A REVIEWOF REGENERATIVE BRAKING IN HYBRID VEHICLES

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***Abstract*-The necessity to improvethe fuel economy continues to gain more importance with increasing pollution levels, higher fuel prices and depleting natural resources. The use of regenerative braking system in hybrid vehicles to improve the fuel economy and efficiency is reviewed in this paper. The paper studies different strategiesof regenerative braking to improve the efficiency of vehicle. The paper studies the different methods of storing the regenerated energy. Theimprovement in fuel economy through the use of regenerative braking is compared across different models. The paper presents technical knowledge in the use of regenerative braking to improve the fuel economy of vehicle**.

***Keywords*: Regenerative Braking, Hybrid Vehicle, Fuel Economy, Regeneration Efficiency.**

I.INTRODUCTION

Hybrid Vehicles

With the continuously rising pollution levels and increase in concern about global warming, there is a growing awareness about moving towards cleaner technology. Moreover, with decreasing levels of petroleum reserves andcontinuous energy crisis in the modern world, it is necessary to produce automobiles which can run on alternate sources of energy. The automobile industry is responsible for roughly 25% of the total greenhouse gas emissions and hence the industry needs to run on cleaner fuels to reduce the adverse effects it has on the environment.Thomas' [19] paper shows that a shift towards hybrid vehicles and ultimately to all electric vehicles need to be made in order to reduce greenhouse gas emission to below 80% of 1990 level. The paper through computer simulations concludes that the hydrogen power fuel cell electric vehicles in conjunction with hybrids and bio-fuels canachieve this goal by the year 2067.

Hybrid vehicles are vehicles which use two or more sources to produce the energy. Usually a hybrid vehicle uses an internal combustion engine(ICE) and an electric motor as power sources but other than them hydrogen, solar energy, wind energy, compressed air etc. can all be used to propel the vehicle as studied by Hannan et al[9]. Fuel cells can be used to power the hybrid vehicle. Energy storage can be done through batteries and supercapacitors or a combination of both.

Hybrid electric vehicles are the most common type of hybrid vehicle using an internal combustion engine and an electric motor to propel the vehicle. Based on the powertrain configuration the hybrid vehicle may be of parallel type or the series type or power split type which is a combination of both.

Parallel type

In this system both the internal combustion engine and the electric motor are connected to the road wheels and provide the power to drive the vehicle. The ICE and the motor must rotate at the same speed while transferring power to the transmission system.The torque supplied by them is added and supplied to the driving wheels through the transmission system. The use of parallel hybrid system allows the use of a smaller ICE as the motor supplies additional torque and this leads to better fuel economy of the vehicle. Saxena et al [20] show that parallel hybrid vehicles can reduce fuel consumption by up to 25.5% in China and in US the fuel saving can be up to 13.2% by using the power split hybrid. Figure.1 shows the basic layout of parallel hybrid.

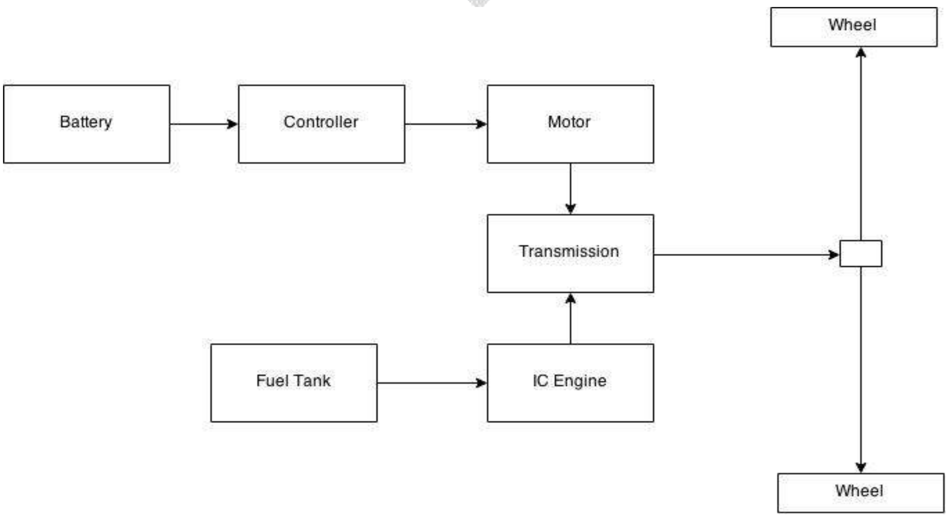

Figure 1.Basic layout of parallel hybrid

Series type

In this configuration the ICE is not coupled to the driving wheels.The basic layout of a series hybrid is shown in the Fig.2. The engine is coupled to a generator and provides the energy required by the generator to produce the current. The generator then provides the energy to charge the battery pack of the vehicle. The battery supplies the energy to the motor. The motor is connected to the driving wheels and provides the torque to propel the vehicle. The series configuration allows the ICE to be switched off when not required and the vehicle to be run in all electric mode. When the battery loses charge then the engine is switched back on to charge the batteries.

