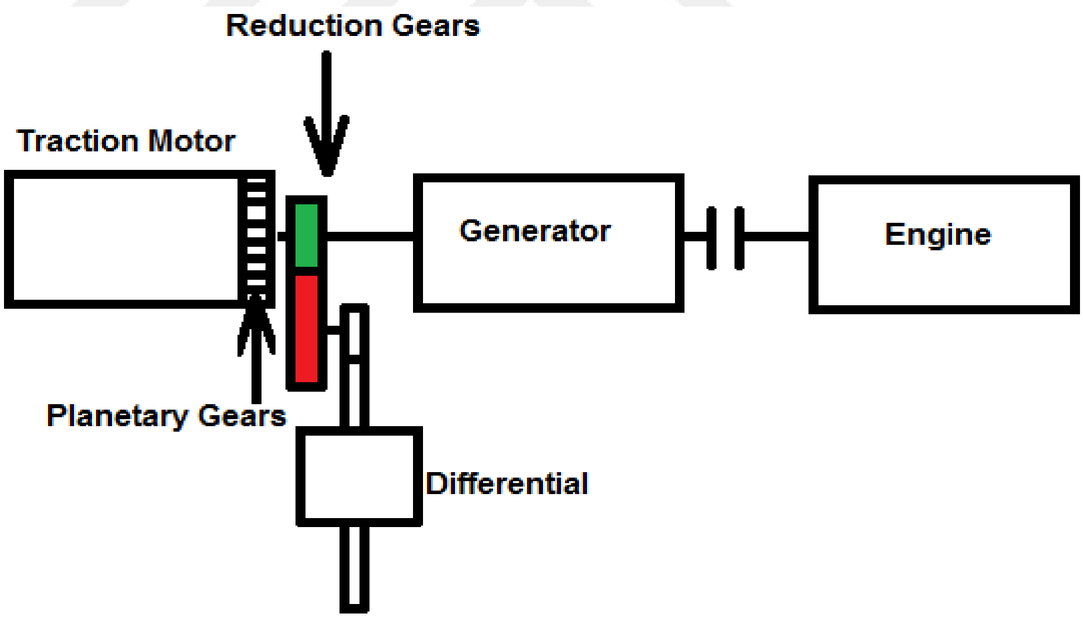

Figure 7.3: Drive unit of Chevrolet Volt

The drive unit consists of a traction motor, a generator and reduction gears. There are three clutches in drive unit, two of them are in the traction motor and one is in generator. Moreover, one clutch in traction motor is used for holding the ring gear of planetary gears in order to adjust gear ratio, and the other one is to make the generator connect to ring gear which can keep the generator's speed to the traction motors. Beside the traction motor, there are planetary gears which are mainly used to change the gear ratio. The complete vehicle powertrain diagram can see Figure 7.3.

Usually, a common series hybrid car can be only driven by traction motor no matter the power is from battery (battery – power inverter – traction motor) or engine (engine – generator – traction motor), this will require the traction motor more powerful than parallel one, but as one of most popular and high fuel - efficiency hybrid vehicle, Volt has another different drive mode, which called "Two – Motor Drive". This specific motion is achieved by two clutches in traction motor, one let the generator connect to ring gear of planetary gears, and the other is to release the ring gear. By those clutches, the generator will work as the traction motor. In this mode, the drive power is supplied by traction motor and generator. When the vehicle in 70mile per hour, the speed of traction motor can decrease from 6500rpm (that speed occurs when the power is only supplied by traction motor) to 3250rpm, and generator speed is nearly 1500rpm. Therefore, it can relieve the damage of motor when it works in maximum speed and extent the operating life. Moreover, that mode can provide more power and make the car's speed achieve up to 100mph.

Model	2011 Chevrolet Volt
Battery chemistry	Lithium – ion
Battery energy	16 kWh
Engine type	1.4L DOHC I – 4
Electric drive motors (two)	Traction motor, 111kW Generator motor, 55kW
Overall width	1788 mm
Height	1430 mm
Aero drag coefficient	0.28
Overall mass	1588 kg

Table 7.2: Chevrolet Volt specification [38]

7.2.2 Modified system of Chevrolet Volt

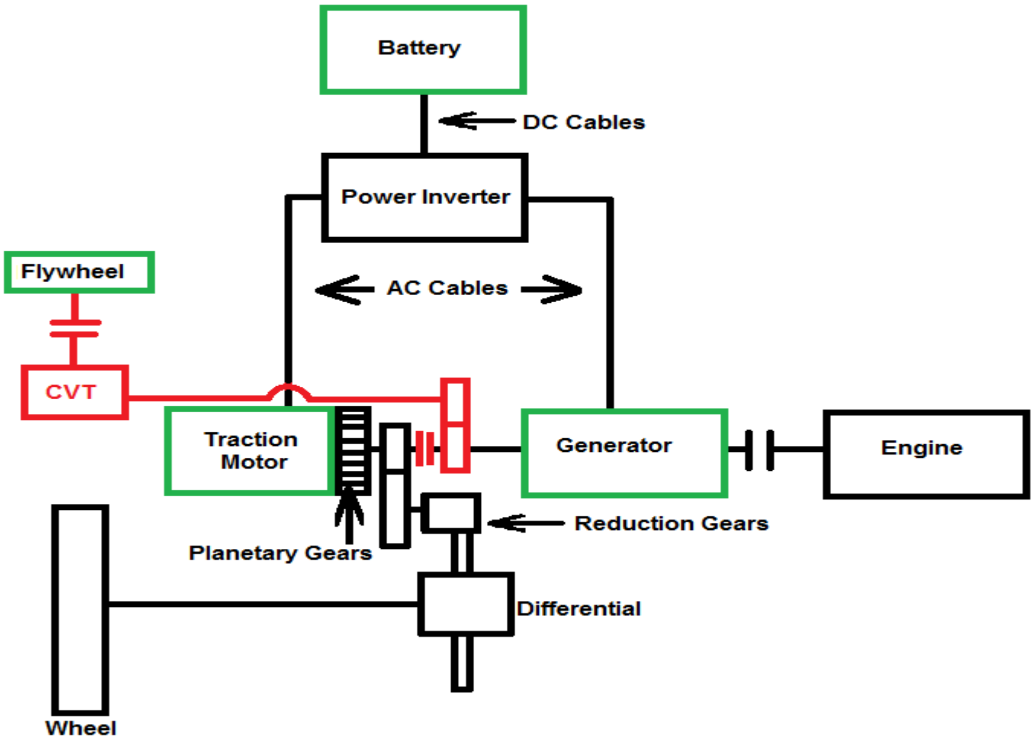

Figure 7.4: Chevrolet Volt modified powertrain

Motor/Generator

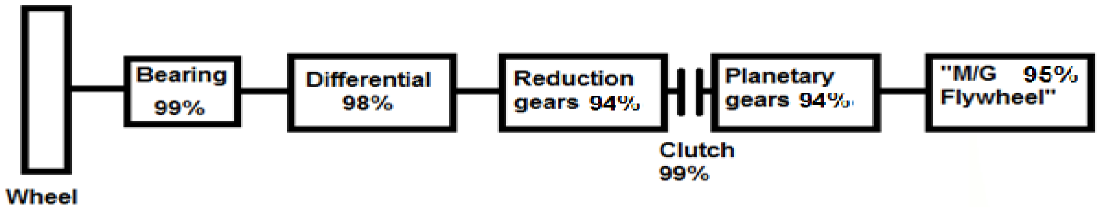

Figure 7.5: Power transmission of the M/G flywheel

In the figure 7.5, the efficiencies of each component are showed, for instance, the wheel bearing is deep groove ball bearing, its efficiency is 99%, differential is 98%. The reduction gears consist of two gears that have the same size teeth but are of different diameters and they are used to reduce the rotational speed of the input shaft to a slower rotational speed on the output shaft. For each pair of gears, the efficiency is 95% - 97%. For reduction gears, they are totally coupled with two gears, one is differential's, the other is on the hub axle of M/G, so the efficiency will be $97\%^2$, which is 94%. The same calculating method is also suitable for planetary gears. When turning to the "M/G Flywheel", based on it structure, the energy loss is just caused by bearings at both ends. Normally, bearing and joint efficiency is nearly 98% - 99%, hence, the "M/G Flywheel" efficiency is $99\%^2$, which is 98%. To sum up, the total storage efficiency of "M/G Flywheel" is

$$\eta_{M/G\ overall} = \eta_{bearing} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{clutch} \times \eta_{PG} \times \eta_{flywheel} = 80.6\%$$

Flywheel

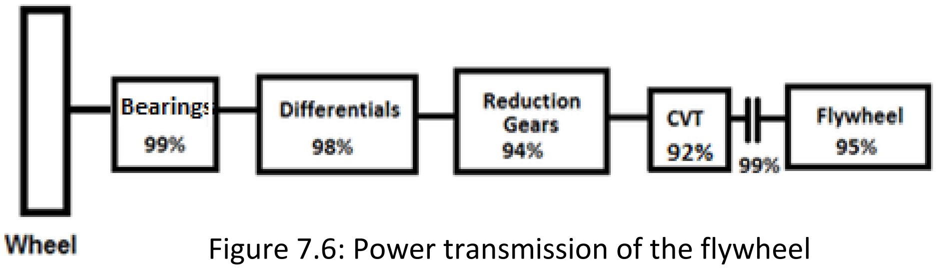

Figure 7.6: Power transmission of the flywheel

Figure 7.6 shows the power transmission to the flywheel. Similarly the efficiency of the flywheel can be calculated by multiplying the efficiency of each component:

$\eta_{flywheel\ overall} = \eta_{bearing} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{CVT} \times \eta_{clutch} \times \eta_{flywheel}$=78%

Battery

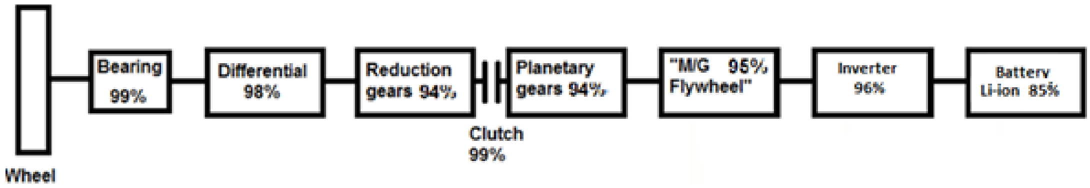

Figure 7.7: Power transmission of the battery

Figure 7.7 shows the method of transmission to the battery. This is the least efficient energy storage method for two main reason, first because the power transmission has the most components which all have their own associated inefficiency. Second, because energy storage in batteries are less efficient than mechanical storage system due the electro-chemical reaction which takes place during storage, which means mechanical energy is transferred to electrical energy to then transfer to electro-chemical potential. The method of calculation is as follows:

$\eta_{battery\ overall} = \eta_{bearing} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{clutch} \times \eta_{PG} \times \eta_{M/G} \times \eta_{inverter} \times \eta_{battery}$=66%

7.3 Volkswagen Jetta Hybrid

7.3.1 Existing system of Volkswagen Jetta

The Jetta is the first turbocharged hybrid vehicle released by VW and received overwhelming reviews on both performance and fuel economy. It also recorded the highest top speed of all commercial hybrids on the market to date with a top speed of 185 mph. This model is a full hybrid that combines 7.2.1 Existing System

