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A REVIEW OF REGENERATIVE BRAKING SYSTEMS

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Introduction to Regenerative Braking Systems

When a conventional vehicle applies its brakes, kinetic energy is converted to heat as friction between the brake pads and wheels. This heat is carries away in the airstream and the energy is effectively wasted. The total amount of energy lost in this way depends on how often, how hard and for how long the brakes are applied.

Regenerative braking refers to a process in which a portion of the kinetic energy of the vehicle is stored by a short term storage system. Energy normally dissipated in the brakes is directed by a power transmission system to the energy store during deceleration. That energy is held until required again by the vehicle, whereby it is converted back into kinetic energy and used to accelerate the vehicle. The magnitude of the portion available for energy storage varies according to the type of storage, drive train efficiency, drive cycle and inertia weight. A lorry on the motorway could travel 100 miles between stops. This represents little saving even if the efficiency of the system is 100%. City centre driving involves many more braking events representing a much higher energy loss with greater potential savings. With buses, taxis, delivery vans and so on there is even more potential for economy.

Since regenerative braking results in an increase in energy output for a given energy input to a vehicle, the efficiency is improved. The amount of work done by the engine of the vehicle is reduced, in turn reducing the amount of prime energy required to propel the vehicle. In order for a regenerative braking system to be cost effective the prime energy saved over a specified lifetime must offset the initial cost, size and weight penalties of the system. The energy storage unit must be compact, durable and capable of handling high power levels efficiently, and any auxiliary energy transfer or energy conversion equipment must be efficient, compact and of reasonable cost.

To be successful a regenerative braking system should ideally have the following properties [1]:

- Efficient energy conversion
- An energy store with a high capacity per unit weight and volume
- A high power rating so large amounts of energy can flow in a short space of time
- Not require over complicated control systems to link it with the vehicle transmission
- Smooth delivery of power from the regenerative system
- Absorb and store braking energy in direct proportion to braking, with the least delay and loss over a wide range of road speeds and wheel torques.

Hybrid Vehicles

A vehicle which contains two such sources of propulsion (an internal combustion engine (ICE) and an energy storage device) is known as a hybrid system [2,3,4]. Generally, a **series** hybrid drive, figure 1, has three main system components, ICE, generator and electric motor, which are arranged in series. The mechanical energy generated by the ICE is converted to electrical energy by the generator and this is again converted into mechanical energy in the electric motor. Inherent in the process are losses which result from each of the energy conversion processes. This is acceptable when the ICE and generator are very small relative to the electric motor, since most of the driving energy is delivered as electricity from the battery via the electric motor to the wheels. Series hybrid drives are also feasible if the combined efficiency of the generator and electric motor is as good as the efficiency of the conventional gearbox.

In a **parallel** hybrid drive, the ICE and electric motor are arranged in parallel, figure 2. A generator is not needed because the electric motor can also function as a generator to recharge the batteries. This is a more efficient arrangement since the mechanical energy is transmitted directly to drive axle. Weight and size are reduced because there are only two major components. Alternative hybrid drives replace the electric motor with an alternative form of energy storage to be discussed later. Hybrid configurations, although well known in concept, have not been widely accepted because of complexity, packaging and reliability considerations. Improvements in electronics, control, energy storage, materials and lubrication mean that these concepts are continually re-evaluated.

The use of a hybrid power unit is most suitable in applications where [1]:

- The vehicle is operated in traffic with frequent stops or a highly variable speed.
- Annual mileage is sufficient to pay off the initial investment in the hybrid system
- The vehicle and the driving pattern is such that acceleration resistance is dominant.

In hybrid systems the fuel burning unit can operate under steady state conditions which allows exhaust emissions to be kept to a minimum [5]. Energy is stored when the steady state output is greater than vehicle requirements (at low speed in traffic) and the stored energy is used to supplement the power when needed (when accelerating). The engine can be decoupled from the road load which allows the engine to be operated near its most efficient fuel consumption conditions or else turned off.

The Need for Regenerative Braking Systems

In the years following the energy crisis of the early 70's numerous researchers have studied the feasibility and practicality of implementing hybrid power trains incorporating regenerative braking which have the potential to improve the fuel economy of vehicles operating under urban driving conditions [6, 7, 8]. The price increase of petroleum based fuel in the past few years has also given rise to various research and development efforts for energy conservation. However, reduced fuel consumption and therefore operating cost and reduced gaseous emissions including primarily carbon dioxide (hence global warming) are the major driving forces behind commercial considerations of such systems [9, 10, 11, 12].

Regenerative braking only promises significant gains in town driving since 62.5% of energy is dissipated in the Metropolitan cycle due to frequent braking. If all brake energy could be regenerated with no loss in the regenerative system, fuel consumption would be improved by 33% [13]. Alternative sources state that the addition of regenerative energy storage systems to motor vehicles can achieve theoretical fuel savings of up to 23% in a 1600 kg vehicle on a level road urban driving schedule. This relative saving is reduced as the weight of the vehicle reduces. A 1000 kg vehicle can achieve theoretical savings of 15% [14, 15]. Research by Volkswagen has shown that a hybrid drive with both electric drive and ICE offers potential fuel saving of over 20% compared with just 5-6% from purely electric [16].

Concerns over fuel economy, pollution and government regulations maintain the interest of the automotive technical community in these alternative powertrain configurations [17]. Interest in non-polluting vehicles increased significantly when the Californian Air Resources Board mandated that 2% of all vehicles lighter than 1700 kg sold by each manufacturer in the state in 1998 be zero emission vehicles. This must increase to 5% by 2001, and 10% by 2003 [18]. The term non-polluting is relative, electric vehicles do not pollute but the original source of the energy does cause pollution during its generation. However, centrally generated pollutants can be controlled and reduced more easily than the distributed pollution sources of individual vehicles.

Most American motor vehicle manufacturers believe that hybrid systems are the way to achieve more flexibility and range out of electric vehicles until better batteries are available. This would allow them to meet the stringent Californian exhaust emission standards being phased in for passenger cars over the next few years. Ultra Low Emission Vehicles (ULEV) standards are expected to provide a niche for hybrid drive vehicles which is why manufacturers interest is heightened at present. It is widely believed that most of the electric/hybrid vehicles sold are likely to be second or third vehicles used specifically for local commuting and not needing to provide the same all round performance as conventional cars.

European manufacturers believe hybrid vehicles are a way to achieve high fuel efficiency and very low emissions from liquid fuelled vehicles. This differing view is due to fact that in the LA basin the air pollution problem extends over a vast area requiring a vehicle with good range and zero emission capability. In Europe pollution tends to be a localised event concentrated in urban areas, this combined with the fact that fewer European families have two or more cars means manufacturers need to provide a car that can deal with local air quality but also travel at higher speed for interurban and long distance driving.