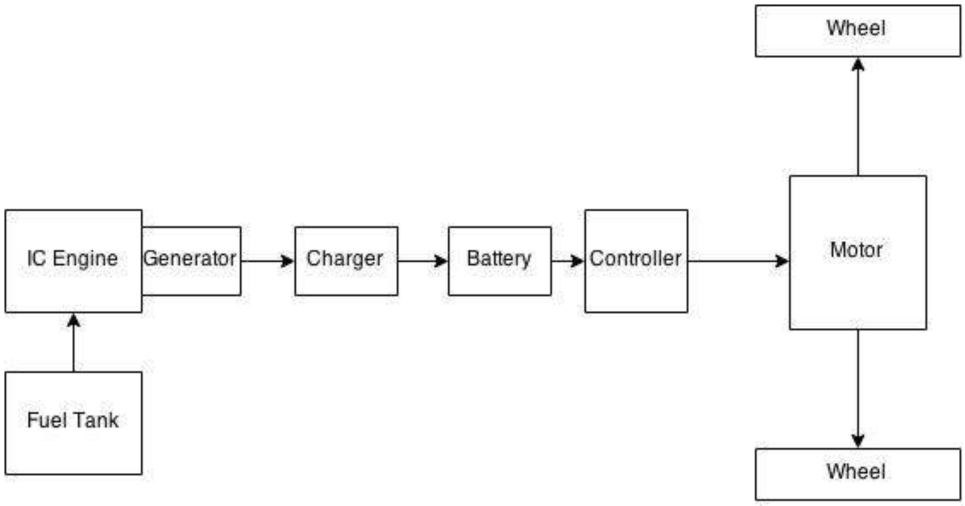

Figure 2.Basic layout of series hybrid

The power split hybrid system allows the vehicle to be run either through the IC engine or through the motor. Taymaz and Benli in [24] study the power split hybrid in comparison with a conventional vehicle. Their work shows a theoretical reduction of 30% in fuel economy and CO2 emission using the power split hybrid.In [20]it is shown that by using hybrid vehicles can reduce fuel consumption by up to 53% in China by using a power- split type arrangement and in US the fuel saving can be up to 32% by using the power split hybrid.

II .Fuel EconomyAnd Emission Control through Hybrid Technology

Various studies have been carried out to study the fuel efficiencies of hybrid vehicles. The comparison between a mixed hybrid vehicle and conventional vehicle showed that the hybrid vehicle had 30% better fuel economy than the commercial vehicle. Additionally the Co2 emission level of the hybrid vehicles studied was upto 30-60% lower than the conventional vehicles as studied by Baumhefner et al[1]. Similar study carried out by Bender [2]inStuttgart, Germany on a hybrid refuse truck showed that the fuel consumption of a hybrid refuse truck was lowered upto 20.4% than a conventional refuse truck.Energy management strategies developed by Nüesch et al [17] may meet the Euro 5 emission standards without any engine after treatments takes into account the fuel consumption, particulate matter and nitrogen oxide emissions for a diesel hybrid electric vehicle.

Mourad et al [16] study was based on using biodiesel as a fuel in hybrid vehicle. The results showed a decrease in carbon monoxide emission using biodiesel by 18%. When vehicle speed is increased the fuel consumption increases and emission level increase too.Similar results are obtained for oxides of nitrogen and hydrocarbons with a decrease in 7% and 35% respectively. There was a slight decrease in the power output from engine using biodiesel.

III.The Market For HEVs

Japan is the leading nation when it comes to market for hybrid electric vehicles.The Toyota Prius was the best selling car in Japan for three consecutive years. Over 4 million hybrid cars have been sold in Japanas of December 2014 with Toyota Prius familymodels accounting for more than 2.5 million of it. The Japanese government,in 2009,provided incentives and tax breaks on the purchase of hybrid vehicles which led to a threefold increase in the sale of hybrid cars in Japan compared to 2008. Japan accounts for 48% of the total market share in the world for hybrid cars and also has the highest market penetration with 30% of the new passenger cars being sold being hybrid as of 2014.

United States is the second largest market for hybrid vehicles in the world. It accounts for 42% of all the hybrid vehicles that have been sold. Above 3.5 million hybrid vehicles have been sold in the United States as of December 2014 with the Toyota Prius family of vehicles accounting for more than 1.7 million of it. The market penetration for hybrid vehicles was 2.75% of all the new passenger cars sold.

The total sales of HEV in Europe are around 925000 as of December 2014. The market penetration is only 1% for hybrid vehicles of all the new cars sold in Europe. The Netherlands has the second highest market penetration for hybrid vehicles with 4.5% of all the new cars sold.

It has been studied that by increasing awareness about clean energy there would be been an increase in demand for electric vehicles. In [1] to improve the awareness and promote the use of plug-in electric vehicles and make it more economical for the customers in the state of California it is suggest that by upgrading the residential energy efficiency or installing rooftop solar panels the extra cost for charging a plug in electric vehicle can be nullified.

IV. Energy Recovery

Energy recovery is the process to convert the energy which usually gets wasted into some useful form of energy which can be stored and used at a later time.The recovery of energy decreases the amount of input that needs to be supplied in a process and more output is obtained. The energy can be recovered from different forms of energy for example from thermal energy, vibrational energy or from kinetic energy.