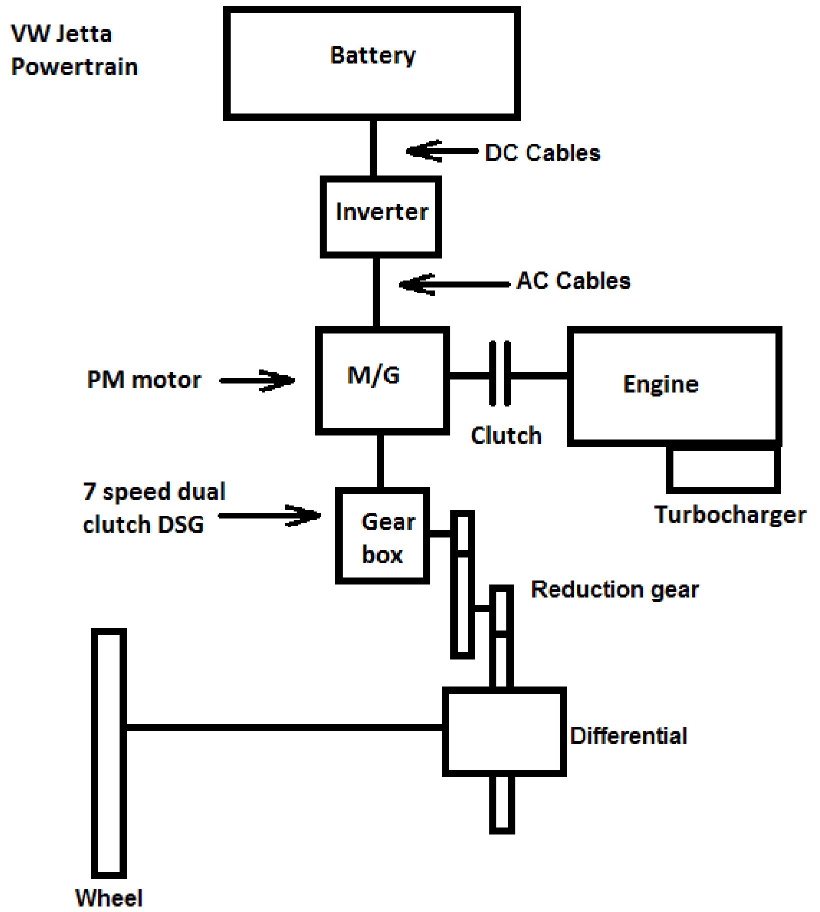

Figure7.8: Volkswagen Jetta (2013 model) Powertrain

Components

Model	2013 Volkswagen Jetta
Battery chemistry	Lithium – ion

Battery energy	1.1 kWh
Engine type	1.4L Turbocharged
Transmission	7 Speed DSG duel clutch Automatic
Electric drive motors and Generator	20 kW
Front Area	2.1 m^2
Aero drag coefficient	0.29
Overall mass	1498 kg

Table 7.3: Volkswagen Jetta specification[39]

The Jetta works as a typical parallel hybrid in the sense that it combines energy from a 1.1kWh battery and from a 1.4L engine. By combining the two sources of energy at the same time like this the overall power output is 170hp, which is an astonishing amount for a hybrid vehicle. The turbocharger also plays a key role in increasing the power output at high revolutions, which explains how the Jetta can travel at such high speeds, although this come at a cost to fuel consumption.

The Jetta opts for a 7 speed duel clutch automatic gear box which is rare for hybrid vehicles. This system is 20% more efficient according to the official VW hybrid home page.

7.3.2 Modified system of Volkswagen Jetta

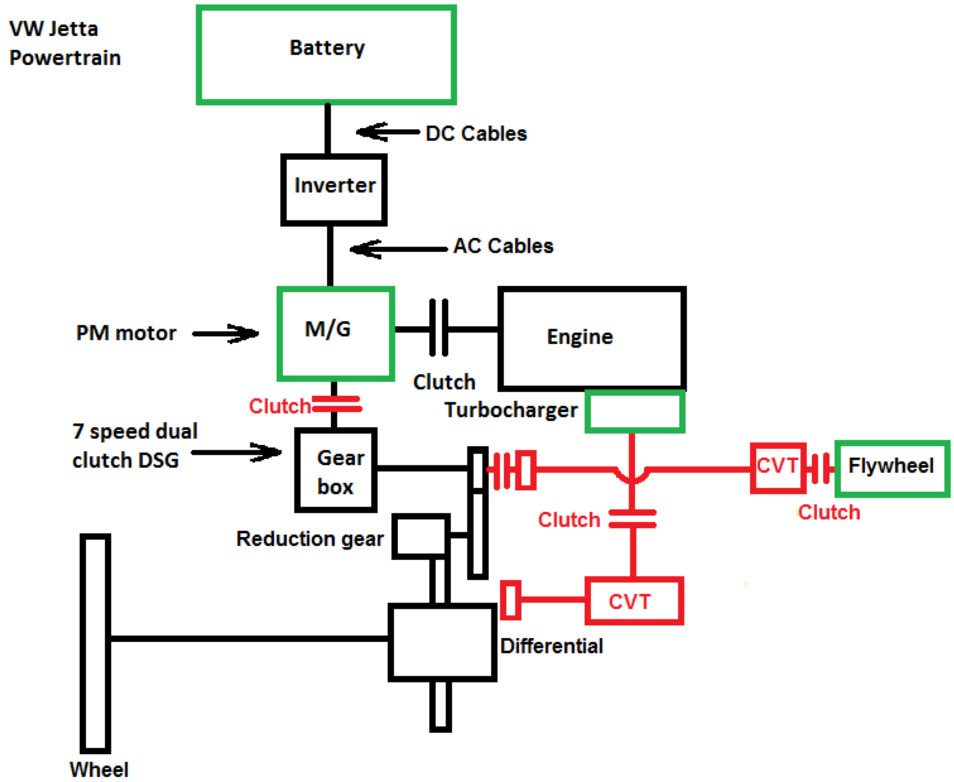

Figure 7.9: Volkswagen Jetta (2013 model) Modified Powertrain

When modifying the Volkswagen Jetta, the possibility to use all four energy storage devices were exploited. To achieve the improvements in regenerative braking the following components were added to the powertrain: a flywheel, 4 clutches and 2 CVT's, also the reduction gears were altered to an enable switching between modes. These modes allow the differential to transfer power from the wheels to and from the flywheel, the turbocharger when used for energy storage and finally the to the gear box.

The power transmission for each of the storage device and the source of efficiency are outlined below.

Turbocharger

Figure 7.10: Power transmission of turbocharger

Figure 7.10 shows the transmission for a turbocharger which is added to the driveline via a CVT and clutch. The overall efficiency of this system can be calculated by multiplying the individual efficiencies.

$$\eta_{TC\ overall} = \eta_{wheel} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{CVT} \times \eta_{clutch} \times \eta_{TC}$$
$$= 75\%$$

Motor/Generator

Figure 7.11: Power transmission of Motor/Generator

Figure 7.11 shows the transmission to the motor/generator and is calculated below:

$$\eta_{M/G\ overall} = \eta_{wheel} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{gearbox} \times \eta_{clutch}$$
$$\times \eta_{M/_G} = 75\%$$

Battery

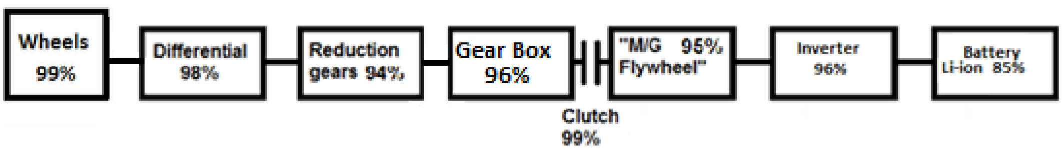

Figure 7.12: Power transmission of battery

Figure 7.12 shows the power transmission for storing restored energy in the battery of a VW Jetta. Although the efficiency of the Li-ion battery is relatively high, the increased in number of components make the overall efficiency of the system decrease, this is shown below:

$$\eta_{battery\ \ overall} = \eta_{wheel} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{gearbox} \times \eta_{clutch} \times \eta_{M/G} \times \eta_{clutch} \times \eta_{M/G} \times \eta_{inverter} \times \eta_{battery} = 67\%$$

Flywheel

Figure 7.13: Power transmission of flywheel

This system is sophisticated in the sense that it allows for the energy stored in the flywheel to be used to charge the battery certain situations such as when the vehicle has come to the end of its journey . by modifying the reduction gears to allow three separate connections to be made, the turbocharge and the flywheel can be added to the normal driveline. The clutch closest to the reduction gear allows power to be added to the normal driveline which goes to the M/G, refer to figure #. The efficiency of this system is shown below:

$$\eta_{flywheel\ overall} = \eta_{wheel} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{CVT} \times \eta_{clutch} \times \eta_{TC} = 75\%$$

7.4 Honda CR-Z

The CR-Z is the first hybrid electric automobile manufactured by Honda which is equipped a 6-speed manual transmission. It is one of the least polluting vehicle which has a low consumption and clean emission. It has a low fuel consumption in both city and highway, in the city is 36mpg and on highway is 39mpg which is lower than any other small vehicles. It also includes the unique version of Honda's IMA technology.

7.4.1 Existing system of Honda CR-Z

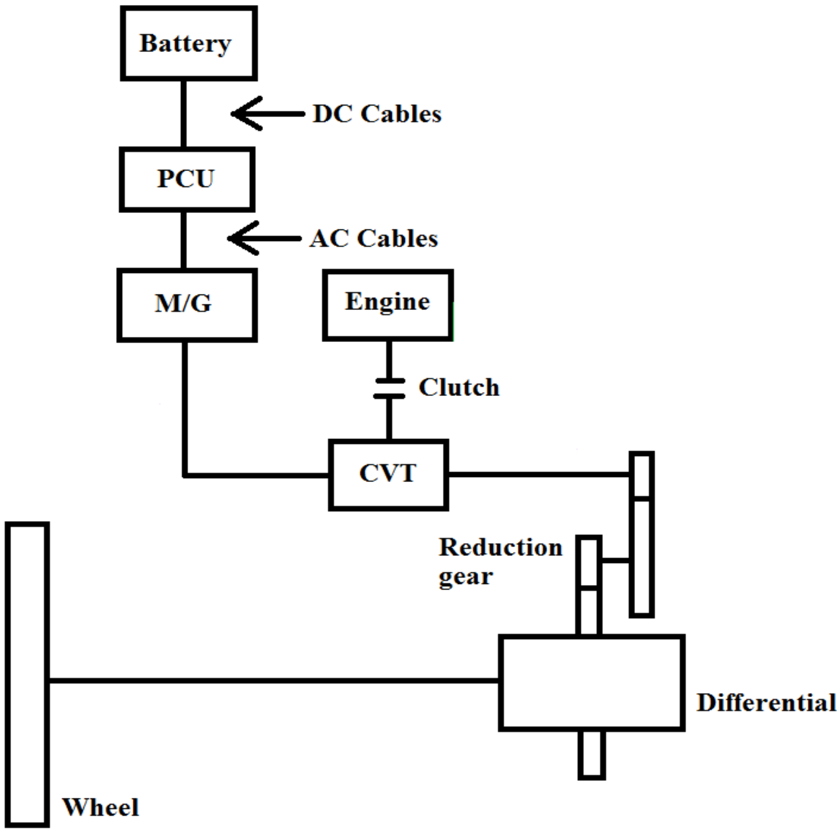

Figure 7.14: Existing Honda CR-Z powertrain

Components

Model	2011 Honda CR-Z
Battery chemistry	Lithium – ion
Battery energy	0.4 kWh
Engine type	1.5 L i-VTEC
Electric drive motor	80 kW
Overall width	1740 mm
Height	1394 mm
Aero drag coefficient	0.30
Overall mass	1204 kg

Table 7.4: Honda CR-Z specification[40]

The Honda CR-Z works as a parallel hybrid vehicle which is powered by a 1.5-liter four-cylinder i-VTEC engine and a 0.4kWh Lithium-ion battery, and the battery drive a 15-kilowatt electric motor, combined both the engine and electric motor, it can provide overall 130 horsepower.