The main advantages of regenerative braking systems can be summarised [19] as:

- Improved fuel economy - dependent on duty cycle, powertrain design, control strategy and the efficiency of the individual components.
- Emissions reduction - engine emissions reduced by engine decoupling, reducing total engine revolutions and total time of engine operation (engine on - off strategy).
- Improved performance.
- Reduction in engine wear - engine on/off strategy.
- Reduction in brake wear - reducing cost of replacement brake linings, cost of labour to install them and vehicle down time.
- Smaller accessories - hybrid powertrain offers potential for eliminating (electric starter) or downsizing (fuel tank) some accessories, thus partially offsetting the increased vehicle weight and cost due to the hybrid hardware additions.
- Operating range is comparable with conventional vehicles - a problem not yet overcome by electric vehicles.

The possible disadvantages of regenerative braking systems can be summarised as:

- Added weight/bulk - extra components can increase weight increasing fuel consumption, offset by smaller engine operating at its best efficiency.
- Complexity - depends on control necessary for operation of regenerative braking system.
- Cost - of components, engineering, manufacturing and installation. Mass production would bring costs down to a more reasonable level.
- Noise - dependent on system.
- Safety - Primary concern with any energy storage unit of high energy density. There must be very little chance of dangerous failure during normal vehicle operation. Passengers must be protected from risk that may be caused by the failure of the hybrid system.
- Size and packaging constraints - most important for cars.
- Added maintenance requirement - dependent on complexity of design.

Required Vehicle Performance

The amount of stored energy and maximum power extraction depends on vehicle performance specifications, the conversion efficiency and the efficiencies of the components in the drive train. Performance specifications should be similar to existing automobiles to obtain acceptance in the market place. Typical specifications [18] are:

Mass	Vehicle (inc. fuel)	1600 kg
	Passengers	400 kg
	Luggage	200 kg
	Total	2200 kg
Range	250 km at constant speed of 48 km/h	
	200 km at constant speed of 88 km/h	
	10 km 10% slope constant speed of 48 km/h	
Speed	Maximum 120 km/h	
Acceleration	From 0-96 km/h in 10 s	
Deceleration	From 96-0 km/h in 7 s	
Rapid recharge	Fully charged in less than 40 min	
Slow recharge	Fully charged in 8 h	
Aux.power	Air-conditioning/heating	3 kW
	Windscreen wipers	0.1 kW
	Lights	1 kW
	Radio / hi-fi	0.2 kW
	Electric windows	0.2 kW
	Cooling pump and fan	1.5 kW
	Total	6 kW

Efficiencies	Motors	95%
	Gearboxes	99%
	Controllers (inverters)	97%
	Controlled rectifier	98%
	Flywheel generator	95%
	Batteries	92%

A minimum energy storage of 78 kWh is required to give the automobile a range of 200-250 km. This is based on a total vehicle weight of 2200 kg and is significantly less if a lighter vehicle is used. The power requirements depend upon the maximum acceleration/deceleration rates of the vehicle and the allowable time to recharge the batteries or flywheel. A minimum power of 94 kW is required to meet the specified acceleration/deceleration rates.

Development of Vehicles Incorporating Regenerative Braking Systems

The idea of regenerative braking has been widely exploited in electrified railways by using the motors of trains as generators whilst braking [20, 21]. This concept has been utilised for many years [22], and with increasing electrification of the railways many new trains have been designed with such systems in mind [23, 24, 25]. The increasing availability of sophisticated electronic components [26] and improvements in control circuitry [27, 28] has improved the efficiency of regenerative braking on the railways. One article quotes a reduced electrical energy consumption of 37% [29]. Various computer simulations studies have modelled the effect of regenerative braking on power flow [30, 31, 32] and load flow [33]. Complete metro systems have been built incorporating regenerative braking in Shanghai [34], Vienna [35], Sao Paulo [36], Dublin [37], Caracas [38] and Hamburg [39]. In addition, the Japanese Maglev superconducting rail system also incorporates regenerative braking attempting to create a super-efficient rail system [40].

For vehicles powered by ICE's it is much harder to implement a regenerative braking system because unlike an electric motor the energy conversion processes involved in an ICE are irreversible. Additional equipment is therefore needed to both convert and store the energy. Such devices, which will be discussed later, include:

- Batteries
- Hydraulic/Pneumatic Accumulator
- Flywheel
- Elastomeric

and in addition

- Superconducting [40, 41]
- Fuel Cells [42, 43]
- Solar [44]
- Regenerative engines [45, 46]

Electric Vehicles

Electrically driven vehicles can give a saving of energy if, with suitable control equipment, they can convert KE to electrical energy for storage and re-use [47, 48]. The drive motor of an electric vehicle can be made to operate as a generator supplying a resistive load and braking torque to the wheels. In regenerative braking, the electric vehicle motor operates as a generator to charge the battery [49]. The process is less efficient at low power because of the substantial fixed mechanical losses, thus regeneration is not possible at low speeds and must be supplemented by mechanical brakes.

Research and development to find and improve electric vehicle batteries has been active since 1945 [50, 51]. By 1994 the lead acid was still the only commercially economical and viable battery technology suitable and is far from ideal [52]. Electric vehicles have limited range and relatively poor performance because of weight and volume of battery, and energy transfer rate and lifetime limitations. The constraints for high performance batteries are high specific energy density, high discharge rate or specific power and high number of deep discharge cycles (life cycles). At present all three together are mutually exclusive. The difficulty in achieving high values for all these parameters has led to the suggestion that electric vehicles may best be powered by a pair of batteries. The main unit would be optimised for range (specific energy) and another for power (specific power). The second unit would be recharged from the range unit during stops or less demanding driving [18].

Batteries provide electrical power in DC form. An inverter is required to convert DC into AC suitable for driving an induction motor. A pulse width modulated inverter is the preferred controller which gives flexible, low harmonic output distortion [18]. Switching losses are reduced at high switching frequencies by the use of transistors as power switches. Low power applications require MOSFET switches and high power applications require IGBT switches. IGBT's are available in voltages up to 600 V and currents up to 750 A. Microprocessor control of the PWM inverter provides flexibility to incorporate optimising strategies [53].