Energy Recovery systems (ERS)are based on the energy recovery process and are designed to harness the waste energy.The aim of the energy recovery system is to recover as much energy as possible. The more energy the energy recovery system is able to recover the more efficient it is and at the same time the ERS should be able to provide this recovered energy for further useful work without much loss. An example of energy recovery system is a heat recovery steam generator which recovers heat from steam and may use this energy for driving steam turbines

The various classification of energy recovery is studied by Buenaventura and Azzopardi[7]for automotive purpose. This study analyses the various energy recovery systems that can be used in an automobile to make it more fuel efficient and more environment friendly.

V. Kinetic Energy Recovery System (KERS)

Kinetic Energy Recovery system is an energy recovery system which stores the Kinetic energy of a moving vehicle and uses it at a later time to accelerate the vehicle. When a moving vehicle is brought to rest by applying the brakes then all its kinetic energy gets converted into heat energy. This heat energy is lost by the system to its surroundings. Hence the entire energy gets wasted. Applying the KERS technology this kinetic energy is converted into some other form of energy and stored in the vehicle. When the vehicle accelerates again then the KERS system provides it with the required power by allowing the stored energy to go back into the system.

The energy harnessed can be stored in the vehicle in different ways. In hybrid electric vehicles the kinetic energy can be converted into electrical energy and stored in electrical batteries or in super capacitors. Energy may also be stored in the flywheels as studied by Kumar [12].

Mechanism

The hybrid electric vehicles have electric motor generator unitsto produce power. The electric motor generator unit may function as a motor or generator separately. Hence during braking, the kinetic energy of the vehicle turns the motor generator unit which acts as a generator and produces electrical energy which is stored in the battery and this external load provides the braking effect. However the KERS cannot be alone used to stop the vehicle completely as the KERS is less effective at slow speeds and hence KERS is used in addition to the hydraulic or pneumatic brakes.

The driving style in cities involves lots of start-stop. Hence a large amount of kinetic energy gets wasted in the form of heat energy. Hence a large amount of this kinetic energy can be recovered by the KERS and be stored in the battery.This will improve the fuel economy of the car as less input power would be required from the internal combustion engine of the hybrid car and in turn less greenhouse gases will be emitted to the surroundings.

Depending upon the method of storing the energy, KERS can be classified as Electric based storage or Flywheel based storage.

Electric based storage system

In this type of KERS the kinetic energy during braking is converted into electrical energy by the generator and is stored in the battery. The basic components of this system are

- Motor generator unit(MGU)
- Power Control Unit
- Battery
- *Motor Generator Unit*

The motor generator unit during braking acts as a generator and converts the kinetic energy into electrical energy. This external load slows down the vehicle and provides the braking effect.

- *Power Control unit*

The power control unit's main function is to control the flow of energy from the motor to the battery during the charging cycle and then from the battery to the motor during thedischarging cycle. It reverses the direction of the current when required.

- *Battery*

Battery acts as the storage unit for the converted energy. The electrical energy provided by the MGU is used to charge the battery and is stored as chemical energy in the battery. Usually lithium ion batteries are used for storing the energy. When the vehicle is to be accelerated then the driver presses the boost button which causes the battery to discharge and provide the electrical energy to the motor generator unit through the power control unit. The MGU then acting as a motor provides the necessary boost to the driving wheels and accelerates the vehicle.Super capacitors may also be used to store the electrical energy as instead of the battery.

Efficiency

The efficiency of the Electrical KERS system is 30-35%. Many energy conversion processes takes place in the electricalKERS. The kinetic energy is converted to electrical energy which is again stored as chemical energy in the battery and then during the regenerative cycle the chemical energy is converted into electrical energy by battery and then this electrical energy is converted by the MGU into mechanical energy.Since every energy conversion leads to a loss of energy, the efficiency of electric KERS is low.

Flywheel Energy Storage

In this kind of KERS the kinetic energy of the vehicle is converted into the rotational energy of a flywheel.The flywheel has large inertia which stores the energy and provides it to the driving wheels during the regenerative mode. The flywheel has to be connected to the drive live to transmit power to the drive wheels during the regenerative cycle.The flywheel is connected to the driving wheels through a CVT as studied by Cibulka,J. in[5]. Use of CVT is necessary due to the continuously varying speed ratio of the flywheel and the driving wheels as the vehicle accelerates and decelerates.In [5] flywheel has been used as a rotor in a reluctance motor to acts as an energy storage device. Belt drives may be used to transfer power to and from the flywheel. Belts clamped between pulleys whose radii can be changed ae used to transmit the power. The radii of the pulley are changed by changing the axial forces acting on them which are controlled through hydraulics. Planetary gear sets normally used in automatic transmission can be used to act as a CVT for transmission of power from a flywheel. Another method is to use a power split CVT system in which a part of the power is transmitted through direct mechanical linkage and the remaining power can be transmitted via any other transmission system discussed above. In hybrid vehicles electromechanical, hydromechanical or traction drive power split CVTs can be used.

Efficiency

The flywheel based KERS has a high efficiency higher than that of an electric based storage system. This is due to the fact that fewer energy conversionstake place in FES as compared to electric KERS.The kinetic energy of the wheels is converted into the rotational energy of the flywheel and during the boost mode when the driving wheels need to be accelerated the rotational energy of the flywheel is converted into the kinetic energy of the driving wheels.