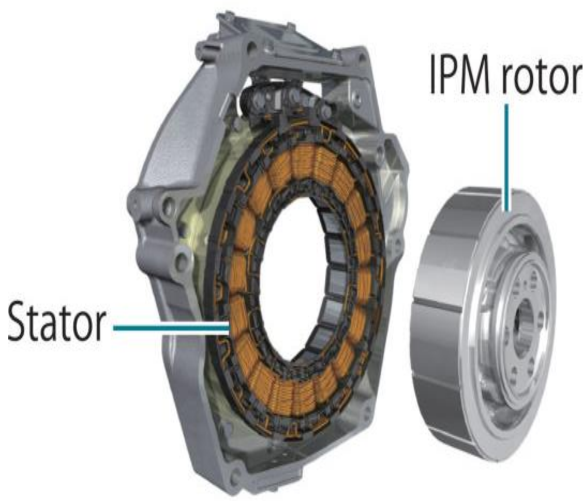

Figure 7.15: Honda CR-Z electric motor[41]

In the Honda CR-Z it also includes a CVT, the CVT can give more ratios than a conventional automatic transmission, so it can provide a better performance and increase fuel efficiency.

A very interesting thing is that The Honda CR-Z add a "Plus Sport System", when you press this button it will give you an extra boost for the vehicle and give you an excellent feeling.

7.4.2 Modified system of Honda CR-Z

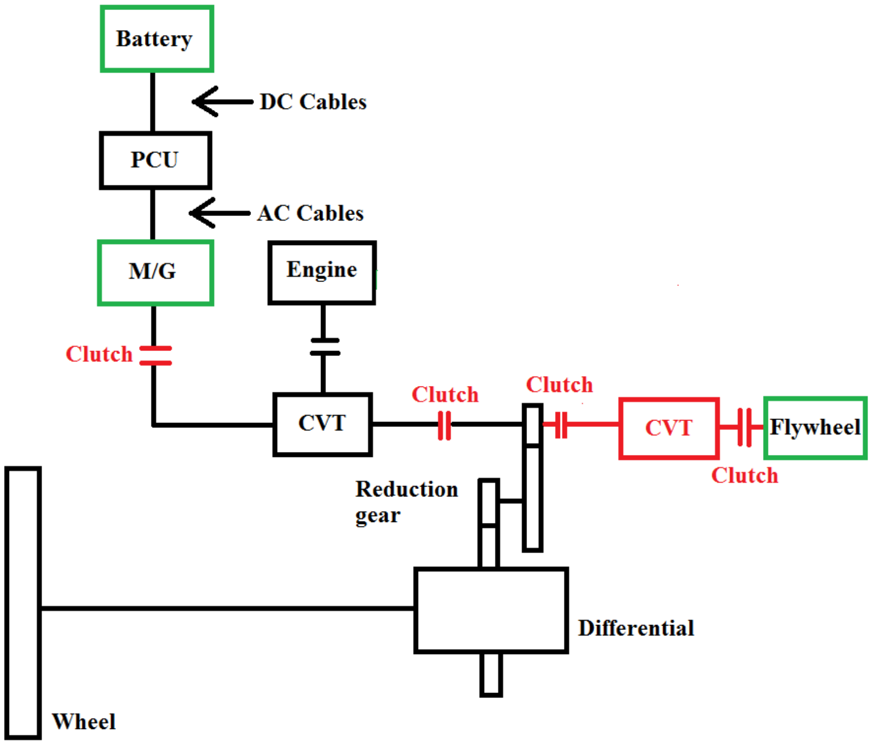

Figure 7.16: Honda CR-Z modification powertrain

When we do the modify the powertrain for Honda CR-Z, first we should know the three possible components(battery, motor/generator and flywheel) to storage which are shown in the figure above in the green line, then the red parts of the figure is shown the components which we have added into the system, they are four clutches and one CVT. This mode can allow the energy transfer from wheel to flywheel and store the energy into the flywheel.

First of all, for these four vehicles the modification of flywheel is almost the same, so I do some analysis as a whole to introduce the flywheel transmission to you.

For all the four vehicles, we want to use flywheel to store the energy, so we connect the flywheel directly to the wheel to reduce the energy lose, so finally we get the transmission step like this:

wheel---bearing---differential---reduction gear---clutch---CVT---clutch---flywheel.

Why we add the clutch before CVT is because that if when the vehicle is running on the road, we do not want energy goes into the flywheel, it will affect the power of vehicle when boost or acceleration, only just when the vehicle brakes, we use the clutch to connect to the CVT and flywheel and store the energy, so that the transmission is almost the same, and I will show you all the modification powertrain in the following sections. By the way, there is a little between the Honda C-RZ and other three vehicle, for Honda CR-Z the flywheel is connect directly to the wheel, we just use clutch to control to make sure whether it is working or not, but for other three modification powertrain, all the reduction can move to choose which gear should we connect, so they have a moveable reduction gear to control whether the flywheel is connected or not.

The powertrain for each of the storage components and the efficiency are shown below.

Flywheel

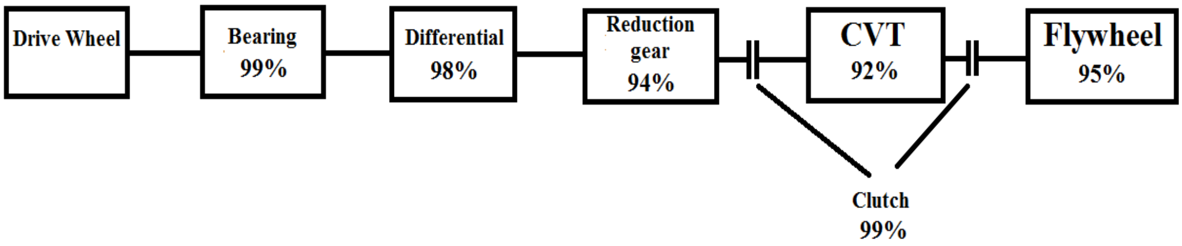

Figure 7.17: Honda CR-Z flywheel transmission

The figure above shows the transmission for a flywheel which is adding two clutches and a CVT. The overall efficiency of the flywheel transmission can be calculated by using the equation below.

$$\eta_{TC\ overall} = \eta_{wheel}\ x\ \eta_{differential}\ x\ \eta_{reduction\ gear}\ x\ \eta_{clutch}\ x\ \eta_{CVT}\ x\ \eta_{clutch}\ x\ \eta_{f}$$

$$\eta_{\ TC\ overall} = 78\%$$

Electric motor

For the Honda CRZ, the whole powertrain is a little different with Volt or Prius, as it is a parallel. Moreover, there is difference in transmission part - Continuously variable transmission(CVT). Moreover, this car just has single electric motor whose power is 15kW. The powertrain of **"M/G Flywheel"** of CRZ can see, Figure 7.18.,

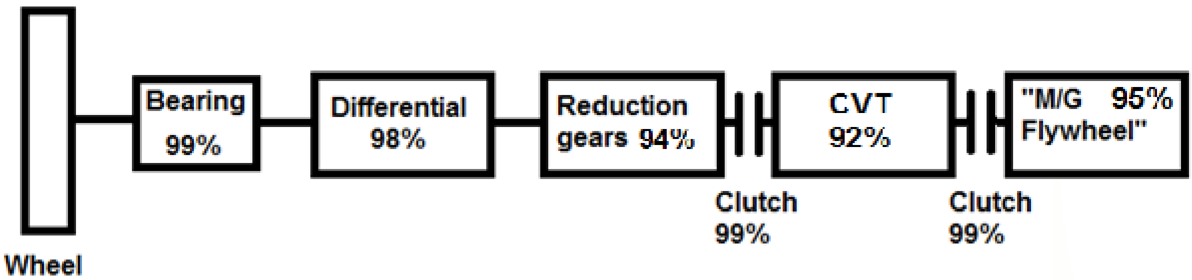

Figure 7.18: Powertrain of "M/G Flywheel" in Honda CR-Z

In that figure, there are two clutches, the one between reduction gears and CVT is used for changing the gears corporation depended on the vehicle situation, break or drive. The second one is to disconnect the M/G when it is applied as storage place. So its "M/G Flywheel" storage efficiency is,

$\eta_{M/G\ Flywheel}$ = 78.1%

$E_{capacity}$= 15/ 0.94 x 1second= 15.9kJ.

Battery

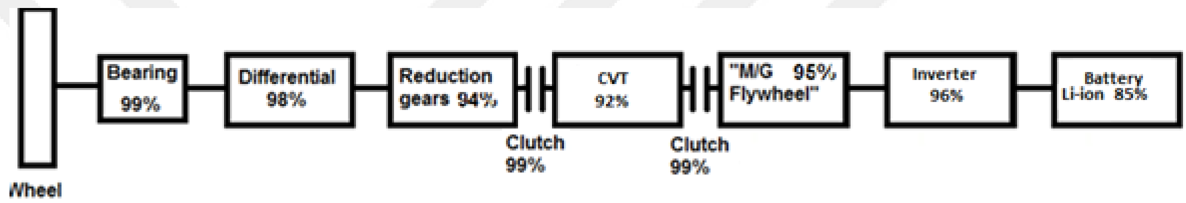

Figure 7.19: The schematic structure of energy flowing of Honda CR-Z

When the looking Honda CR-Z ;only difference between Chevy Volt and Toyota Prius & Honda CR-Z is gear box type. These two (Chevy Volt and Toyota Prius) are used planetary gear, Honda CR-Z is used CVT(Continuously variable transmission). So its efficiency is different from them and also where the efficiency of CVT (Continuously variable transmission) come from is explained previous section.

Efficiency of the Chevy Volt for the regenerative braking energy storing:

$$\eta_{M/G\ overall} = \eta_{wheel} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{clutch} \times \eta_{CVT} \times \eta_{clutch} \times \eta_{M/_G} \times \eta_{inverter} \times \eta_{battery} = 64\%$$

7.5 Toyota Prius

The first model of the Toyota Prius was launched in 1997 and was he first HEV that was widely available. Since then there have a larger number of modifications to ensure its popularity, this work was not in vein as the Prius is the bestselling HEV and surpassed the one million sale mark in April 2011. Toyota Prius hybrid system powertrain is very economic for fuel consumption and extremely clean emission . The fuel consumption of the vehicle is 60 mpg in city and 51 mpg on highway.