The squirrel cage induction motor is the preferred machine for heavy duty, high speed transportation applications because of its rugged brushless motor. There is a concentrated research effort investigating chopper fed DC motors [54, 55, 56, 57] and switched reluctance motors [58] under regenerative braking conditions. Automobile applications require the motor to operate under full field and constant torque conditions from zero to base speed and under constant power (weak field) conditions from base speed to top speed. To reduce weight a high speed motor and fixed gears should be used. The power converter technology can be either pulse width modulation [59] or direct AC to AC conversion [60, 61] with cycloconverter techniques. For contactless power supplies, research is in progress on a bi-directional DC to DC converter [62]. The induction motor must operate in an adverse environment characterised by ambient temperatures between -30°C and 45°C and splashing of water, snow and dirt will occur. Furthermore, corrosive atmosphere and vibration and shocks would be experienced.

A block diagram of a front wheel drive electric vehicle is shown in figure 3 [49]. The induction motor has two stator windings, each connected to its own inverter. The inverters can be connected in series or parallel. During motoring, the series connection is used. During regenerative braking the parallel connection is used. If two motors are used in the vehicle each motor will have only one winding and one inverter. Again the two inverters may be connected in series or parallel.

Research Effort

Research has furthered the development of both purely electric and hybrid electric vehicles. The following summarises the development of **purely electric** vehicles which incorporate regenerative braking:

The CleanAir LA301 was a four seat hybrid electric/gasoline car designed for Los Angeles complete with electric windows, power steering and air conditioning [63, 64]. The four cylinder, fuel injected, 650 cc, 25 kW gasoline engine had a preheated catalytic converter. The power train management system is a microprocessor which blends the power from the motor and the auxiliary power unit to the wheels. The system makes decisions based on the state of charge of the battery, driving conditions, acceleration, regenerative braking and continually monitors and informs driver of all vehicle function conditions, at the same time storing information for service diagnostic purposes. The two speed automatic gearbox drives the front wheel, and the vehicle could achieve 0-50 km/h in 7 s with a maximum speed of 120 km/h. The maximum range was 240 km, although 100 km is considered sufficient range for 90% of the car journeys in LA, and emissions complied with Californian ULEV standards [65]. It was scheduled to be on the road by 1993, however in 1994 CleanAir transport ceased trading due to financial difficulties and the development of the LA301 was abandoned [66].

The Nissan Future Electric Vehicle (FEV) has heating and air conditioning. The powertrain consists of two 20 kW, four pole, single phase AC motors in tandem capable of delivering maximum power of 40 kW with a peak torque of 96 Nm. The motor controller includes IGBTswitches capable of 10 kHz high speed switching which governs two 280 V DC/AC converters, one for each motor. The controller system includes regenerative braking capability to recover energy and extend range. The motor is powered by NiCd batteries and the vehicle can achieve 0-40 km/h in 3.6 s, 0-400 m in 20 s, a top speed of 130 km/h, and a range of 250 km at level road speed of 40 km/h [67].

The General Motors HX3 (Impact) van is powered by two 45kW AC induction motors, one driving each front wheel. The motor controllers include dual MOSFET DC/AC inverters to supply the three phase power needed. The electricity is supplied by lead acid batteries and solar cells and the vehicle has special tyres with half the rolling resistance of conventional tyres, allowing a range of 95 miles [68].

An electric bus for operation in New York [69] has also been developed. This runs on Nickel Cadmium batteries and features regenerative braking.

The following manufacturers have also produced electric vehicles featuring regenerative braking [67]:

Peugeot	205, lead acid battery, range of 75 miles at 45 mph, top speed is 62 mph and achieves 0-30 mph in 12 s. J% Electrique van also uses lead acid battery.
Volkswagen	Golf, lead gel battery, range 81 km at 50 kmph, maximum speed 100 kmph and achieves 0-30 kmph in 6 s and 0-70 kmph in 27 s Jetta, sodium sulphur battery
BMW	E1 concept car, sodium sulphur battery, range 155 miles, top speed 75 mph, acceleration 0-30 mph in 9 s
GM	Impact, lead acid battery, range 120 miles, acceleration 0-60 mph in 9 s, top speed 100 mph. 1 tonne G-van, range 50-60 miles, top speed 50 mph, acceleration 0-30 mph in 12 s.
Chrysler	TEVan, lead acid battery, testing nickel-iron batteries, range 120 miles, 0-30 mph in 9s, top speed 65 mph.
Fiat	Uno, lead acid battery, similar characteristics to Peugeot 205
Toyota	2 seater car, motor caravan and a bus, zinc-bromide batteries.
Nissan	March, top speed 68 mph, range 150 miles

The following summarises the development of **hybrid** electric vehicles incorporating regenerative braking:

Iveco have developed a range of petrol electric buses because of the excessive weight and limited range of battery only vehicles. A small combustion engine powers the electric generator which drives the bus, and regenerative braking allows more efficient use of power [70].

Volvo have developed an Environmental Concept Car based on the Volvo 850 [71]. The vehicle, a gas turbine/electric hybrid driven by a Nickel Cadmium traction battery, has low exhaust emissions and good fuel economy.

DAF's vision of the truck of the future is the concept vehicle Advanced Transportation Design (ATD). This features a diesel/electric powerpack with electric driving and braking in each wheel unit [72].

PSA Peugeot Citroen were developing a hybrid drive vehicle equipped with its own electric generating system. The first phase involved the use of a diesel engine to recharge the batteries, and in the second phase the electricity was produced by a gas turbine driving a high speed alternator [73].

Volkswagen have also been involved in the developed of hybrid vehicles. The VW Chico was unveiled at the 1991 Frankfurt Motor Show. Switching between the two types of motive power is automatic with the petrol engine cutting in at around 60 km/h [74]. A hybrid diesel electric Golf has also been developed. The engine gearbox drive unit only had to be increased by 58 mm to accommodate automatic clutch on either side of the electric motor [75], and comparisons between the Golf diesel and Golf hybrid show comparable exhaust emissions and energy consumption [16].

Finally, a hybrid bus incorporating a diesel engine and battery pack was developed in Chicago. A fuel economy study taking into account regenerative braking revealed results comparable to a conventional diesel bus [76].

An alternative electric car is the Sunraycer, a solar powered car which won the World Solar Challenge Race, powered solely by energy from the sun [44]. Electric motors are energised by solar cells, assisted by batteries charged by the cells. Conventional DC motor mechanical brushes switch DC voltage from the battery in order to maintain a constant unidirectional torque on the spinning coils. In Sunraycer, the motor has an electronic inverter or motor driver which exploits advantages in new semiconductor switches. The inverter switches the circuit for variable intervals to modulate the amount of direct current coming in from the battery. An element of Sunraycers efficiency was its use of regeneration: most of the braking was accomplished by operating the motor as a generator and recycling half the energy through the battery instead of dissipating it as heat in the brake disks. During this process the inverter works in reverse, converting the AC energy from the motor into the correct DC voltage for returning energy to the battery. Thus an electric car, instead of requiring a large and expensive battery charger at a servicing station, can recharge its battery with an onboard inverter. The basic simplicity of this vehicle is most appealing. The motor has only one moving part. The transmission has a single ratio. Most of the braking is done by the motor and much of the braking energy can be recycled. There is no need for a clutch because the motor stops when the car stops. This eliminates the wasted fuel and pollution generated by idling engines.