VI. DIFFERENT MODELS AND STRATEGIES

Lv et al [15] have proposed different ways to study the impact of regenerative braking system. The first methodology analyses the total energy consumption for non-regenerative vehicles (E_{drive}) and regenerative vehicles (E^*_{drive}). The factor ΔE_{drive} represents the difference between the two and is given by Eq.1

$$\Delta E_{drive} = E_{drive} - E^*_{drive} = \eta_{fd}\eta_{gen}\eta_{charge}\eta_{discharge}\eta_m\eta_g\eta_{fd}.E_{regen} \quad -(1)$$

Where E_{regen} represents the total regenerative energy and N factor represents the total efficiency of different transmission components. The total contribution of regenerative system is given by Eq.2

$$\delta = \frac{\Delta E_{drive}}{E_{drive}} \times 100\% = \frac{\eta_{fd}\eta_{gen}\eta_{charge}\eta_{discharge}\eta_m\eta_g\eta_{fd}.E_{regen}}{E_{drive}} \quad -(2)$$

Another proposed methodology focusses on how much improvement is seen in the ratio of driving range extension and reduction in energy consumption by the use of regenerative braking system. In the driving range extension, the focus is on the total distance covered by using a given amount of energy with and without the regenerative braking technology in a fixed driving cycle. The δ_S parameter represents the increase in driving range extension using the regenerative braking system and is given byEq.3

$$\delta_s = \frac{S_{regen\_on} - S_{regen\_off}}{S_{regen\_off}} \times 100\% \quad -(3)$$

Similarly reduction in energy consumption focuses on the total amount of energy used in covering a given distance with and without the regenerative braking technology in a fixed driving cycle. The δ_E parameter represents the overall decrease in energy consumption by using the regenerative braking system and is given byEq.4

$$\delta_E = \frac{E_{regen\_on} - E_{regen\_off}}{E_{regen\_off}} \times 100\% \quad -(4)$$

Both of the above parameters show the impact of the regenerative braking system in vehicles but the relationship between the parameters is give by Eq.5

$$\frac{1}{\delta_S} - \frac{1}{\delta_E} = 1 \quad -(5)$$

This shows that the two parameters ae not the same. The δ_E parameters represent the decrease in energy consumption whereas the δ_S parameter represents the increase in driving range using the regenerative braking technology.

Further different control strategies are proposed to study the importance of regenerative brakes.

The first strategy uses only the normal friction brakes to cause retardation of the vehicle. In this strategy the use regenerative brakes absent. The second strategy is the parallel regenerative braking in which the regenerative brakes are used in addition to normal friction brakes. In this system the two different types of brakes work independent of each other due to which the regeneration efficiency of the braking system is affected and reduction in brake comfort is observed. In the third strategy the use of serial braking system is done. On this system the regenerative brakes and friction brakes work in coordination with each other and this is done by making use of sensors. This leads to enhancement in brake comfort and improvement in regeneration efficiency of brake energy. Based on the New European driving cycle experiments were carried out using the three different control strategies.

In the first non regenerative strategy with no kinetic energy recovery the total energy consumption for the NEDC cycle is 1.8334 kWh. Using the second strategy the energy recover to the battery using in one NEDC cycle is 0.17 kWh. Using the third strategy the energy recovered in one NEDC cycle is 0.229kWh.

The test results for the experiment are shown in the Table .1

Table 1.Test results of non-regen strategy under NEDC driving cycles.[15]

Strategy	Vehicles Energy Efficiency Under NEDC (kW h/100Km)	Contribution to energy efficiency improvement, δ_E (%)	Range under NEDC (Km)	Contribution to Range extension δ_s (%)
Non regen	20129	-	87.456	-
Parallel	18335	8.91	96.056	9.83
Serial	17879	11.18	98.463	12.58

Hence from Table 1 it is observed that using the parallel and serial regenerative brakes the overall improvement in energy efficiency is 8.91% and 11.18% respectively and the overall improvement in driving range is 9.83% and 12.58% respectively.

Zhang et al [26] focus on the application of regenerative brakes in fuel cell hybrid bus. The fuel cell produces energy which is used to drive the electric motor. The battery is used as an auxiliary power source. The bus has pneumatic braking system and regenerative braking technology is added to further improve the fuel economy. The coordinate regenerative control strategy is used in which the braking force is divided between regenerative brakes and pneumatic brakes. When less braking torque is required then only regenerative brakes are applied but when a larger braking torque is required the both the regenerative brakes and pneumatic brakes are needed. The brake pedal stroke determines the distribution of braking force between the brakes. The total braking force required is given by Eq.6

$$F_{\mu F} + F_{\mu R} + F_{mot} = F_{tgt} \quad \text{-(6)}$$

This shows that the braking force of the motor and the braking force at front and rear wheels should be equal to the total target braking force. To coordinate the braking force between the regenerative brakes and the pneumatic brakes two modulating valves are added in the pneumatic braking lines. These valves control the amount of pneumatic brake force depending upon the total brake pedal stroke. When the brake pedal stroke is low then only regenerative brakes are used and at higher strokes the pneumatic brakes become active.In the configuration of the braking system in the FCHB the position sensor sends the brake stroke information to the brake controller which then directs the opening and closing of the modulating valves.