7.5.1 Existing system of Toyota Prius

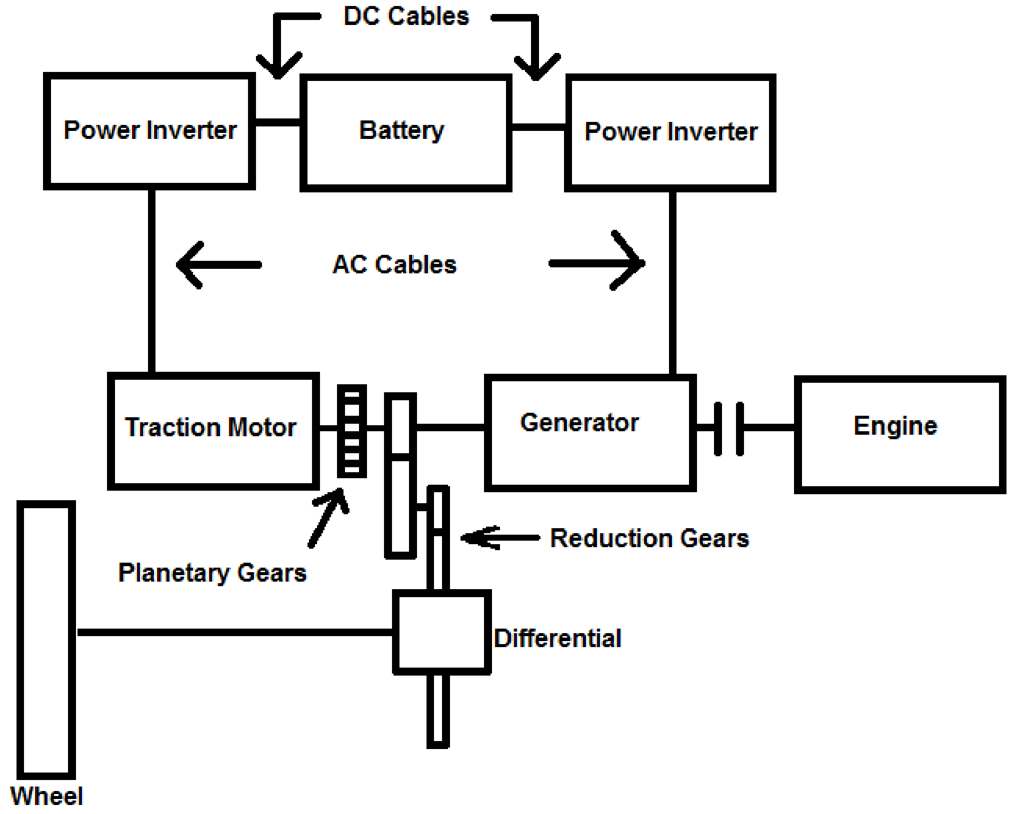

Figure 7.20: The schematic of Toyota Prius powertrain

Toyota Prius is plug in series- parallel hybrid vehicle. The schematic of its powertrain is shown at figure 7.20. The vehicle has a large battery because it is plug in hybrid vehicle. The vehicle include two generator to transfer the power to the powertrain; one of them acts as a generator and the other one acts as traction motor. [31]

Model	Toyota Prius
Battery chemistry	Ni-MH
Battery energy	1.78 kWh
Engine type	1.5 L VVTi
Traction Motor	33kW
Generator	18kW
Overall width	1694 mm
Height	1463 mm
Aero drag coefficient	0.29
Overall mass	1300 kg

Table 7.5: Toyota Prius specification[42]

Motor/generator-1

The motor/generator-1 acts generator of electricity to charge the battery and to supply the electricity to motor/generator-2.The element for the power splitting planetary gear set is operated by motor/generator-1. Its capacity is 18 kW.

Motor/generator-2

The motor/generator capacity is 33 kW. At low speed it is used for motive force and at high speed it used supplemental force. It helps the internal combustion engine when the vehicle needs more power such as acceleration, high performance etc. The motor/generator-2 acts as a generator during the regenerative braking.

Planetary gear set

Planetary gear unit is power spilt device. The motor/generator-1 is connected the sun gear of planetary gear, the motor /generator-2 is connected the ring gear of the planetary gear and the internal combustion engine is connected to planetary carrier. The power which produce internal combustion engine and motor/generator-2 is transferred to drive shaft and regenerative braking energy is transferred to the battery pack by using these components.

Inverter

Inverter controls the current between motor/generator-1, motor/generator-2 and battery pack. It converts current from direct current (DC) to alternative current (AC) and regulate the voltage.

Battery pack

The Prius battery is high voltage battery which include 228 cells of 1.2 volts. The total voltage is 273.6 volts. The cells are arranged as module. Each module consists six cells. There are 38 module in the battery pack. It is put into behind the rear seat.. The state of charge is allowed to vary only between 40% and 80% of the rated full charge when driving but can be charged to full once connected to external supply. Multiplying up the battery voltage and current capacity, its rated energy storage capacity is 6.4 MJ (mega joules) and its usable capacity is 2.56 MJ. This is enough energy to accelerate the car, driver and a passenger up to 65 M.P.H. (without help from the internal combustion engine) four times. Alternatively, it is enough to raise the car through 600 vertical feet. To produce this amount of energy, the internal combustion engine would consume about 230 millilitres of gasoline. [43]

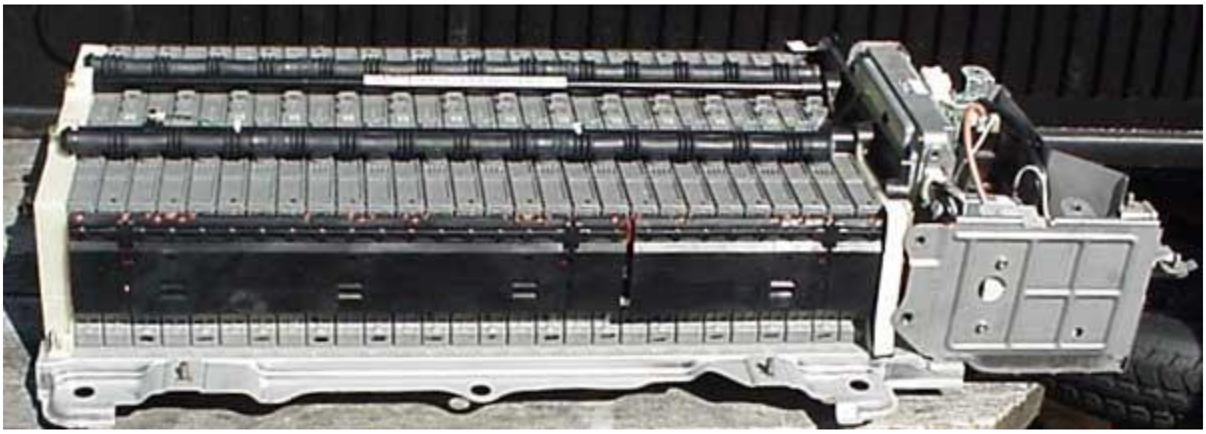

Figure 7.21: Toyota Prius hybrid battery pack [44]

Engine control unit (ECU)

The engine's power is divided two parts, some portion to wheel and the other portion to motor/generator-1 to generate an electricity. The hybrid ECU controls the energy distribution ratio for maximum efficiency.

7.5.2 Modified system of Toyota Prius

The modification of the Prius included using the motor and generator as an energy storage device also adding a flywheel as an additional peak power storage. To enable these changes all that was needed was to add a CVT and a clutch for the flywheel, also to modify the reduction gear to allow power o be transferred to and from the flywheel as illustrated by figure 7.22.

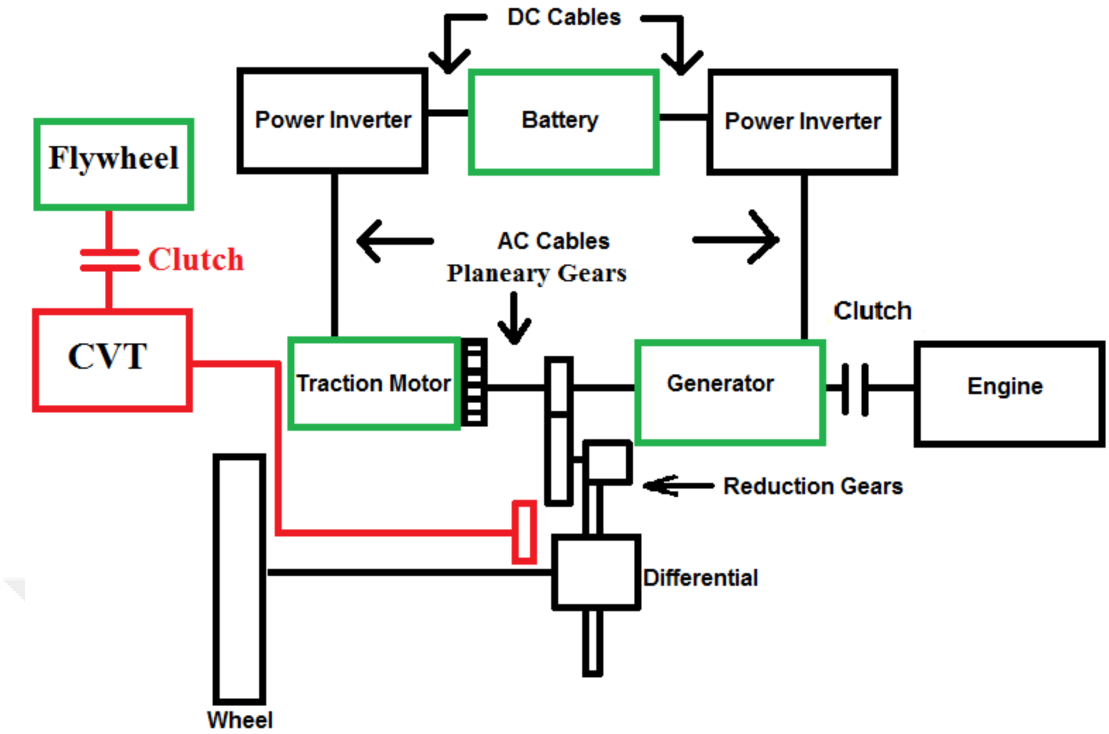

Figure 7.22: Toyota Prius modified powertrain

The calculations to establish the efficiency of each storage systems use the same principle as for that of previous vehicles so is shown not explained.