Hydraulic Accumulators

Hydraulic regeneration systems have been considered by the automotive industry for implementation in hybrid vehicles for a number of years [1, 19, 77]. A gas charged hydraulic accumulator is a potential energy storage device in the form of a cylindrical or spherical vessel that can hold relatively large amounts of hydraulic fluid under pressure. The device stores energy by compressing a gas (usually nitrogen), and has proved to be much more practical than the weight or spring loaded type. They are also lighter, cheaper and more compact. The hydraulic system consists of an accumulator, an oil reservoir and a variable displacement pump/motor. The wheel driven hydraulic pump builds up pressure in the accumulator and energy is transferred by the pump/motor unit. A variable displacement unit of this type is simple to control. As with electric vehicles, these systems are also less efficient at low power because of their substantial fixed mechanical losses. In addition care must be taken in selecting the energy storage capability and construction of the hydraulic accumulator to minimise the weight penalty. Hydraulic accumulator based vehicles have suffered from the unavailability of efficient variable displacement pump/motor units, but new high efficiency prototype designs appear to have partially overcome this problem [78].

There are three system configurations [19]. The pure hydrostatic (integrated or **series**) system is based on pure hydrostatic transmission and requires a pump and pump/motor. The function of the pump/motor is dependent on whether the vehicle is being driven with positive torque or using regenerative braking. This configuration permits regenerative braking and allows the accumulator to be bypassed and the vehicle to be driven as conventional CVT when advantageous. (CVT - constantly variable transmission, which involves raising the gear ratio to maintain a required minimum motor speed as the vehicle speed decreases during braking (automatic down shifting during regenerative braking). The power assist (add on or **parallel**) system requires only a single pump/motor plus some type of transmission either a discrete ratio gearbox or CVT. If a gearbox used, the engine speed is not completely independent of vehicle speed. This configuration is unique in that failure of the hydraulic system will not stop vehicle being operated. The power split (**hydromechanical**) system consists of two variable displacement hydrostatic units, a power dividing differential and an accumulator. This configuration offers the advantages of regenerative braking and the possibility of running the engine at its most efficient point much of time and at efficiencies equivalent to a conventional car the rest of the time. If properly implemented, the parallel concept will provide better fuel economy than the series and has additional advantages of simplicity and reliability. The power split configuration combines the benefits of series and parallel at the cost of complexity of design, manufacturing and control.

Figure 4 shows a schematic diagram of the arrangement used to evaluate pump/motor performance and measure overall efficiency of the regeneration process [79]. In the system shown kinetic energy of the flywheel (used to simulate vehicle mass) is converted to hydraulic energy by the pump and stored in the hydraulic accumulator through compression of the gas. The stored energy can be returned to the flywheel during a process in which the accumulator gas expands and the oil is pushed through the pump/motor operating in the motor mode which results in acceleration of the flywheel. This is analogous to storing the kinetic energy of a vehicle during deceleration. The hydraulic system of a hybrid vehicle must cope with large variations of pressure as well as flow. Traditional pump configuration systems will incur substantial efficiency losses. The development of a dual pump hydraulic supply system consisting of a low volume fixed displacement pump and a high volume variable displacement pump was necessary to fulfil the requirements of constantly variable transmission [80].

Research Effort

Volvo's ongoing work with energy storage by regenerative braking for city buses has reached the stage where two prototype passenger vehicles with flywheel and alternative hydraulic accumulators are in trial route service in Stockholm [81]. Recycling power in this way gives fuel savings of up to 30% in the regular stop start driving of urban bus operation. The drive concepts have been developed by Volvo Flygmotor.

The development project for hydraulic accumulators to recycle braking energy is currently felt to have greatest promise. There is only a single energy conversion between mechanical and hydraulic drive (compared with three for the flywheel system). The hydraulic system permits a more flexible layout in the vehicle making it possible to retain the basic elements of a conventional driveline - extensive chassis modifications are unnecessary. The energy storage capacity of 0.4 kWh (much less than flywheel) which allows for an operating range of 400 m with one intermediate stop without running the engine. Fuel economy is not affected because recuperative cycling occurs more frequently. Stored hydraulic pressure is used to accelerate the bus from rest when the energy demand and hence the fuel consumption is the greatest. The engine idles and takes over the drive when the accumulators are exhausted after the vehicle reaches cruising speed. They are recharged during subsequent braking. The bus uses a Volvo B10M chassis with mid mounted underfloor engine. Three hydraulic cylinders of about 2m length are mounted between frame members at the rear and charged up to 35,000 kPa (same as flywheel pump/motor). An auxiliary gearbox is positioned in the prop shaft between the main bus transmission and axle. A lateral shaft coupled to a single hydraulic pump/motor is used in the accumulator system. This standard modular unit is claimed to have a 95% conversion efficiency and is connected by pipes to the three storage cylinders. The microprocessor control unit is also standardised component. The relative simplicity, flexibility and cost advantage of the hydraulic system make it a likely prospect for future production vehicles.

Various vehicle simulation programs have been used to evaluate fuel economy and performance of existing and proposed vehicle configurations [79, 82]. The results have appeared promising with a significant (30 - 79%) improvement in urban fuel economy resulting from use of hydraulic accumulator being evident from all simulation studies found in literature. Practical examples have confirmed the simulation. The fuel economy of a 1360 kg hybrid VW Jetta was improved by 44% [83, 84], and a hybrid Landrover designed at the National Engineering Laboratory in Glasgow shows an improvement of 43% [85]. A Ford Escort van with a 20 litre accumulator offering an energy storage capacity of 165 kJ shows a fuel saving of 14% [86]. This technology is also more easily adapted to larger vehicles and hybrid buses with hydraulic accumulators have been designed and tested. Three such examples are the MAN hydrobus (25% improvement) [87], the Volvo bus (43-54%) [88] and the Canadian National Research Council bus (43%) [89]. Another bus developed was one based on a Leyland vehicle having a fuel economy improvement of 49% [90, 91].