Table 2 Fuel economy test results of the FCHB under China city bus typical driving cycle.[12]

Control strategy	Regenerative energy (kJ)	Hydrogen consumption (kg/100 km)	Fuel economy improvement (%)
Without regen brake	-	9.3	-
Parallel regen braking strategy	2200	8.6	7.5
Coordinated regen braking strategy	5100	7.8	16.1

The test results show that there is a decrease of 7.5% in fuel consumption using theparallel regenerative braking system and the fuel economy improves by 16.1% when coordinated regenerative braking technique is used. Further by making use of Lithium ion batter as the storage device instead of Ni-Mh battery the fuel economy is improved by 11.5%. This is due to the fact that there is less energy loss in Lithium ion batteries during the charging and discharging process. The Table2 shows the result of using regenerative brakes in FCHB.

The use of KERS in a DI-JI H2IC engine is studied by Boretti [3]. The DI-JI engine uses a pre combustion chamber connected to the main chamber through orifices. The pre combustion chamber is filled with a slightly rich mixture which is ignited by means of a spark plug. The spark plug ignites this mixture and this produces high temperature gases which enter the main chamber. The main chamber has a direct fuel injector which injects a lean stratified charge into the main chamber which gets ignited by the multiple jets of incoming hot reactive gases.

The test results as shown in Table 3 are computed for a DI-JI H2IC engine coupled with KERS system having a mechanical flywheel as the energy storage system and the test was based on the New European Driving Cycle (NEDC).The test compares the fuel economy of a DI-JI H2IC engine coupled with KERS with a 1.6lTDI engine with and without KERS and 1.2lTDI engine with and without KERS. The results show that the DI-JI H2IC engine coupled with KERS system uses 8gm of fuel per km while using 0.99Mj/km of fuel energy compared to 3.16 used by 1.6lTDI engine with KERS and 3.04l/km used by 1.2lTDI engine with KERS.

Table.3 Fuel economy of *C* class (compact car) vehicle with traditional powertrains and KERS[3]

Configuration	Fuel [l/100 km]	CO2 [g/km]	Energy [MJ/km]
1.6TDI	3.81	99.2	1.38
1.6TDI + KERS	3.16	82.4	1.15
1.2TDI	3.66	95.4	1.33
1.2TDI + KERS	3.04	79.2	1.10
1.2H2ICE + KERS			0.99

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Cipollone et al [6] did a model based study of a fuel cell hybrid vehicle has been carried out using brake energy recovery system. The model in study is based upon a prototype developed by Italian National Agency for New Technologies, Energy and Environment (ENEA) called Urb-E. The model is a parallel hybrid in which the fuel cell provides the necessary power demands to the electric traction motor and the battery acts as the auxiliary power source. The test is performed using World Harmonized Light-Duty Test Procedure Cycle (WLTP) as the reference driving cycle. The test uses three different braking strategies. The first is the constant front-rear braking force distribution as in conventional vehicles. The second strategy is optimal brake strategy to obtain minimum stopping distance and the third strategy aims to recover maximum brake energy.

In the parallel hybrid model the power to driving wheels can be supplied by both electric traction motor and the battery .The fuel cell has constant power output. At low load condition the entire power demand of the traction motor is provided by the fuel cell. The extra power of the fuel cell is used to charge the battery. The negative valued represent the charging mode of the battery. At no load condition all the fuel cell power is used to charge the battery. When higher power demand is present than the power output of the fuel cell then the extra power demand is provided by the battery. When the battery is fully charged then supplying fuel cell power will lead to overcharging of the battery. To prevent this the fuel cell is turned off when the state of charge SOC of the battery reaches the upper limit and is turned back on when it falls below the lower SOC limit.

ECE driving cycle has lower power demands. Due to this in this cycle the SOC reaches the upper limit frequently and the fuel cell is shut off to prevent overcharging of battery. Lower fuel consumption takes place in this driving cycle.

In terms of braking strategy the figure shows the braking efficiency based on the three different braking strategies in ECE driving cycle and the WLTP cycle. The maximum recovery strategy has the highest efficiency of around 90% in WLTP cycle whereas the optimal braking strategy has the lowest braking efficiency of around 40%. The ECE cycle can recover about 38% of the total energy but the braking efficiency is low because of high SOC of battery in the ECE cycle.

Xu et al [25] have made the use of brake energy recovery system (BERS) to improve the fuel economy of proton exchange membrane (PEM) fuel cell hybrid vehicle. The BERS is used in addition to a energy management system to improve the fuel economy of the vehicle. The hybrid powertrain used in the vehicle utilises a Vehicle control unit (VCU). The powertrain is composed of electric motor, DC/DC converter, Ni-Mh battery and PEM fuel cell and several controller units. The powertrain uses a time-triggered controller area network (TTCAN) to coordinate the hybrid system. The TTCAN receives signals from controller units which in turn is send to the VCU which sends data to the motor controller unit and the DC/DC controller to control their output torque and current. The test results were calculated based on drive cycle of 'China city bus typical cycle'. The hydrogen consumption for the vehicle without the use of brake energy recovery system was 67.313MJ. When the BRES system was applied in addition to the energy management system the hydrogen consumption was brought down to 50.072MJ.The kinetic energy recovered was 6.06MJ. The fuel economy dropped from 9.5(100km)$^{-1}$ to 7.8kg(100km)$^{-1}$. The total decrease in hydrogen consumption is 17.8% out of which the BERS is responsible for 15.3% reduction.