Motor/Generator

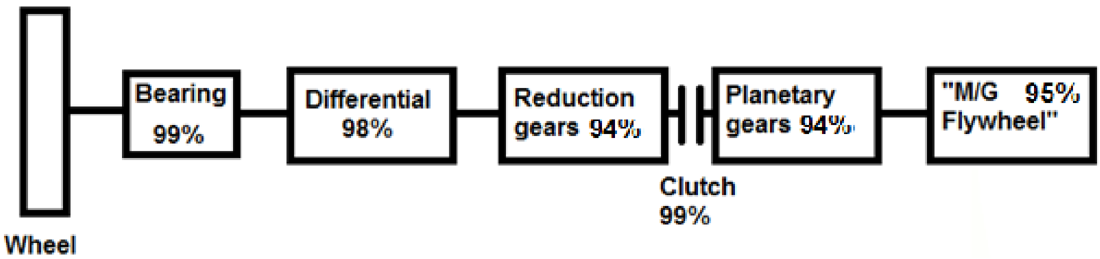

Figure 7.23: Modified powertrain`s power transmission of M/G Flywheel

$\eta_{MG\ overall}$

$= \eta_{wheel} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{clutch} \times \eta_{P.G} \times \eta_{M/G}$

$= 80\%$

Flywheel

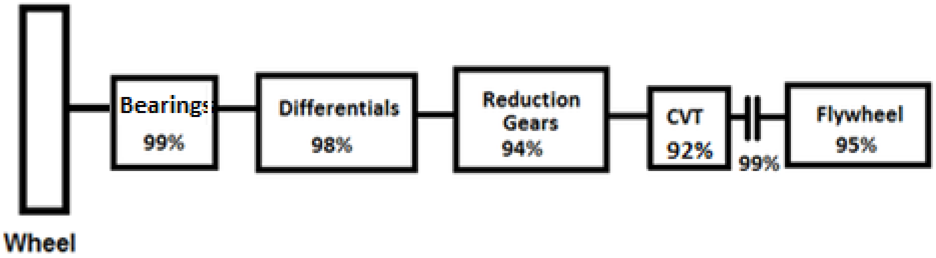

Figure 7.24 Modified powertrain`s power transmission of Flywheel

$\eta_{flywheel\ overall}$

$= \eta_{wheel} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{CVT} \times \eta_{clutch} \times \eta_{flywheel}$

$= 79\%$

Battery

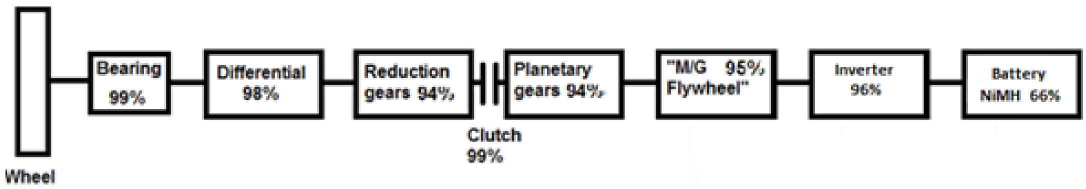

Figure 7.25: Modified powertrain`s power transmission of battery

$\eta_{battery\ overall}$

$$= \eta_{wheel} \times \eta_{differential} \times \eta_{reduction\ gear} \times \eta_{clutch} \times \eta_{gearbox} \times \eta_{M/G} \times \eta_{inverter} \times \eta_{battery} = 51\%$$

8. Table of Results

8.1 Potential braking energy efficiency of each vehicle

Driving condition(mph)	80-70	70-60	60-50	50-40	40-30	30-20	20--10	10-0
Difference in kinetic energy(kJ)	237.9	206.2	174.5	142.7	111.0	79.3	47.6	15.9
Energy losses(kJ)	43.8	31.7	22.2	15.1	9.8	6.0	3.2	1.0
Efficiency potential braking energy (%	81.6	84.6	87.2	89.4	91.2	92.5	93.4	93.8

Table 8.1: Chevrolet Volt potential braking energy efficiency in low energy braking

Driving condition(mph)	80-0	70-0	60-0	50-0	40-0	30-0	20-0	10-0
Difference in kinetic energy(kJ)	1015.1	777.2	571.0	396.5	253.8	142.7	63.4	15.9
Energy losses(kJ)	97.8	68.6	46.3	29.8	17.8	9.5	4.0	1.0
Efficiency potential braking energy (%	90.4	91.2	91.9	92.5	93.0	93.4	93.6	93.8

Table 8.2: Chevrolet Volt potential braking energy efficiency in high energy braking

Driving condition(mph)	80-70	70-60	60-50	50-40	40-30	30-20	20--10	10-0
Difference in kinetic energy(kJ)	194.8	168.8	142.8	116.9	90.9	64.9	39.0	13.0
Energy losses(kJ)	38.3	27.5	19.2	12.9	8.3	5.0	2.6	0.8
Efficiency potential braking energy (%	80.3	83.7	86.6	89.0	90.9	92.4	93.3	93.8

Table 8.3: Toyota Prius potential braking energy efficiency in low energy braking

Driving condition(mph)	80-0	70-0	60-0	50-0	40-0	30-0	20-0	10-0
Difference in kinetic energy(kJ)	831.0	636.2	467.4	324.6	207.7	116.9	51.9	13.0
Energy losses(kJ)	83.0	57.8	38.8	24.8	14.8	7.8	3.3	0.8
Efficiency potential braking energy (%	90.0	90.9	91.7	92.4	92.9	93.3	93.6	93.8

Table 8.4: Toyota Prius potential braking energy efficiency in high energy braking

Driving condition(mph)	80-70	70-60	60-50	50-40	40-30	30-20	20--10	10-0
Difference in kinetic energy(kJ)	180.4	156.3	132.3	108.2	84.2	60.1	36.1	12.0
Energy losses(kJ)	45.5	32.0	21.7	14.1	8.7	5.0	2.5	0.7
Efficiency potential braking energy (%	74.8	79.5	83.6	87.0	89.7	91.7	93.1	93.8

Table 8.5: Honda CR-Z potential braking energy efficiency in low energy braking

Driving condition(mph)	80-0	70-0	60-0	50-0	40-0	30-0	20-0	10-0
Difference in kinetic energy(kJ)	769.6	589.3	432.9	300.6	192.4	108.2	48.1	12.0
Energy losses(kJ)	89.1	60.7	39.8	24.9	14.4	7.5	3.1	0.7
Efficiency potential braking energy (%	88.4	89.7	90.8	91.7	92.5	93.1	93.5	93.8

Table 8.6: Honda CR-Z potential braking energy efficiency in high energy braking

Driving condition(mph)	80-70	70-60	60-50	50-40	40-30	30-20	20--10	10-0
Difference in kinetic energy(kJ)	224.4	194.5	164.6	134.7	104.7	74.8	44.9	15.0
Energy losses(kJ)	41.4	29.9	21.0	14.2	9.2	5.6	3.0	0.9
Efficiency potential braking energy (%	81.5	84.6	87.2	89.4	91.2	92.5	93.4	93.8

Table 8.7: Volkswagen Jetta potential braking energy efficiency in low energy braking

Driving condition(mph)	80-0	70-0	60-0	50-0	40-0	30-0	20-0	10-0
Difference in kinetic energy(kJ)	957.6	733.1	538.6	374.0	239.4	134.7	59.8	15.0
Energy losses(kJ)	92.4	64.7	43.7	28.1	16.8	8.9	3.8	0.9
Efficiency potential braking energy (%	90.4	91.2	91.9	92.5	93.0	93.4	93.6	93.8

Table 8.8: Volkswagen Jetta potential braking energy efficiency in high energy braking

8.1.1 Description of tables

The potential braking energy efficiency is the amount of energy which can totally through into the different potential energy storage places. Based on the Anirudh Pochiraju's report, *Design Principle of A Flywheel Regenerative Braking System(F – RBS) for Formula SAE Type Race car and System on A Virtual Test Rig Modeled on MSC Adams*, it mentions the actual available braking for any braking instance is given by the change in translational kinetic energy of the vehicle plus the change in rotational kinetic energy of the whole vehicle(including that of wheels, half shafts etc.) minus the losses due to aerodynamic drag, rolling resistance. The equation of available braking energy,

$$\Delta E_{a,b} = \Delta E_k + \Delta E_{k,rot} - W_{losses} \qquad (8.1)$$

$$W_{losses} = F_{losses} \times d \qquad (8.2)$$

$$F_{losses} = F_d + \mu_r(mg) \qquad (8.3)$$

$$F_d = \frac{1}{2}\rho v^2 C_D A \qquad (8.4)$$

$$d = v_0 t - \frac{1}{2} a t^2 \qquad (8.5)$$

$$a = \frac{(v - v_0)}{t} \qquad (8.6)$$

Where

$\Delta E_{a,b}$: Available braking energy at any instance of braking

ΔE_k : Change in translational kinetic energy of the vehicle during any braking instance

$\Delta E_{k,rot}$: Change in rotational kinetic energy due to all rotating parts

W_{losses} : Work done to overcome aerodynamic and rolling resistance losses

F_{losses} : Force at vehicle/ wheel due to losses (aero and rolling)

d : Braking distance

F_d : Aerodynamic drag force

ρ : Air density

v : Vehicle speed

C_D : Aerodynamic coefficient

A : Drag area

μ_r : Coefficient of rolling friction

g : Acceleration due to gravity = 9.8m/ s^2

So in order to calculate the potential energy or the efficiency of potential energy, some relative data need to be clear, such as whole vehicle mass, aerodynamic coefficient, drag area, see Table 8.9,

	Volt	**Prius**	**CRZ**	**Jetta**
Mass (kg)	**1588**	**1300**	**1204**	**1498**
C_D	**0.28**	**0.29**	**0.30**	**0.29**
Area (m^2)	**2.30**	**2.00**	**2.53**	**2.10**

Table 8.9: Mass, aerodynamic coefficient, drag area of different HEV

Moreover, we classify the decreasing speed range in to two kinds, one is 10 mile per hour, such as decreasing from 80 mph to 70 mph, 70 mph to 60 mph etc., the other is decreasing to zero. The decreasing time is set of 2 seconds, so based on the equation 5, deceleration equals to $2.23m/s^2$.

8.1.2 Calculation example of Chevrolet Volt (speed changes from 80 to 70 mph)

The final purpose is to find out the energy change during break(ΔE_{tot}) and losses(W_{losses}) caused by aero dynamic force and rolling resistance, later, the potential braking energy can be calculated, the calculation flow can see Figure 8.1,