Flywheels

The kinetic energy of a vehicle to be decelerated is used to accelerate a flywheel; this flywheel is subsequently coupled to the transmission to assist in starting the vehicle from rest, thus conserving energy [92]. The first passenger bus was made more than 25 years ago by the Oerlikon Engineering Company of Zurich, Switzerland. The kinetic energy stored in a flywheel is given by $E = \frac{1}{2} J \omega^2$ where J = moment of inertia and ω = angular rotating speed. This energy is proportional to the rotational speed squared and by increasing this speed one can store more energy [93]. However the stress in the material increases with speed squared and once the maximum tensile strength is exceeded the flywheel disintegrates. The shape of the flywheel is important and must be designed such that stress in the material is the same throughout. Older flywheels were made of materials equally strong in all directions. Some materials have significantly higher strengths in one particular direction e.g. piano wire, carbon fibres, glass fibres, Kevlar fibres. A new type of flywheel has evolved in which high stress fibres are embedded in a plastic matrix. The fibres are aligned so that the centrifugal force acts along the fibre in the direction of its high tensile strength. The specific energy density of a flywheel is proportional to the ratio of tensile strength to specific density [94].

A flywheel used as an energy store will dissipate some of its stored energy continuously as friction and aerodynamic losses. The estimated practical energy density is significantly lower than the theoretical value because of the additional weight of the bearings, motor/generator, shaft and containment vessel. The flywheel rotates in a vacuum to reduce windage losses. This vacuum would have to be checked regularly. Magnetic bearings are the only type suitable for high speed operation in a vacuum with low losses. To extract energy from a flywheel an electrical generator is used. This generator must be able to withstand high rotating speeds in a very difficult cooling medium (vacuum). The electrical machine of choice for this application is the permanent magnet motor because of its high efficiency [95]. The stator winding has to be cooled by using a liquid circulating through the hollow conductors. The stator core is cooled by conduction through the stator winding and through the vessel wall. When flywheels are used, the electric power generated is AC with variable frequency and voltage. The required power for the induction motor is also AC with a different adjustable frequency and voltage. The desired converter is therefore a direct AC - AC converter, usually the cycloconverter.

A schematic diagram of a flywheel driven vehicle is illustrated in figure 5 [18]. The variable speed of the flywheel causes a variable frequency and output of the permanent magnet generators. The output of these generators is converted into a controllable AC power which drives the induction motors. A master controller will regulate the appropriate frequency difference between the two motors. A hybrid system consisting of a flywheel and a battery is shown. The flywheel will provide the energy during the demanding parts of the operating cycle, while the battery will recharge the flywheel during the slow speed and stand still parts of the driving cycle.

Safety is a major concern since a number of accidental events can occur in a flywheel based system. These include a) Loss of vacuum resulting in an increase in temperature of the air, the flywheel and the casing and the speed of the flywheel will decrease rapidly b) Overspeed where the diameter of the flywheel will expand, rub against the casing, and the resulting friction will cause the flywheel to slow down. The temperature of the flywheel and the casing will increase but no physical damage will occur and c) Damage to the casing which will result in a loss of vacuum and/or the flywheel will hit the casing. The stored energy will be dissipated in the disintegration of the flywheel but will be contained within the containment vessel [94].

A typical flywheel/motor/generator combination will have top design speed of 30000 to 50000 rpm and a minimum design speed of 7500 to 12500 rpm [18]. This 4:1 range would utilise about 94% of the available kinetic energy. Such a flywheel system would have a higher energy density than the best available batteries and would have the additional advantages of high rate of power extraction and practically unlimited number of life cycles. Although flywheels possess a higher energy density than hydraulic accumulators for a given size, they have not become the preferred option for hybrid applications because of their complexity, control hardware weight and cost. They have not displayed fuel economy improvements as substantial as those provided by accumulator systems. Several other factors make the accumulator comparable or favourable including silent operation, reliability, durability, no requirement for supporting hardware (gear bearings) and unlike the flywheel the accumulator is capable of retaining the stored energy almost indefinitely.

Research Effort

As well as flywheel systems for larger vehicles (usually buses) smaller passenger car sized systems are under development as an alternative energy storage medium to batteries in hybrid electric vehicles [96, 97]. An American coalition of government, industry and academia started investigating the use of flywheels as energy storage systems in 1975. The seven year programme ended in 1982 [98].

More recently a small American company has designed and patented a compact, high speed flywheel which is claimed will store five times as much energy as an advanced chemical battery of similar size and would last the lifetime of the vehicle [99]. The AFS flywheel contains two contra-rotating wheels spinning at exactly the same speed eliminating the gyroscopic effects of a single spinning wheel. To minimise friction the wheels are contained in a vacuum and rotate on electronically controlled magnetic bearings. The flywheel is constructed using an advanced filament winding technique allowing it to spin at higher speeds than conventional flywheels. Due to the high tangential forces, solid discs can disintegrate at high speeds and rim and spoke designs can separate. The AFS wheel is connected by spokes to the hub and as the rotational speed increases the hub expands and grips the spokes tighter. Doubts remain as to the commercial viability of using the AFS flywheel. A full size system has still to be funded and built. The current cost of such a flywheel would add several thousand pounds to cost of a car.

A minitram powered by a rapidly spinning flywheel is being developed by the Midlands based company Parry People Movers [100, 101]. The power is stored in a flywheel which is charged in 90 seconds. Electric charging points at each stop would feed a low voltage supply to the electric motor on the tram. When the minitram slows down energy is fed back through the gearbox to the flywheel. The anticipated range is 3 - 4 kilometres, and it is envisaged that this vehicle could be used to carry people short distances around shopping precincts.

United Technologies Corporation has concentrated on an automotive Flywheel Power Surge Unit (FPSU) and utility power quality unit having a rated power of 25 to 50 kW and an energy storage capability of 800 Wh at 35000 rpm [102]. The recent availability of suitable and affordable high strength lightweight composite materials for flywheel construction is a major reason for recent technical developments. Interest has also been influenced by improved low loss bearings and application demand for vehicular energy storage. For vehicular applications the FSPU would be designed to supplement the energy source in Zero Emission or Hybrid Electric vehicles. With such devices, acceleration performance may equal that of conventional vehicles, range may be extended through regenerative braking and battery life may be extended. The power requirement may be placed on the FSPU while the energy requirement may be placed on the battery and/or engine. Major factors have influenced the design including energy storage capacity, cost, number of cycles and size constraints. High specific strength composite materials provide attractive properties for flywheel energy storage devices. High strength fibres would allow rotational speeds that provide large amounts of energy density, however fibre architecture requires careful design. The energy increases rapidly with rotational speed and is maximised by using the largest diameter wheel the application will allow. This particular development in conjunction with BMW shows great promise for improving the performance of all electric and hybrid vehicles. Early device demonstrations have provided system trade-offs and improved component performance leading to overall optimisation of system cost, size and weight, and the development of larger units for buses has also begun.