Junzhi et al[10] study the effect of regenerative braking on electrified minivans with the electric motor present on the rear axle of the vehicle. The study carried out is simulation based and the model was prepared using the MATLAB/Simulink software. The author in this study has proposed two different control strategy to study the efficiency of regenerative braking. The two strategies in discussion are the baseline control strategy and the modified control strategy. The baseline control strategy uses coordinate braking between the hydraulic brakes and the regenerative brakes based on the original front-rear brake force distribution coefficient. To improve the regeneration efficiency the author proposed a modified control strategy. This strategy aims to improve the regenerative braking efficiency by increasing the braking torque on the rear axle of the vehicle. Since the greater braking torque may lead to locking of the rear wheels of the vehicle, quantitative calculation of the front-rear brake force distribution has been done using Eq.7 and Eq.8 by the author

$$\varphi_f = \frac{\beta z}{\frac{1}{L}(b + zh_g)} \quad \text{-(7)}$$

$$\varphi_r = \frac{(1-\beta)z}{\frac{1}{L}(a - zh_g)} \quad \text{-(8)}$$

where φ_f and φ_r denote the utilization adhesion coefficients of the front axle and rear axle, respectively, β denotes the front–rear braking force distribution coefficient, L denotes the wheelbase, a denotes the longitudinal distance between the center of gravity of the vehicle and the front axle, b denotes the longitudinal distance between the center of gravity of the vehicle and the rear axle. h_g denotes the height of the center of gravity of the vehicle. The value of β is taken as 0.58 from ECE brake regulations.
The test was carried out for an initial vehicle speed of 60km/h, an adhesion coefficient of 0.7 and braking pressure is taken as a ramp input stabilizing at 3 MPa. Using the baseline control strategy the total energy recovered was 55.7kJ which was near 32.1 % of the total energy recoverable. Using the modified control strategy the total energy recovered was 82.26kJ which was near 47 % of the total energy recoverable which is about 15% greater than the energy recovered by the baseline control strategy.

The total regeneration efficiency is calculated by from Eq.9, Eq.10, Eq.11

$$\eta_{reg} = \frac{E_{reg1}}{E_{brk}} \times 100\% \quad \text{-(9)}$$

$$E_{reg1} = \int_{t_0}^{t_1} UIdt \quad \text{-(10)}$$

$$E_{brk} = \frac{1}{2}mv^2 - \int_{t_0}^{t_1} fmgvdt - \int_{t_0}^{t_1} \frac{C_d A}{21.15}(3.6v)^2 vdt \quad \text{-(11)}$$

where E_{reg1} is the energy regenerated by the electric motor, E_{brk} is the total energy recoverable in braking, t_0 is the initial braking time, t_1 is the end braking time, U is the output voltage of battery pack, I is the charging current of battery, m is total vehicle mass, f is the coefficient of rolling resistance (taken as 0.012), C_d is the coefficient of air resistance, and A is the frontal area of the vehicle. The following table shows the result for the recovered energy. The Table 4 shows the regeneration efficiency is 15% more for modified control strategy.

Table 4.The simulation results of regeneration efficiency.[10]

Control strategy	Recoverable energy (J)	Regenerated energy(J)	Regeneration efficiency (%)
Baseline Control Strategy	1.738×10^5	5.617×10^4	32.3%
Modified Control Strategy	1.761×10^5	8.394×10^4	47.7%

The Table 5 studies the effect of the control strategy on the fuel economy of the vehicle in ECE drive cycle. The modified strategy shows an improvement of 10% in fuel economy about 3% greater than the baseline control strategy.

Table 5.Contribution rate simulation results of ECE driving cycle.[10]

Control strategy	Consumed energy (J)	Regenerated energy(J)	Contribution rate
Baseline Control Strategy	4.144×10^5	3.05×10^4	7.36%
Modified Control Strategy	4.147×10^5	4.18×10^4	10.08%

Kim et al [11] study the application of regenerative braking system on a Polymer Electrolyte Membrane Fuel Cell (PEMFC) hybrid system. In this simulated system, the study uses a motor to accelerate a flywheel to a set speed. Supercapacitor with a 15V capacity and a 12V, 50Ah Ni-Mh battery are used for storing the regenerated energy. The supercapacitor is used because of its low energy density, high power density, high charge/discharge efficiency and longer life than the battery. In the test energy is taken from the fuel cell battery and supercapacitor to run a brushless direct current (BLDC) motor. A DC/DC converter is set at 26V to supply the current to the motor from the fuel cell system. A 1.5kW BLDC motor is used to accelerate the flywheel to a 3000rpm.The flywheel stores this energy as kinetic energy. Once the flywheel reaches its set speed the motor shut off. Now, in the regenerative braking mode, a generator is used to convert the kinetic energy from the flywheel into regenerated energy to be stored in the secondary power sources thus decelerating the flywheel. The initial SOC of the battery and the supercapacitor are set at 26% and 85% respectively.

The regenerative energy becomes zero when the voltage of both the battery and the supercapacitor become equal. The result shows that the out of a possible 13804J of recoverable kinetic energy the regenerated energy of the generator is 5177J.Hence the regenerative efficiency is 38% for the generator. The supercapacitor stores 2958J of the regenerated energy, i.e. 21% of the total energy and the battery stores 1858 J of energy, i.e. 14% of the total energy. Hence the total regenerated energy of the system comes out to be 35%.