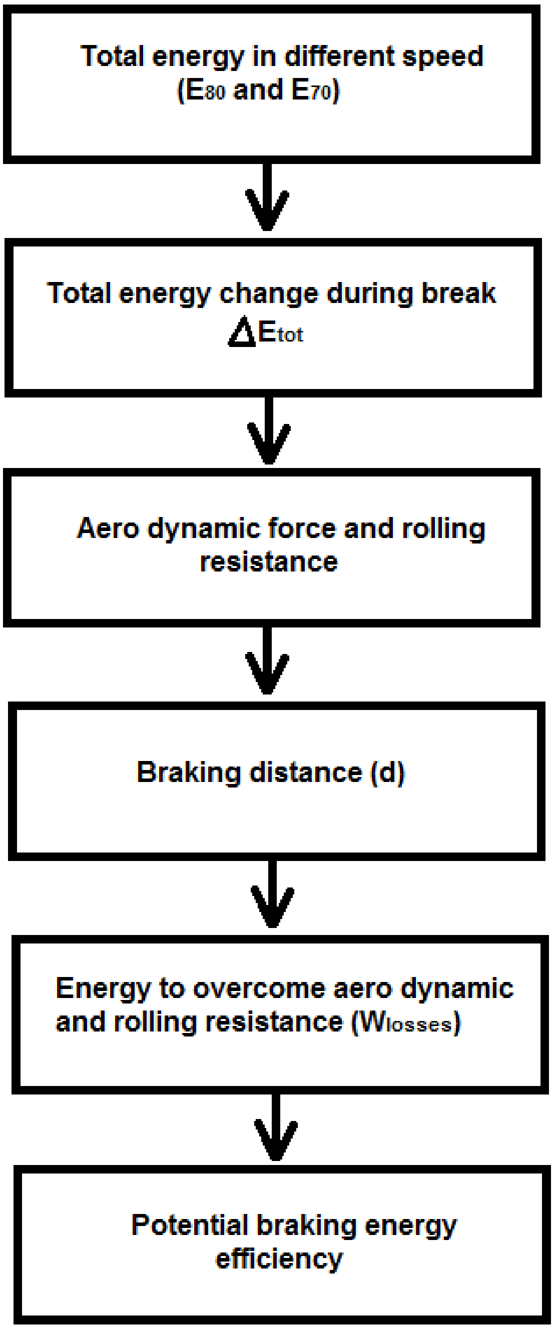

Figure 8.1: Calculation flow of potential braking energy efficiency

8.2 Modified System efficiency – For high and low energy braking

Volt								
Driving condition(mph)	80-70	70-60	60-50	50-40	40-30	30-20	20--10	10-0
Total stored energy (kJ)	155.3	139.6	121.8	102.1	81.0	58.7	35.5	11.9
Modified system efficiency when storing (%)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
Reused energy (kJ)	124.2	111.7	97.4	81.7	64.8	46.9	28.4	9.5
Total modified system efficiency (%)	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0

Table 8.10: Chevrolet Volt low energy braking for modified system

Volt								
Driving condition(mph)	80-0	70-0	60-0	50-0	40-0	30-0	20-0	10-0
Total stored energy (kJ)	667.1	529.4	408.0	290.5	188.5	106.6	47.5	11.9
Modified system efficiency when storing (%)	72.7	74.7	77.8	79.2	79.9	80.0	80.0	80.0
Reused energy (kJ)	489.0	398.1	318.0	230.1	150.5	85.3	38.0	9.5
Total modified system efficiency (%)	53.3	56.2	60.6	62.7	63.8	64.0	64.0	64.0

Table 8.11: Chevrolet Volt high energy braking for modified system

Prius								
Driving condition(mph)	80-70	70-60	60-50	50-40	40-30	30-20	20--10	10-0
Total stored energy (kJ)	123.4	111.6	97.8	82.5	65.8	48.0	29.1	9.7
Modified system efficiency when storing (%)	78.9	79.0	79.1	79.3	79.6	80.0	80.0	80.0
Reused energy (kJ)	97.4	88.1	77.4	65.4	52.4	38.4	23.3	7.8
Total modified system efficiency (%)	62.2	62.4	62.6	62.9	63.4	64.0	64.0	64.0

Table 8.12: Toyota Prius low energy braking for modified system

Prius								
Driving condition(mph)	80-0	70-0	60-0	50-0	40-0	30-0	20-0	10-0
Total stored energy (kJ)	487.7	401.2	324.8	235.2	151.9	86.4	38.9	9.7
Modified system efficiency when storing (%)	65.2	69.4	75.8	78.5	78.7	79.2	80.0	80.0
Reused energy (kJ)	331.9	287.8	248.9	184.5	119.6	68.5	31.1	7.8
Total modified system efficiency (%)	44.4	49.8	58.1	61.6	61.9	62.8	64.0	64.0

Table 8.13: Toyota Prius high energy braking for modified system

CRZ								
Driving condition(mph)	80-70	70-60	60-50	50-40	40-30	30-20	20--10	10-0
Total stored energy (kJ)	105.4	97.2	86.4	73.6	59.1	43.2	26.4	8.9
Modified system efficiency when storing (%)	78.1	78.2	78.2	78.2	78.3	78.3	78.6	79.0
Reused energy (kJ)	82.4	75.9	67.6	57.6	46.2	33.9	20.7	7.0
Total modified system efficiency (%)	61.1	61.1	61.1	61.2	61.2	61.4	61.7	62.4

Table 8.14: Honda CR-Z low energy braking for modified system

CRZ								
Driving condition(mph)	80-0	70-0	60-0	50-0	40-0	30-0	20-0	10-0
Total stored energy (kJ)	483.3	386.0	299.3	215.3	139.0	78.8	35.3	8.9
Modified system efficiency when storing (%)	71.0	73.0	76.1	78.1	78.1	78.2	78.4	79.0
Reused energy (kJ)	346.5	284.3	228.8	168.1	108.6	61.6	27.7	7.0
Total modified system efficiency (%)	50.9	53.8	58.2	60.9	61.0	61.1	61.5	62.4

Table 8.15: Honda CR-Z high energy braking for modified system

Jetta								
Driving condition(mph)	80-70	70-60	60-50	50-40	40-30	30-20	20--10	10-0
Total stored energy (kJ)	143.7	129.3	112.9	94.8	75.4	54.9	33.6	11.4
Modified system efficiency when storing (%)	78.5	78.6	78.6	78.8	79.0	79.3	80.2	81.4
Reused energy (kJ)	112.8	101.6	88.8	74.7	59.6	43.6	27.0	9.3
Total modified system efficiency (%)	61.6	61.7	61.9	62.1	62.4	62.9	64.3	66.3

Table 8.16: Volkswagen Jetta low energy braking for modified system

Jetta								
Driving condition(mph)	80-0	70-0	60-0	50-0	40-0	30-0	20-0	10-0
Total stored energy (kJ)	622.0	490.2	373.9	265.0	171.2	97.6	44.5	11.1
Modified system efficiency when storing (%)	71.9	73.3	75.6	76.6	76.9	77.6	79.4	79.0
Reused energy (kJ)	449.9	361.6	283.7	207.4	134.3	76.9	35.5	9.0
Total modified system efficiency (%)	52.0	54.1	57.3	60.0	60.3	61.1	63.3	64.4

Table 8.17: Volkswagen Jetta high energy braking for modified system

8.2.1 Description of Tables

For Volt, Prius and CRZ, the first choice of storage place is “M/G Flywheel”, after that is flywheel, the last one is battery, as the different storage efficiency. In addition, for the Jetta, the first place is “M/G Flywheel”, then is the turbocharger, followed by flywheel and the last one is battery. The calculation step of total modified system regenerative braking efficiency of CRZ as follow:

Calculate the potential energy through wheel axle (based on the efficiency mentioned in the last section)

1. Calculate the energy stored in “M/G Flywheel”. If the value is bigger than its capacity, the rest will go to the second choice (flywheel)
2. Calculate the how much energy left
3. Calculate the energy stored in battery
4. Plus all the energy restored in each potential storage place
5. Calculate the modified system efficiency when storing
6. Calculate the reused energy
7. Calculate the Total modified system efficiency

8.2.2 Calculation example of Honda CRZ (speed changes from 80mph to 0)

The following tables show all the data that is required for calculation.

Vehicle type	Air density (kg/ m^3)	C_d	Drag area(m^2)	U_r	Mass (kg)
CRZ	1.2	0.300	2.530	0.014	1204

Table 8.18 : Constant of Honda CR-Z for calculation of speed change

	M/G flywheel	Flywheel	Battery
Storage efficiency	79%	78%	64%
storage capacity	15kJ	250kJ	1.4MJ

Table 8.19: Relative data of Honda CR-Z

According to the Table 8.6(potential energy efficiency), the vehicle's kinetic energy of 80mph is 769.6kJ and the efficiency of potential braking energy is 88.4%, so the potential energy through wheel axle is,

$$E_{potential} = E_{tot} \times \eta = 769.6 \times 88.4\% = 680.6\text{kJ}$$

In other words, there is totally 680.6kJ can be stored and reused. The first storage place is "M/G Flywheel", its storage efficiency is 79% and capacity is 15kJ. Since "M/G Flywheel" is full, the rest of energy need to be find out,

$$E_{rest} = E_{tot} - \frac{E_{MG}}{\eta_{MG}} = 680.6 - \frac{15}{79\%} = 661.6kJ$$

So there is 661.6kJ of energy available to store after the "M/G flywheel" as stored 15kJ, and those energy will go to the second storage place, a flywheel with 250kJ of storage capacity and 78% of efficiency. When it is full, the rest of energy will also go to the next place, the rest of energy after flywheel is,

$$E_{rest} = E_{tot} - \frac{E_{MG}}{\eta_{MG}} - \frac{E_{FW}}{\eta_{FW}} = 680.6 - \frac{15}{79\%} - \frac{250}{78\%} = 341.1kJ$$

Those energy will go into the last storage place – battery with 64% of storage efficiency and 1.4MJ of capacity. Thus, the energy stored in the battery is,

$$E_{battery} = E_{rest} \times \eta_{battery} = 341.1 \times 64\% = 218.3kJ$$

The total amount of stored energy is,

$$E_{tot\ stored} = E_{MG} + E_{flywheel} + E_{battery} = 15 + 250 + 218.3 = 483.3kJ$$

Hence, the modified system efficiency when storing is

$$\eta_{tot\ stored} = \frac{E_{tot\ stored}}{E_{potential}} = \frac{483.3}{661.6} = 71.0\%$$

When those energy in different place need to be reused, the working efficiency is nearly the same as storage efficiency since the route of working is the same as storage. Here we take storage efficiency as working efficiency, and the total reused energy is,

$$E_{tot\ reused} = E_{MG} \times \eta_{MG} + E_{flywheel} \times \eta_{flwheel} + E_{battery} \times \eta_{battery}$$
$$= 15 \times 79\% + 250 \times 78\% + 218.3 \times 64\% = 346.5kJ$$

Therefore, the total modified system's efficiency is,

$$\eta_{tot\ stored} = \frac{E_{tot\ reused}}{E_{potential}} = \frac{346.5}{661.6} = 50.9\%$$

Here is the table of calculation detail,

Driving condition(mph)	80-0
Potential energy through wheel axle (kJ)	680.6
Energy stored in M/G Flywheel (15kJ) (79%)	15.0
Energy stored in flywheel (250kJ)(78%)	250.0
Energy stored in battery (1.4MJ)(64%)	218.3
Total stored energy (kJ)	483.3
Modified system efficiency when storing (%)	71.0
Reused energy (kJ)	346.5
Total modified system efficiency (%)	50.9

Table 8.20:Calculation detail of regenerative energy for storage

The rest calculations of different speeds are the same as this, so here just the table of four HEVs.

9. Analysis of Results

Based on our modification, the fuel consumption of Volkswagen Jetta can be improved up to 11.7% compared to the original one and the regenerative braking efficiency can be achieved extra 18.5% by using different storage places. The following is the calculation detail of Jetta.

According to the urban area duty cycle, we categorise it into different kinds of driving conditions, which can see table 9.1.

Driving condition (km/h)	Acceleration/Deceleration time (s)	Mode
from 0 to 35	25	Acceleration
35 - > 0	25	Braking
0 - >35	45	Acceleration
35 - > 0	15	Braking

0 - >28	30	Acceleration
28 - >8	20	Braking
8 - >43	25	Acceleration
43 - >0	15	Braking
0	30	Stop
0 - >51	30	Acceleration
51 - >18	40	Braking
18 - >35	10	Acceleration
35 - >18	40	Braking
18 - >40	25	Acceleration
40 - >26	25	Braking
26 - >44	60	Acceleration
44 - >0	40	Braking
0 - >38	50	Acceleration
38 - >0	50	Braking

Table 9.1: Categorised urban area duty cycle

After that, using the same calculation method which is mentioned in section 8 during break, energy losses are reckoned, see table 9.2.