As mentioned in the previous section, Volvo have developed a prototype flywheel powered passenger vehicle [81]. A small 105 kW diesel replaces the standard 170 kW engine of a 16 ton Volvo B10R city bus and drives only the 330 kg flywheel, not the road wheels. An arrangement of swashplate pump/motors functions as a continuously variable hydrostatic transmission. There is no clutch or fluid coupling. The engine operates at constant 3000 rpm and is used to wind up the flywheel, and to speed it up if the revs drop below 6000 rpm. The flywheel consists of a stack of five 300 mm diameter steel discs. This layered design reduces the risk of disintegration by centrifugal force. The flywheel runs in an evacuated casing up to 10000 rpm with an equivalent maximum power of 125 kW. The stored energy, equivalent to 2.3 kWh, is capable of propelling the bus 1.2 km with three full stops before the flywheel revs drop below the threshold level. Operation of system is completely automatic, controlled by microprocessor circuitry that starts and stops the engine, governs speed, alters the transmission ratio according to power and braking demands and switches the rotary hydraulic units between pump and motor roles for the reversible drive and brake functions. The control unit has inputs from different speed and pressure sensors and from the drivers brake and accelerator pedals. The road speed is regulated by an accelerator pedal via the hydrostatic transmission pressure and ratio, and torque delivery is from the flywheel rather than the engine. Initial depression of the brake pedal inverts the modes of the hydraulic units so the bus drive axle then feeds the retarding energy back to the flywheel.

This progressive action is proportional to pedal movement up to the maximum storage capacity. Movement beyond this point decouples the flywheel and engages standard friction brakes, normally applied to bring the bus to a final stop. There is no engine braking on the overrun with accelerator lift off so the foot brake is always needed to slow vehicle, maximising energy recovery. The drive system can cut fuel consumption by 25% [88].

MAN have also developed flywheel buses, the Gyrobus I and the Gyrobus II, both having a 350 kg flywheel with a storage capacity of 750 Wh. Mark I showed a fuel saving of 8% and Mark II a saving of 25% [103].

Another bus has been developed which utilises the band variable inertia flywheel concept for the intermediate storage of recoverable energy suitable for stop go operation. A model has also been developed for the dynamics of the flywheel and evaluation for 'real life' performance of the bus. Advantages include fuel savings and extended brake shoe life [104].

Elastomeric

Elastomeric energy storage is promising because of its inherent simplicity. In theory one need only connect the axle or driveline to an elastomer such that the vehicle motion stresses the elastomer. All of the other energy storage systems previously considered require more complex energy transfer equipment. In addition, the deceleration and acceleration characteristics of a system consisting of an elastomer and a clutch are similar to actual stop-start driving characteristics. There are various stressing schemes which may be implemented to enable energy storage. These include tension, shear, compression and torsion. Tension is superior on the basis of energy stored per unit of elastomer volume. However, in an automotive application, total volume is more important than elastomer volume since the total space required to accommodate the system is at a premium. In a tension scheme a device to convert linear into rotary motion is also necessary, adding complexity and additional volume requirements.

There are various potential problems associated with elastomers which must be considered. The most important is hysteresis or energy loss associated with cycling the material. Hysteresis causes the elastomer to get hot with repeated cycling thus reducing the efficiency achievable. It may also assist in decomposing the material leading to poor reliability and expensive running costs. Another problem is scalability and the possibility of fabricating units which have suitable capacity for energy storage at a reasonable size and cost.

Research Effort

Research specifically on elastomeric regenerative braking systems appears limited. However some interesting work in related areas has been found and is discussed later.

Elastomeric Regenerative Braking

In the work done by the Eaton Corporation, tension is dismissed in favour of torsionally induced tension [105]. A relationship was empirically deduced for the torque rotation characteristics:

$$T(\theta) = K_n \theta \qquad \text{when } \theta \leq \theta_{min}$$
$$= T_{min} + (0.2) K_n (\theta - \theta_{min}) \qquad \text{when } \theta \geq \theta_{min}$$

where $K_0 = \pi/2 \; (G R^4) / L$

$K_n = 2/3 \; n^2 K_0$

$\theta_{min} = (L / R) / (n + 1)$ rads

$T_{min} = K_n \theta_{min}$

and n is the number of adjacent elastomeric rods, radius R, length L and shear modulus G.

For $\theta \geq \theta_{min}$ the stress distribution causes buckling leading to the formation of knots. It was found that the energy stored in a given volume of elastomer is significantly increased if buckling is permitted. For energy storage comparable to the tension scheme $n \geq 3$. In this case $n = 4$ was chosen with the elements made from natural rubber. It was projected that the kinetic energy of a 1400 kg vehicle travelling at 13.2 m/s could be stored in 34000 cm^3 (32 kg) of natural rubber.

The behaviour of various elastomers was compared and synthetics such as polybutadiene, polyester and polyurethane were rejected on the basis of low fatigue life and/or high hysteresis loss. Unfilled natural rubber and synthetic natural rubber were found to be the most promising. Natural rubber was found to have a fatigue life of 10^5 cycles.

A full size unit was tested, with the 7.3 cm diameter rubber extrusion wrapped around pins 1m apart to produce 4 rods. The unit was sized to store 10^5 J, the kinetic energy of 1150 kg vehicle at 13.2 ms^{-1}
At failure:

Revs	39
Torque	1380 Nm
Axial Load	7430 N
Energy stored	183 kJ
Vol.energy density	10.8 J cm^{-3}
Gravimetric energy density	11.6 J g^{-1}

In cycling tests, 90% of energy delivered to elastomer was redelivered by elastomer which means that hysteresis and friction loss run at 10%. In cyclic testing with $n = 1$ the fatigue life is 10^5 cycles, however with $n = 4$ the fatigue life decreases to 10^3 cycles. The lifetime was substantially reduced by abrasion and surface tears.

In the search for an improved rotational stressing scheme, isolated rods were initially stretched, then restrained from motion in the axial direction. The energy was delivered to the elastomer by rotating one end relative to other. In a small scale test, with rod diameter 0.95 cm and length 9.5 cm the effect of changing the ratio of the final to initial length was examined.

$\lambda = l_f / l_i$ final to initial length ratio

The effect on torque rotation characteristics shows a dip in the curve at the point where the elastomer buckles. The important result was that the energy stored prior to first knot increases significantly with λ. The following expression for the energy density of a non buckling, axially loaded torsion bar was determined:

$$E_{max} / V_{elas} = E_{max} / V_{tot} = (M / 2)\,(\pi / 2)^2\,\lambda^2$$

For soft natural rubber, M is approximately 0.17 M Pa. The energy per unit of total volume required is slightly better than the tension only scheme if λ is equal to 4. If no knots are allowed to form there will be no surface abrasion. Small scale fatigue tests reveal a lifetime of 10^5 cycles, therefore at two stops per mile this represents a lifetime of 50,000 miles.

The design to incorporate into an automobile consists of two units, each 0.61 m long and 0.19 m diameter stretched to 2.44 m long and 0.10 m diameter. This is illustrated in figure 6. Endurance tests with λ equal to 3 were carried out. The unit was rotated from 0 to 7.2 revs and back in 15 s, 100,000 cycles completed. Round trip efficiency was close to unity. The energy density decreased 6%. The unit was then loaded with λ equal to 4, and the endurance test continued. Failure was achieved at 159 kcycles, with an efficiency of 96.3% and an energy density of 1.06 J cm^{-3}.

The tests confirmed the following:

1. Torque, axial load and energy density at given revs. can be adequately predicted from size, geometry and material properties.
2. Efficiencies higher than anticipated are achievable in full size units at $\lambda = 4$.
3. A fatigue life of 10^5 cycles is achievable.

The energy density was found to be only half that of the small scale samples. The modulus of the full size unit was only half that of small scale unit. Attempts were being made to alter the curing cycle and compounding of the elastomer to correct the situation. As the elastomer was stressed and relaxed, no variation in surface temperature could be detected with the bare hand.

Stress relaxation tests were carried out along the way.
1. The torsional stress relaxation rate is less than the axial load stress relaxation rate.
2. The stress relaxation rate is not a significant function of elongation for large elongations ie rates are the same for $\lambda = 3$ or 4.
3. The long term effects of stress relaxation are not yet known, but the effect could be compensated for in the initial design by using an appropriately larger amount of elastomer.

In summary, an elastomeric regenerative braking system is technically feasible. Improvements in the properties of the elastomer would enhance the prospects of such a system. Improvements in energy density are desirable since this would directly reduce the required volume. Reductions in stress relaxation rates are desirable to allow less weight compensation in the initial design. An improved fatigue life is also desirable. In the course of the research, many people and institutions were approached with regard to what the most suitable material might be. The general consensus of opinion was that natural rubber would probably be the most appropriate.

The following two articles raise points which might be worth considering in an alternative regenerative braking scheme.

Elastomer Flywheel

The flywheel has been used for centuries as a cheap short term energy store. The modern machine is an efficient and adaptable piece of precision engineering but at the price of increased complexity and cost. A new concept, which is both simpler and cheaper, exploits the nonlinear expansion of an elastomer ring together with its variable moment of inertia [106]. The combination of elastic and centrifugal energy results in a remarkable energy speed characteristic that allows the extraction of around 80% of the stored energy for a speed variation of only a few percent, against a drop of more than 50 % for a conventional flywheel. Operating in this optimal mode the elastomer machine has a lower energy density than its metallic equivalent, but the low cost of natural rubber could make the elastomer flywheel competitive with existing machines.

Traditionally flywheels have been constructed from steel. In the early 1970's it was realised that a big increase in the energy/weight ratio could be obtained by the use of reinforced plastic materials. The proposed flywheel is essentially an elastic ring which rotates at a low angular velocity - lower than conventional (steel) flywheels. Reduction in centrifugal energy is offset as the flywheel expands by the effect of the increase in diameter and by stored elastic energy. The principle advantages of an elastomer flywheel are:

- An optimal operating characteristic that allows the extraction of some 80% of stored energy for a speed change of only a few percent.
- Low angular velocity, leading to the possibility of direct coupling to an alternator at the supply frequency.
- Low cost of the raw material based on natural rubber at about 60 p per kg.

One disadvantage is that because of its low density and requirement for expansion, the elastomer flywheel occupies more space than an equivalent conventional machine.

For a continuous extraction of some 80% of its stored energy in the optimal range, the elastomer flywheel displays a speed increase (122 rads/s to 129 rads/s) before returning to 122 rads/s. Conventional flywheels suffer a speed loss of more than 50% for 80% energy extraction. It also appears possible to absorb or release a discrete amount of energy at a constant frequency (speed) over a part of the speed range. To be of practical use in automobile applications the 10 Wh stored energy of this model would need to be increased to around 50 Wh so that a stack of 5 modules would provide 250 Wh. Two ways of achieving this are:
1. Increase the elongation beyond optimal 500%
2. Develop an elastomer with a specifically tailored Young's Modulus.

It might be expected that the elastomeric performance might be improved by the use of a stiffer material. However this has the effect of constricting the modified Hooke's Law region of the stress strain curve. Thus the special advantage of operating in that region - large change in energy for small speed variation - does not appear to be available with existing stiffer materials. Nevertheless because of the elastic energy component, a flywheel using one of these stiffer elastomers still has a better energy speed characteristic than conventional machines, and can store an acceptable amount of energy.

As in any flywheel energy store, the drag loss at atmospheric pressure will be significant. Potential erosion of stored energy could mean a steady power drain on the drive motor when it should be in neutral idling mode. Generally it is usual to run an energy store flywheel in an enclosure that is filled with a low density gas or evacuated to a pressure that allows the drag loss to be acceptably small. Other frictional losses common to all flywheel systems will be in the bearings. An additional loss in an elastomer system will come from its hysteretic behaviour on expansion and contraction 1-2% except for stiffer rubbers where the losses may be up to 10%.

The high speeds of conventional flywheels and their wide variation when charging and discharging necessitate some form of matching the driving and driven components of the system. For electrical power this is performed by a cycloconverter or an induction motor/generator requiring sophisticated control systems. The optimal operating mode of the elastomer machine at low speed and small speed variation should eliminate the need for such interfaces for some uses, allowing direct drive of a synchronous generator. The generator would operate as an induction motor when charging, the wound rotor being switched to become a field winding for power generation. It will be necessary to build into the flywheel design the right parameters to achieve frequency matching to the associated power supply.

Elastomer ejection system

The ability of elastomers to store large quantities of energy which can be recovered very quickly makes them attractive materials for propulsion devices. This article [107] is concerned with an elastomeric ejection system for launching torpedos. Such a system represents a large reduction in weight, a ten fold reduction in cost and superior acoustic properties to the conventional design. Another important benefit is that the elastomeric device can be situated in sea water outside the inner hull. The current concept for an elastomeric torpedo ejection system envisions a 2m diameter disc comprised of one or more plies with a total thickness of 20 cm. A small pump inflates the disc with seawater to a biaxial extension of 100%. With an anticipated 15 year lifetime, the elastomer will experience more than 10^3 inflation cycles. The purpose of the present study was to determine the material requirements for an elastomeric torpedo launcher. Most of these considerations are relevant to energy storage devices in general.

The main properties governing an elastomers performance in this regard are:

1. The magnitude of the recoverable energy which along with geometry governs the power.
2. The propensity of the rubber to creep which depletes the stored energy.
3. The failure properties which determines the devices lifetime.

For small strains, therefore linear behaviour, the elastic (stored) energy is proportional to the equilibrium modulus and all rubber theories indicate that this modulus is directly proportional to the crosslink density. Hence even at large deformations where stress is no longer proportional to strain one still expects a monotonic increase in recoverable energy with increasing concentration of network junctions.

Failure properties of rubber exhibit a maximum as a function of crosslink density. Beyond the low levels necessary for the mechanical integrity of the network, further crosslinking causes embrittlement due to the loss of energy dissipative mechanisms. Such mechanisms underlie the strength of an elastomer by alleviating stress concentration. The decrease in an elastomers durability with increasing modulus is seen in measurements of tensile strength, fatigue life, tear resistance and so on, although different failure properties differ in their quantitative dependency on crosslink density. In order to avoid excessive creep, practical elastomeric materials have crosslink densities beyond the level corresponding to the maximum failure performance. A compromise exists between the modulus and durability of an elastomer. Achieving higher levels of stored energy necessarily means a reduced mechanical lifetime.

Selection of a material for energy storage thus involves determination of the elastomer having the most favourable relationship between recoverable energy and failure properties. Tensile strength as a function of recoverable energy measured. At low strain the total crosslink density is high, yielding high modulus and recoverable energy. At higher strains mechanically labile ionic bonds dissociate, alleviating stress and delaying rupture. The ionic crosslinks can reform on removal of stress so high recoverable energy is reobtainable. Mechanical dissociation of ionic bonds is reflected in a substantial energy loss accompanying reversing deformations. Elastomers having ionic crosslinks were always observed to have higher hysteresis than the corresponding rubbers with only covalent linkages. The preferred compound for energy storage applications would offer the most recoverable strain energy for a given strength, the efficiency of the device will suffer if there is too high a proportion of ionic crosslinks.

Hysteresis is responsible for the toughness of elastomers. The relationship between hysteresis and failure properties have been proposed previously. The tenuous connection in this work between hysteresis and strength means the former is of importance in the launcher application only because it reduces the efficiency of the energy storage. The lability of ionic crosslinks is not good beyond hysteresis considerations. Reversible crosslink dissociation at extensions near to failure is desirable but even low stresses applied for an extended duration may disrupt the network bonds.

Creep resistance is important when the elastomer is to be maintained in an extended state. There are two aspects to creep: time dependent reversible creep transpiring under load, and permanent deformation effected by mechanical stress., the latter results in a permanent decline of the effectiveness of the energy storage system. Only unfilled elastomers with ionic crosslinks develop permanent set. This reflects dissociation of the ionic junctions whose reformation in the strained state prevents complete recovery of the original dimensions on removal of the stress. Therefore if the stressed state is to be maintained for extended periods, ionically crosslinked rubbers are ill suited for energy storage applications. The problem is aggravated when the material will be exposed to seawater or other polar diluents. Covalently crosslinked material should be suitable e.g. sulphur vulcanised natural rubber. The study found that in the absence of carbon black, the covalently crosslinked elastomers exhibited no permanent set or loss of energy storage capability after prolonged deformation. If the rubber is kept deformed for a period of time, creep will cause a decrement in the propulsion energy immediately available. This loss can be completely recovered by retraction and re-extension of the elastomer provided there has been sufficient time for recovery. In conclusion, the capacity for rapid recovery from large deformation allows even soft rubber to function as a high power energy storage medium.

Summary of the Properties of Regenerative Braking Systems

	Efficiency	**Capacity**	**Power**	**Complexity**
Flywheel	good	good	fair	poor
Hydraulic	fair	fair	good	fair
Batteries	good	poor	poor	good
Elastomeric	poor	fair	good	fair/good

Current Research Programmes

PNGV

The Partnership for a New Generation of Vehicles (PNGV) is a collaboration between the federal government and the United States Council for Automotive Research (USCAR) which represents Ford, Chrysler and General Motors [108]. It is intended to strengthen US competitiveness by developing technologies for a new generation of energy efficient and environmentally friendly vehicles. The partnership seeks to link the research efforts of eight participating federal government agencies and associated national laboratories with those of the US auto manufacturers in the pursuit of three specific interrelated goals:

1. Significantly improve national competitiveness in manufacturing
2. Implement commercially viable innovations from ongoing research on conventional vehicles.
3. Develop a vehicle to achieve three times the fuel efficiency of todays comparable vehicle.

Goal three is the most relevant and comprises energy storage, energy management, hybrids and fuel cells. Alternative fuels are significant in achieving this goal which aims to produce an 80 mpg family sedan.

The primary approaches to improving fuel economy are to increase the thermal efficiency of the propulsion system and to reduce the mass of the vehicle. On the basis of thermal efficiencies that are technically achievable, it is clear that engine improvements alone cannot meet the triple fuel economy goal. A combination of engine and vehicle improvements will be needed. The three pronged approach is aimed at:

- Converting fuel energy more efficiently
- Reducing the energy demands of the vehicle
- Implementing regenerative braking to recapture energy - energy storage devices such as advanced batteries, flywheels, ultracapacitors.

Considerable research efforts are devoted to exploring the potential of hybrid vehicles which would combine an advanced engine with an electric motor and energy storage. Hybrid propulsion offers several key advantages over conventional systems: reduced engine size and increased engine efficiency (combined with lower emissions) due to the contribution of high power energy storage devices (flywheels, ultracapacitors or batteries) to provide transient power. Regenerative braking will be used in hybrids to recover the energy currently dissipated as heat in conventional braking systems.

FLEETS

A European initiative known as FLEETS (Friendly Low Energy Efficient Transport) involves 20 companies and organisations within the European Union aiming to create an efficient hybrid vehicle [109]. The first goal is to produce a transit bus. The research is being led by MIRA (Motor Industry Research Association in the UK).

THRIVE

Finally, a collaborative venture between Hawtal Whiting and Sheffield City Polytechnic began in 1991. The Hybrid Research Integrated Vehicle and Emission Programme (THRIVE) aims to research, develop and build three prototype vehicles to meet the Californian ULEV regulations [3]. Production was scheduled for early 1995.

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