Zou et al [27] study the regenerative braking efficiency for a supercapacitor vehicle and shows that the regeneration efficiency of such vehicles can be as high as 88%.The vehicle uses a supercapacitor as the main power source of the vehicle. During the braking process, the kinetic energy of wheels is converted by the motor having a maximum power rating of 140kW and stored in the supercapacitor and when the vehicle speeds up again then the regenerated energy is used to accelerate the vehicle and increase its energy efficiency and driving range. At no load condition the vehicle provides a regeneration efficiency of about 88%.

Kim et al [8] use a PEMFC hybrid system to study regenerative braking. The model uses a flywheel to store the mechanical energy supplied by a BLDC motor to simulate actual vehicle conditions. During braking the regenerative energy is converted into electrical energy by a separate generator and stored in a NI-Mh battery of 12V which is connected in parallel to the fuel cell. A DC/DC converter is used to supply a constant fuel cell output voltage. For the test the fuel cell was supplied with hydrogen at 1.6 atm at room temperature an d the SoC of the battery was kept between 40to 60%. A 1.5kW BLDC motor was used to accelerate the flywheel to a speed of 2500 rpm. During breaking the generator was used as a flywheel brake and it converted the kinetic energy of the flywheel into electrical energy thereby decelerating the flywheel. In the test when BLDC motor is used for generating regenerative energy a maximum current of 69A is produced which remains constant for 7 sec whereas a voltage if 11868Vis produced which decreases with decrease in speed. The test uses two NI-MH batteries connected in series with a operating voltage of 24V and hence a DC/DC converter is used. The time taken for the flywheel to stop is 16s and the motor generates 2.8 kJ of regenerative energy at an efficiency of 24.2%. When regenerative braking is done using a generator the a maximum current of 60A is generator which decreases almost linearly and an output voltage of 26.3 V is generated. The flywheel stops in 9s. The total energy recovered is 7.39 kJ from the flywheel which has a total energy of 11.57 kJ. Hence the efficiency of the regenerative braking system is 63.8%.

Soylu[22] studies the effect of regenerative braking mechanism on series hybrid buses. The test uses a test vehicle with 5.7 litre diesel engine which drives a generator to produce electrical energy. The generator is coupled to motor/generator unit which provides drive to the vehicle wheels. The vehicle uses an ultracapacitor to store the regenerated brake energy and has a rated power of 0.74kW. The energy harnessed equalled to 6.83 kW h. The total regeneration efficiency of the unit was 27%.

Srbik et al [23] analyse the effectiveness of regenerative braking in three different power train configurations of hybrid vehicle and has compared them over four different drive cycles.
The four different drive cycles selected for the test are US06HWY, NEDC, FTP and NYCC.

Table6 shows the characteristics of the respective driving cycles.

Table 6: Cycle selection characteristics [23]

		US06HWY *Motorway driving*	**NEDC** *Inter-city driving*	**FTP** *Aggressive City driving*	**NYCC** *Stop-and-go driving*
Velocity [km/h]	max:	129.20	120.00	91.29	44.58
	avg:	97.91	33.21	25.82	11.41
Acceleration [m/s^2]	max:	3.08	1.06	1.48	2.68
	avg:	0.34	0.54	0.51	0.62
Deceleration [m/s^2]	max:	-3.08	-1.39	-1.48	-2.64
	avg:	-0.41	-0.79	-0.58	-0.61

The simulation uses the parallel, series and power split. The resultsshow that the parallel configuration has the maximum efficiency in the US06HWY cycle even though the energy regenerated is the lowest. The series configuration had a maximum efficiency of 80.1% in the NYCC cycle but the regenerated energy is the highest in the motorway driving cycle. The power split configuration has the highest efficiency in the NYCC cycle and also the maximum regenerated energy. The power split configuration has the highest regeneration efficiency averaged over all the four cycles.Hence the power split configuration is most suited for all the driving cycle.

Dong et al[18] have studied a control strategy to prevent the lock up of wheels in parallel hybrid vehicles with regenerative braking. Since both regenerative braking torque and hydraulic braking torque is developed to stop the vehicle, the amount of hydraulic braking torque required keeps changing and depends upon the amount of regenerative braking torque developed. The strategy involves using a hybrid control unit (HCU) to calculate the total braking torque required and sends the data to the ABS ECU and the electric motor ECU to develop the required amount of torque. As the vehicle speed decreases the regenerative braking torque falls as the voltage developed by the motor would be low and the regenerative current drops to zero and the vehicle is stopped by using the hydraulic braking torque. Using this strategy a 55.8kJ of regenerative energy from a vehicle kinetic energy of 617.28kJ was obtained on a low adhesion coefficient road. Similarly in [26], Yu-shan et al use the coordinated control strategy to improve the efficiency of a PHEV bus and the improvement of 15-20% is observed in energy consumption. Similarly Chu et al [4] have developed a strategy to improve the regeneration efficiency of a hybrid vehicle by changing the brake force distribution on the front and rear axles using braking strength which depends upon the brake pedal travel distance. For different values of braking strength the brake force distribution is changed to the front and rear axle to optimize the regeneration efficiency and to improve the vehicle stability. Regeneration efficiency of 85% and 86% are obtained in UDDS drive cycle and EUDC drive cycle respectively.