Driving condition(km/h)	35-0	35-0	28--8	43-0	51-18	35-18	40-26	44-0	38-0
Difference in kinetic energy(kJ)	70.8	83.5	41.6	106.9	131.6	52.1	53.4	111.9	83.5
Decreasing time (s)	25.0	15.0	20.0	15.0	40.0	40.0	25.0	40.0	50.0
Fd(N)	8.7	8.7	2.8	13.1	7.7	2.0	1.4	13.7	10.2
F(losses) (N)	155.6	155.6	149.8	160.0	154.7	149.0	148.3	160.6	157.2
Deceleration (m/s^2)	0.4	0.6	0.3	0.8	0.2	0.1	0.2	0.3	0.2
Braking distance(m)	121.5	72.9	100.0	89.6	383.3	294.4	229.2	244.4	263.9
Energy losses(kJ)	18.9	11.3	15.0	14.3	59.3	43.9	34.0	39.3	41.5

Table 9.2: Energy losses by rolling resistance and aero drag force

After that, the calculation of regenerative braking efficiency is totally the same as section 8.1, here is the table of braking energy efficiency of modified model and original one,

Vehicle speed(km/h)	35-0	35-0	28--8	43-0	51-18	35-18	40-26	44-0	38-0
Potential energy through wheel axle (kJ)	51.9	72.1	26.6	92.5	72.3	8.2	19.4	72.6	42.0
Energy stored in M/G Flywheel (21.3kJ) (81.5%)	21.3	21.3	21.7	21.3	21.3	6.7	15.8	21.3	21.3
Turbocharger (23.2kJ)(78%)	20.1	23.2	0.0	23.2	23.2	0.0	0.0	23.2	12.4
Flywheel (250kJ)(78%)	0.0	12.7	0.0	28.6	12.8	0.0	0.0	13.1	0.0
Battery (6.4MJ)(67%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Stored energy (kJ)	41.4	57.2	21.7	73.1	57.3	6.7	15.8	57.6	33.7
Modificating storage efficiency	79.8	79.3	81.5	79.0	79.3	81.5	81.5	79.3	80.2
Reused energy (kJ)	33.0	45.3	17.7	57.8	45.5	5.4	12.9	45.6	27.0
Total modificating storage efficiency	63.7	62.9	66.4	62.4	62.9	66.4	66.4	62.8	64.3
Regenerative braking efficiency									63.4
Original storage efficiency (6.4MJ)(67%)	67.0	67.0	67.0	67.0	67.0	67.0	67.0	67.0	67.0
Total original efficiency	44.9	44.9	44.9	44.9	44.9	44.9	44.9	44.9	44.9
Reused energy (kJ)	23.3	32.4	12.0	41.5	32.5	3.7	8.7	32.6	18.8
Regenerative braking efficiency									44.9
improvement of energy recover	9.7	13.0	5.7	16.2	13.0	1.8	4.2	13.0	8.2

Table 9.3: Regenerative braking energy efficiency of modified powertrain and original powertrain

So the regenerative braking energy efficiency of modified powertrain is 63.4% and original powertrain is 44.9% which means the efficiency can be achieved extra 18.5%. Moreover, the amount of energy which is recovered by the new model is 290.2kJ and 205.4 for the original type which is only using battery to regenerate the braking energy. By divided the total kinetic energy which applies to accelerate the vehicle(see Appendix D). Under this modified system can save additional 11.7% of energy which means it can save the same amount of fuel.

For the other three types of HEVs, the calculating processes are the same as Jetta's, these three vehicles' efficiencies are shown in Table 9.4.

Overall Efficiencies	Volt	Prius	CRZ	Jetta
Original Regenerative braking efficiency %	43.6	29.2	41.0	44.9
modified Regenerative Braking Efficiency %	64.0	64.0	61.5	63.4
Improvement of fuel consumption%	12.9	22.0	12.8	11.7
Improvement of regenerative braking efficiency%	20.4	34.7	20.6	18.5

Table 9.4: Calculated efficiency of these four vehicle

10. Discussion

By modifying the existing powertrains of the HEVs, all 4 vehicles show an improvement in the fuel consumption and regenerative braking efficiency. Table # shows that the efficiency of the Toyota Prius increased by the largest percentage in both fuel consumption and regenerative braking by a significant amount. The Chevrolet Volt and the Honda CRZ were second and third respectively but had a marginal difference. The least improved vehicle was the Volkswagen Jetta in both measures. The order of improvement can be put down to the fact that the Toyota Prius had a far lower initial efficiency than that of the other vehicles, so although the overall efficiency of all modified systems were all within 3% of each other, they have different levels of improvement when the urban duty cycle were applied to them.

The reason why the original efficiency were different is due a number of criteria including: the powertrain of each and system, efficiency of storage, the dimension of the vehicle (which dictates the aerodynamic losses) and the weight of the vehicle which effects the rolling resistance.

The improvements in efficiency stem from the usage of mechanical storage rather than electro-chemical storage in the form of a battery. When the modified system was applied to the urban duty cycle there was a substantial improvement in efficiency because the available energy for recovery can be completely stored in the mechanical devices as the vehicle never exceeds 32 mph, therefore the systems avoids losses and inefficiencies that are inherent in battery storage such as energy conversion the long chain of component required to transfer the energy to and from the battery, each adding a loss in energy. This fact was further exploited by storing energy in order of efficiency to ensure losses were kept to a minimum.

The urban duty cycle gave good means for analysis as there is a significant amount of regenerative braking, this puts to test the system in low energy braking. The highway duty cycle was disregarded as there was not enough energy available to store in the additional powertrain. This means that the systems modification are not suitable for highway in drive, this is typical for all regenerative braking systems as there is no energy wasted through braking.

The accuracy of these results are dependent on the assumptions that were made during calculation and are listed below:

- Mechanical efficiency of each components were constant at all speeds
- Battery efficiency depends on the state of charge so for ease of calculation the level of charge was 50%
- Due to the problem of having to charge the battery with the energy from recovered from braking, energy storage in mechanical component will stop once the charge of battery drops below 30% and will be used to charge the battery. For ease of calculation this was not included so all values for efficiency only apply for when the state of charge of battery charge is above 30%.
- The mechanical efficiency of the motor/ generator is equal to that of the flywheel as both their losses are caused by bearing friction, assuming all motor/generator are brushless

- The turbocharger also has bearing losses and also an additional 5% due to the aerodynamic friction.
- The CPU that controls the switching operation is sufficiently advanced to manage the different modes
- All similar components in different vehicles have the same efficiency
- Have not taken into consideration the effect of added weight on the system due to the fact the all added weight to the vehicle is negligible in comparison to the overall weigh t of the car

11. Conclusion

This thesis studied the possibility of improving the regenerative braking efficiency of a hybrid electric vehicle by converting mechanical devices ,already present in the powertrain of existing vehicle, into KERS (kinetic energy recovery systems). This was achieved by modifying 4 existing HEVs and theoretically calculating the improvements in regenerative braking, by comparing them with their original regenerative efficiencies.

The vehicles that were studied all used only a battery to store recovered energy. This study supported the hypothesis that regenerative braking can be improved by using mechanical storage devices rather than electro-chemical.

It was shown that there are mechanical components in existing HEVs that can be modified to store energy as well as carrying out their original purpose without detriment, these components were the motor/generator and turbocharger.

Additionally by introducing an extra mechanical storage component in the form of a flywheel, there is evidence to support the fact that this could further improve the overall efficiency of regenerative braking and hence the fuel consumption of the HEV.

However in high energy braking, i.e. braking form a speed over 50mph or more, the storage capacity of all the mechanical devices is not enough to store all the recovered energy. This means that the battery will have to be used to store the rest of the energy so the losses inherent to energy conversion cannot be completely avoided and will result in a reduction regenerative braking efficiency.

The thesis shows that when the modified vehicles were applied to the urban duty cycle, the energy could completely be stored as mechanical energy, as the urban speed limit is less than 50mph. furthermore for vehicles with relatively large motor/generator storage capacity, the total energy could be stored in this component alone. Generally speaking this occurs in SHEV rather than PHEV due to the different method of power transmission of these HEVs. This gave possibility for substantial improvements in both regenerative braking and fuel consumption.

By modifying the existing powertrain of the following four HEVs, this thesis shows the following improvements were achieved:

Overall Efficiencies	Volt	Prius	CRZ	Jetta
Original Regenerative braking efficiency %	43.6	29.2	41.0	44.9
modified Regenerative Braking Efficiency %	64.0	64.0	61.5	63.4
Improvement of fuel consumption%	12.9	22.0	12.8	11.7
Improvement of regenerative braking efficiency%	20.4	34.7	20.6	18.5

Table 11.1: Overall efficiencies of HEVs

12. Further Work – Design of Experiment

The main power of turbocharger comes from exhaust air, and it is driven by the air drag force. Hence, if the turbocharger is not vacuumed, there will be a lot of air friction. So if the turbocharger is acted as storage place, how to decrease the air friction is the most essential problem needed to be solved. Therefore, this experiment aims to find out how long of the turbocharger's half life can be extended when it is vacuumed.

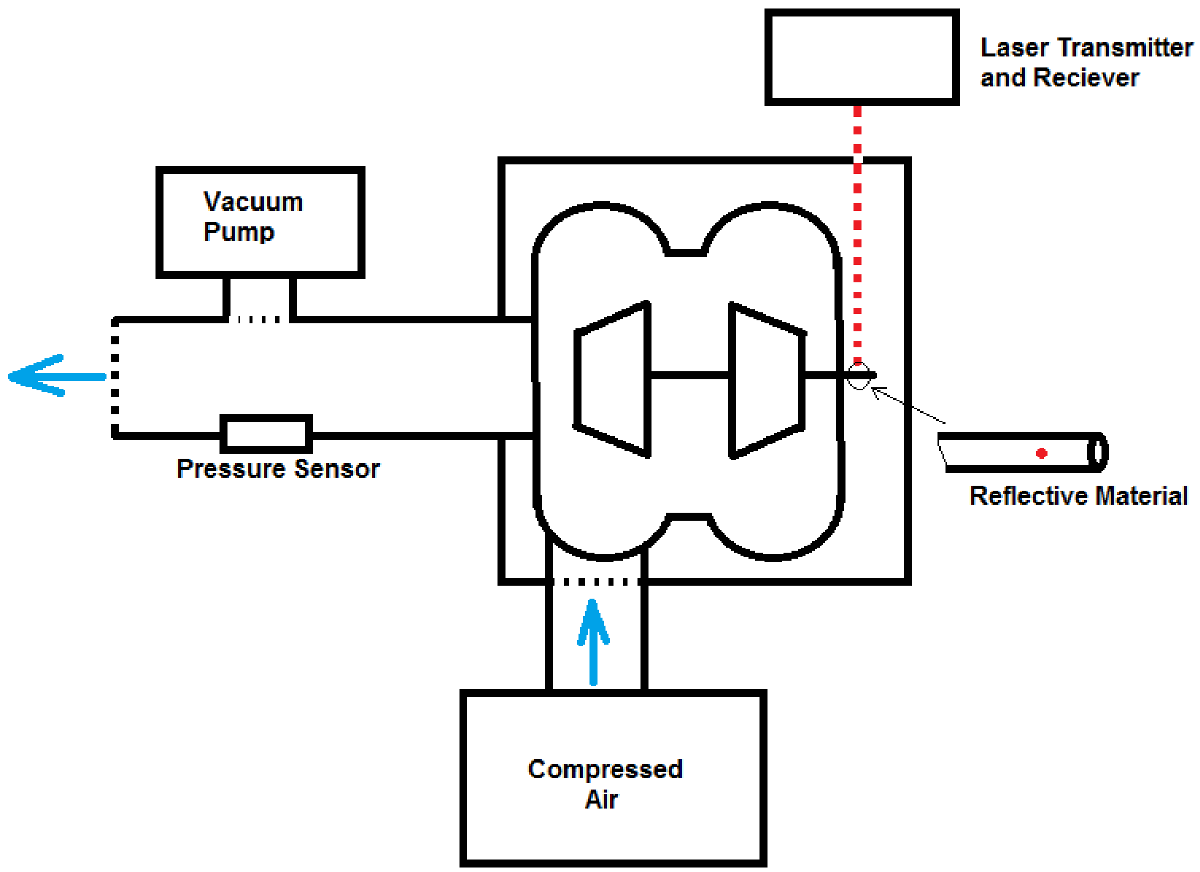

Figure 12.1: Structure of turbocharger experiment

Procedure

1. Using the compressed air to drive the turbocharger and let the rotating speed active in certain speed (e.g. 300,000rpm)