Shuang et al [21] have developed a novel strategy for fuel cell hybrid vehicle to minimize the power loss during transmission. The strategy uses serial regenerative braking strategy in which maximum regenerative braking effect is first applied on the wheels and the frictional braking torque is then supplied to overcome the additional braking torque required to stop the vehicle. In the power split between fuel cell and battery more power is distributed to the fuel cell as it is seen that the battery power loss is more at a given SOC than the fuel cell power loss and furthermore the charging of battery is done using only the regenerative energy and the fuel cell is not used in the charging of battery as it results in greater power loss. This strategy results in better regeneration energy ratio of about 2.6%. The data shows a 79% regeneration energy ratio at a SOC of 0.5.

Liu et al [14] study the regenerative braking on a parallel hydraulic hybrid vehicle. Such vehicle uses a hydraulic pump/motor accumulator to harness the kinetic energy of the vehicle during braking and has a greater power density and higher charging and discharging rates as compared to a battery. The kinetic energy of the vehicle is used to charge a hydraulic fluid from low pressure to a high pressure accumulator. The additional braking torque when required is supplied by frictional braking torque. This study has applied regenerative braking on front wheels only to take advantage of the unequal weight distribution during braking. It is shown that using this strategy a energy recovery rate of 51.02% is possible under light braking.

Table8 and Table9 show a comparative view of the different vehicle studied in this paper. The table shows the regeneration efficiency of the vehicles using the regenerative braking system. The vehicles were tested under different driving cycles and using different techniques. It is seen from the table that for a pure electric vehicle the regeneration efficiency was as high as 87.675% for a supercapacitor electric vehicle in [27]. For a hybrid vehicle the maximum regeneration efficiency was obtained in [8] who used an additional generator to the kinetic energy into the battery .The table shows the improvement in fuel economy of the different vehicles by using regenerative braking. It is seen that the study by Alberto Boretti [3] shows that the diesel engine's fuel economy was improved by up to 17% whereas the study on electric minivan in [26] shows an improvement of 10.08% in fuel economy. The hybrid vehicles studied had an average improvement of 15.64% in their fuel economy using the regenerative braking system

Table8. Comparative study of regeneration efficiency of different vehicles

Author	Vehicle Type	Total available Energy(KWh)/Regenerated Energy (KWh)	Regenerated Energy (KWh)	Regeneration Efficiency (%)
Lv et al [15]	Electric Vehicle	1.814	0.2292	11.4
Zhang et al [26]	Fuel Cell Hybrid Bus	8.917	1.417	13.7
Xu et al[25]	Proton Exchange Membrane Fuel Cell Hybrid Vehicle	6.0	1.68	28
Junzhi et al [10]	Electric Minivan	0.048	0.023	47.1
Kim et al[11]	Polymer Electrolyte Membrane Fuel Cell (PEMFC) Hybrid Vehicle	0.0038	0.001	35
Zou et al[27]	Supercapacitor Electric Vehicle	0.177	0.155	87.68
Kim et al [8]	Polymer Electrolyte Membrane Fuel Cell (PEMFC) Hybrid Vehicle	0.0032	0.002	63.8
SerefSoylu [22]	Hybrid Electric Bus	25.296	6.83	27
Dong et al [18]	Parallel Hybrid	0.171	0.15	87.7
Shuang et al[21]	Fuel Cell HEV	1.952	1.55	79.74
Liu et al [14]	FHHV	160.6	81.9	51.02
Chu et al [4]	HEV	0.147	0.126	86

Table9. Comparative study of improvement in fuel efficiency for different vehicle using regenerative braking

Author	Vehicle type	Fuel Economy Improvement (%)
Zhang et al[26]	Fuel Cell Hybrid Bus	16.1
Xu et al[25]	Proton Exchange Membrane Fuel Cell hybrid	15.3
Zhang et al[10]	Electric Minivan	10.08
M T Von Srbik[23]	Hybrid Electric Vehicle	15.52
Alberto Boretti[3]	Diesel Engine	17
Saxena et al[20]	Power-split hybrid	53.6
Saxenaet al[20]	Parallel hybrid	25.5
Yu-shan et al[13]	PHEV Bus	15-20
Shuang et al [21]	Fuel Cell HEV	14
Chu et al [4]	HEV	2.3

VII. CONCLUSION

In this review, the effect of regenerative braking system on fuel and regenerative cycle efficiencies are compared. The study illustrates thatinclusion of the regenerative braking model will improve fuel saving potential of the vehicle. The use of batteriesor flywheels can be made for the storage of regenerated energy. The supercapacitors can store more energy thanbatteries due to higher energy density and low charging and discharging losses. Further, the lithium ion battery have higher energy density and lower losses compared to a Ni-Mh battery leading to better efficiency in storing energy.
From some of the studies, the use of flywheel in storing the regenerated energy leads to high efficiency compared to an electric KERS system. With further development in the use of flywheel for energy storage the efficiency can be further increased.
In this paper, the study on various models shows scope for further improvement in the design of regenerative braking technology. Hybrid vehicles coupled with regenerative braking system form a highly fuel efficient system and with further development of hybrid vehicles and regenerative braking system and reduction in cost of hybrid vehicles will lead to higher market share for such vehicles.

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