2. Closing the compressed air's and air outlet tunnel, turning on the vacuum pump
3. When the case is vacuumed, using the laser transmitter and receiver device to measure the rotating speed and count the time

The reason why to make the rotating speed higher than 250,000rpm in the first step is that, during the vacuum process, there is still some air drag friction in the case which means the rotating speed will be decreased in that period of time.

Personal Equipment

- Lab coat
- Gloves
- Goggles

Test -rig Equipment

- Case
- Glass
- Reflective material
- Turbocharger
- Compressed air machine
- Vacuum pump
- Case holder

Testing Equipment

- Laser transmitter and receiver
- Timer
- Pressure sensor

The hazard when prepare the experiment

Taking very care of burning of hands, such as hot air compressed machine and welding process when making the case. So during the experiment, wearing glover is very important.

The advantages of this method

- It can achieve good vacuum situation
- The sealing is relatively easy than other ways
- Non-intrusive measurement

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Appendix

[A] - Minutes of meeting

- **22/02/2013 Meeting with Supervisor**

For next meeting need to find these topic:

- To look what is the requirement and set specification
- To search what is the possible technology for the system
- To find out adaptation to meet speed
- To do research about when is energy shifted from using the KERS to store energy or to use it from battery.

- To search how is the turbocharger evacuated.

- **01/03/2013 Meeting**

We discussed next step of research. It was decided that specification for the KERS to be designed, must be determined start designing.

For the following meeting, every member of the group will have researched the following topics:

- Range of energy/power at different point along a drive requirement of C segment car.
- Range of energy output of KERS
- How KERS works to recuperate energy
- Installation of KERS
- Emission regulation

- **08/03/2013 Meeting**

For last meeting, the task set of researching a number of point regarding C-segment cars and KERS was achieved. It was decided that the fly wheel may be the suitable method of storing energy, more research needs to be carried at first.

For the next meeting research topics:

- Schematic diagram of system description and component
- Power output from the system

- Cost of the system to make or to buy
- To find appropriate component for C-segment cars
- Installation of KERS
- Schematic diagram of KERS, labelled diagram of how it works
- How to install the system
- How is the system made
- To make the system is it possible or not?

- **15/03/2013 Meeting**

For last week, we decided to investigate the concept and schematic diagram of the fly wheel and the overall KERS application which was achieved.

We also decided on standardising the definition of a C-segment car. This was covered in the note and is now set in stone. Cost and fuel saving were found out typical power output for KERS estimated.

Task for next meeting, the topics will be researched:

- Method of power transmission and decoupling
- Method of controlled sealing and vacuum sealing
- Design and adaptation of cooling arrangement
- For C-segment cars to find power requirements along different points along the journey. For instance hill, cruise, start etc.
- Emission regulation for C-segment cars in Europe.
- Research range extender and how it works

- **22/03/2013 Meeting with supervisor**

These topics are recommended to search by supervisor:

- What are the break even points for different levels of investment?
- What efficiency improvement do we need to achieve a pay back?
- What is the energy density of the KERS system?
- Transmission system
- How big should the battery be in kilowatt/hour?
- Parallel hybrid system
- What is the maximum range using just the battery?
- Hybrid vehicle based on design
- How long does it take to change a hybrid battery?
- Performance of a standard IC engine with KERS system.
- How fast the energy can be taken out for the system

- **27/03/2013 Meeting**

Our target is finish the interim report until next meeting. The stuff of interim report is shared each other.

Interim Report structure

- Outline(GH)
  - Abstract
  - Executive summary

- Introduction(HL and CK)
    - Introduction
    - Background
    - Literature review
- Project planning (SH)
    - Gantt chart
    - Minutes for meeting
    - Project overview
- Conclusion(All)
    - Discuss achievements and shortcomings

For next meeting need to find these topic

- Find journals on relevant subjects
- We should all look at the following types of hybrid : series, plug-in and parallel and so on

- **04/06/2013 Meeting with supervisor**

We achieved the general idea of hybrid cars and general information of related components which shared each other. Now the specific knowledge about the components are needed to find out.

For next meeting we need to find these topic

- Look at popularity of KERS cars. E.g. Chevrolet Volt(SH)

- How to reduce cost of KERS(HL)
- Good fuel economy and performance are two key approach but regulations will fine companies if not met.(GH)
- Specification on motor generator on hybrid cars(CK)
- Economic boost engine, turbocharger, inertia and storage capacity of related components.(ALL)

Depend on the meeting our targets are shown as following:

- How to stay mechanical to store and transfer energy
- Look into the transmission systems that exist and try to alter the transmission to incorporate the KERS.
- Look into evacuating turbocharger,- what percentage of energy is provided by the turbocharges of a C-segment travelling at 40 mph.
- Need to find figure for specification of relevant vehicles.
- Look at experiments that could be carried out, such as a turbocharger
- How to vacuum sealing for turbocharger
- Adaptation for existing technology

➢ **18/06/2013 Meeting with supervisor**

We found out all existing components specification. We will focus onto how to modify the traditional components for our main aim.

For next meeting we need to find these topic

- Final specification for battery of HEV, find by calculating the power required to accelerate a vehicle from rest to 60 km/h in 5-6 seconds(CK)

- Series hybrid(SH)
- Parallel hybrid combined with range extender(GH)
- Using a drive motor as a KERS by redesigning the transmission .

  See limitation for motor, how much energy in motor, induction motor, how big would it be, if 50 kw.(HL)
- Can an existing motor be used for energy storage as a KERS(SH)
- What are the wind age losses(HL)
- By evacuating a turbocharger or motor how much energy can be stored.(CK)

➢ **20/06/2013 Meeting**

We have searched some information about the topics which are mentioned in the last meeting, then we got some other topics to follow with.

- Focus on two type of system(All)
- Table showing he amount of energy available at varies speeds and the different sources of energy. E.g. Engine rotor, turbo charger rotor and so on possible places for storing energy for the vehicles.(also compare with energy storage requirements)(All)
- Electric motor drive of a parallel hybrid is a good energy storage location.(HL)
- Best to stick with electrical transmission for KERS if located on turbocharger.(GH)
- How much does the evacuation of a turbocharger or motor drive improve/reduce wind age losses.(SH)
- Must devise a control system that optimises the storage of energy, when to store in battery (e.g. When vehicle stop at the end of journey), and when to remain in flywheel.(i.e. When car stops briefly)(CK)

- Quantify improvement in efficiencies.(ALL)

- **21/06/2013 Meeting**

In this meeting we shared our findings at first after that we made decision as shown below:

- Use the turbocharger as a flywheel rather than the motor/generator
- Show that turbocharger is favourable
- Compare the efficiencies of this system when applied to parallel and series hybrids
- There are two methods about transferring issue. There are :

  1^{st} – to connect turbocharger to CVT and hence them connected directly to the drive shaft (decoupling transmission)

  2^{nd} – to connect the turbocharger to the CVT to a motor/generator and use it only to charge the battery directly

  Alternatively we could combine both methods

For next meeting we need to find these topic:

- research working principles of parallel, series hybrids, turbocharger of all other components in the power train to be designed.(turbocharger being most important)(ALL)
- find fundamental equation governing energy storage(ALL)

- **26/06/2013 Meeting**

In this meeting we shared our findings at first to understand the system working

- We designed a block diagram for a possible system
- We decided the next step is to find the weight of the rotating parts of a turbo charger, in order to calculate the available energy and hence possibility of design

For next meeting we need to find these topic:

- If we cannot find the weight for turbocharger, we will assume a weight in order to carry out calculations.(ALL)
- Must have some calculation. All equation needed(ALL)
- Calculate from required energy(ALL)

➢ **30/06/2013 Meeting**

Turbocharger is provided to measure weight, dimensions and these information is gotten.

- Duty cycle
- Higher the duty cycle means more potential for KERS system

For next meeting we need to find these topic:

- Energy density VS power density graph for different sources of energy and energy storage compared with requirements(ALL)
- Test need to be designed(ALL)

➢ **01/07/2013 Meeting with supervisor**

We achieved table about storage place in the existing vehicle. After that supervisor give some advice about it.

For next meeting we need to find these topic:

- Look back of the engine as a storage of energy(HL,GH)
- Quantify energy capability of each component(ALL)
- Make a table to identify most suitable(ALL)
- Understand clearly the working principle of the motor generator and whether it can be used for energy recovery(CK,SH)

➢ **12/07/2013 Meeting**

In this meeting we shared our findings

- From the previous section target, a table of energy storage capabilities was calculated, for all possible pars except the drive motor. It was decided that the turbocharge wan so far most suitable and further research was required to quantity maximum capability after evacuation

For next meeting we need to find these topic:

- Research fundamentals of the drive motor in a hybrid vehicle(CK,SH)
- Look into possibility and feasibility of using the drive motor as an energy storage device(CK,SH)
- Also do the same for the generator(HL,GH)
- Research thoroughly (in depth) the evacuation of the turbocharger (marking it a vacuum) (HL,GH)
- Research into vacuum sealing(HL,GH)

- Include how to carry out the experiment to investigate improvement in friction losses(CK,SH)

➢ **14/07/2013 Meeting**

Depend on the all research information some modifications are done to store the energy into existing components such as drive motor, turbocharger, battery and added flywheel for the reason. Information of the components are needed to compare the traditional ones.

For next meeting we need to find these topic:

- Find power train and components of existing hybrid C-segment cars(ALL)
- Calculate which components can be used to store energy and how much energy can be stored(ALL)
- Look at different energy storage to maximise efficiency(ALL)
- Establish a method for transmitting the energy to the energy storage components(ALL)

Start to write up the interim report outline: