Braking Energy Regeneration using hydraulic systems

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Abstract

With the increase of petrol cost, due to decrease of natural resources, and the necessity of "environmental friendly" solutions, for example, to accomplish the governmental gold's with protocol of Kyoto, we have assisted in the last decade, to the raise of new technologies that use another kind of source to make cars move.

In this way, it is natural that investigators development investigations for alternative systems and also companies, with focus in automotive industry, put in the market revolutionary solutions for cars that help saving money with the fuel and are less aggressive for the environment.

This paper is about one of those technologies, the Braking Energy Regeneration using hydraulic systems or as we can say the Hydraulic Hybrid system. It describes the state of art of this mechanism, how Hydraulic Hybrid work, the benefits, the costs, the possible configurations and gives a prevision of the future of this new technology. His given also one example of a real implementation, the UPS delivering trucks, and his referenced also an investigation work.

1. Introduction

Fossil fuel reserves, petrol in special, are becoming increasingly scarce around the world with rapid economical development of poor countries, which greatly influences petrol prices in areas all over the world. Not only that, but burning fossil fuel increases the pollution of the planet, thus accelerating the climate change and the global warming effects that are now on the verge of taking over the Earth.

There are a lot of alternatives to internal combustion engines, which could decrease the gas prices and reduce the pollution. For example, fuel cell vehicles with run on hydrogen and emit only water vapor. Another example is Biofuel vehicles, they run on fuel made from plant materials. Electric vehicles can run on rechargeable batteries, and some of the most popular hybrids today combine traditional internal combustion engines with alternative power plants, such as electric motors.

In spite of this last kind of vehicles offer a good way to increase fuel economy and help reducing the pollution, they're not perfect, as we will see next.

Another hybrid option has been put forth and tested by a number of businesses, as well as the American Environmental Protection Agency (EPA): hydraulic hybrids. Hydraulic hybrids use many of the same principles as electric hybrids, but instead of using potentially pollutive (and heavy) batteries, they use a Braking Energy Regeneration using a hydraulic system, this system is compose of lightweight components and clean fluid to power the vehicle while it's at slow speeds.

Our work will try to describe how the Braking Energy Regeneration works in the Hydraulic Hybrid vehicles and show their benefits and their disadvantages when compared with the other kind of vehicles that are "environment friends".

2. Regenerative braking

Conventional braking systems use friction to counteract the forward momentum of a moving car. As the brake pads rub against the wheels (or a disc connected to the axle), excessive heat energy is also created. This heat energy dissipates into the air, wasting up to 30% of the car's generated power.[1] Over time, this cycle of friction and wasted heat energy reduces the car's fuel efficiency. More energy from the engine is required to replace the energy lost by braking.

On a hybrid that has regenerative brakes, you can reclaim some of this energy that would normally be lost due to braking using the vehicle's inertia. During braking the kinetic energy is transferred to a hydraulic accumulator (blue) and immediately used when accelerating again (light blue).[2]

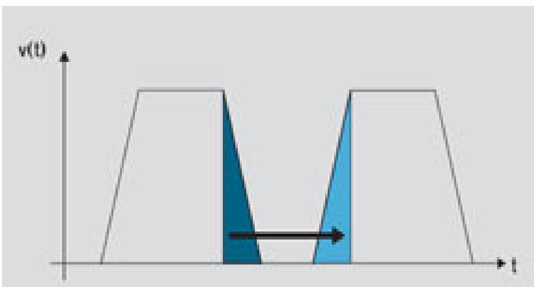

Figure 1 – Cycle of energy

Inertia is the fundamental property of physics that is used to reclaim energy from the vehicle. This property basically explains what makes something difficult to start moving and what makes something hard to stop moving.

Instead of using 100% of the foundation brakes of the vehicle, which are the friction brakes, we now let the linkages back to the motor such as the drive shafts, chains, and gears transfer the torque from the wheels back into the motor shaft.

Regenerative braking takes energy normally wasted during braking and turns it into usable energy. It is not, however, a perpetual motion machine. Energy is still lost through friction with the road surface and other drains on the system. The energy collected during braking does not restore *all* the energy lost during driving. How much energy you can reclaim depends on a lot of factors. There are different regeneration theories and designs, which fall into two groups: one being called parallel regen and the other called series regen, which are different from the parallel and series hybrids. These regen groups strictly are design topologies for braking systems. It also matters how many wheels you are using to reclaim energy. Most vehicles to date are front wheel drive so you can only reclaim energy from the front wheels. The back wheels still waste energy to standard friction brakes unless they are somehow connected back to the drive shaft. But in the overall the Regenerative braking improve the energy efficiency.[1,2]

2. Types of Hybrids

Gas/electric hybrid cars are popular, with many companies like Toyota or Honda offering hybrid models or versions of their models with hybrid drivetrains. This type of vehicles uses both gasoline engines and electric motors powered by lithium ion batteries to move the car. These batteries get charged though a process called regenerative braking. When a car brakes, two pads squeeze the wheel, which causes friction, slowing the wheels and stopping the car. But that friction is also energy, energy that's lost when a conventional car brakes.

When a gas/electric hybrid brakes, that friction is captured and used to charge the battery. The battery then powers the electric motor. But the electric motor in most cars isn't very powerful and only moves the car at slow speeds. In most hybrid models, once the car hits 30 to 50 Km/h, the gas engine will stop and the car work like a usual one.

Using an electric motor at slow speeds means gas/electric hybrids cut down on the amount of fuel they use and the emissions they release into the air. Besides use the regenerative braking energy, the Hydraulic Hybrid has another system to drives the car at low speeds.

Hydraulic Hybrids use three main components to power a vehicle at slow speeds and to augment the gasoline engine. Fluid is stored in a low-pressure reservoir. A pump moves the fluid from the reservoir to a high-pressure accumulator. The accumulator holds not only the fluid brought over by the pump, but also pressurized nitrogen gas.

These three components work together, but to get things started, they need energy. Like gas/electric hybrids, that energy is gathered through regenerative braking. As the vehicle slows, the pump is activated, and moves fluid from the reservoir to the accumulator. As pressure in the accumulator builds, it acts like a fully charged battery in a gas/electric hybrid, ready to power the electric motor.

But here's where hydraulic hybrids differ even more from gas/electric hybrids: Instead of sending power to the electric motor, which then sends it to the driveshaft (the part of the car which sets the wheels in motion), the accumulator sends its energy (in the form of nitrogen gas) directly to the driveshaft. As that happens, the vehicle accelerates, and the pump moves the fluid back to the reservoir, ready to charge the accumulator again.[3]

4. Parallel hydraulic hybrids

There are two ways those components can be coupled with a vehicle. The first, a parallel hydraulic hybrid, simply connects the hybrid components to a conventional transmission and driveshaft. While this allows the system to assist the gasoline engine in acceleration (when the gasoline engine is working its hardest), it doesn't allow the gasoline engine to shut off when the vehicle isn't in motion. That means the vehicle is always burning gas (unlike gas/electric hybrids, which have engines that shut off at slow speeds or during a stop). This is the main disadvantage, when directly compared with the gas/electric hybrids, but, in spite of this, according with EPA, the parallel hydraulic system does have significant benefits, including a 40 percent increase in fuel economy. Though not in widespread use yet, parallel hybrid systems could be added to regular vehicles. As it is now, however, most parallel hydraulic vehicles are built with the system in place and are used in heavy-duty delivery vehicles, not passenger cars. [3,4,5,6]

The next figure demonstrates the high pressure accumulator storing energy during the brake process.

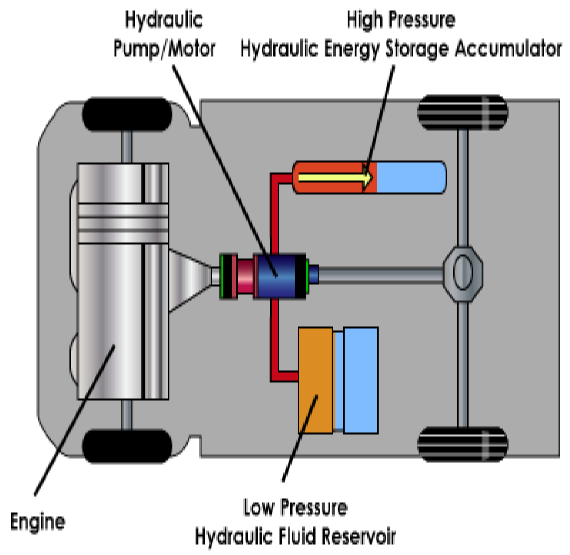

Figure 2 – Storing energy in Parallel Hydraulic Hybrid

This figure demonstrates the inverse, the high pressure accumulator releasing energy during the accelerate process.

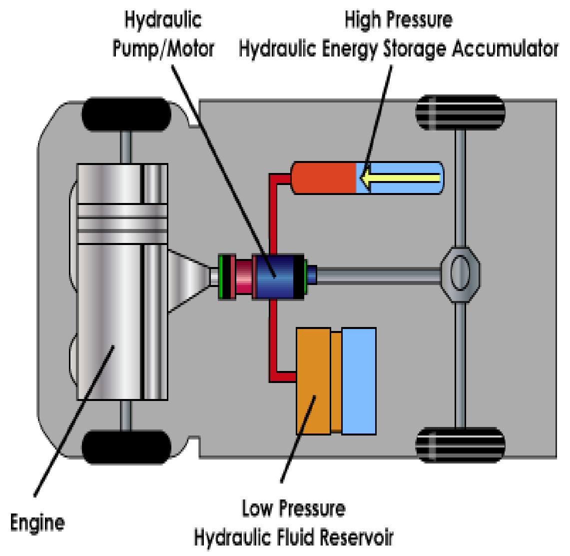

Figure 3 – Releasing energy in Parallel Hydraulic Hybrid

5. Series hydraulic hybrids

Series hydraulic hybrid systems use the same process as parallel, but don't use a conventional transmission or driveshaft and transmit power almost directly to the wheels. As we discussed before, reducing the number of components energy has to pass through before hitting its target makes it more efficient. Because the hydraulic system itself is turning the wheels, not a regular transmission or driveshaft, the vehicle's gasoline engine can be shut off, resulting in even more fuel savings. With the added efficiency and the ability to shut off the gasoline engine, series hydraulic hybrids are estimated to improve fuel economy by 60 to 70 percent, and lessen emissions by as much, according with NextEnergy. [3,4,5,7]

The next Figure demonstrates de process in this case.

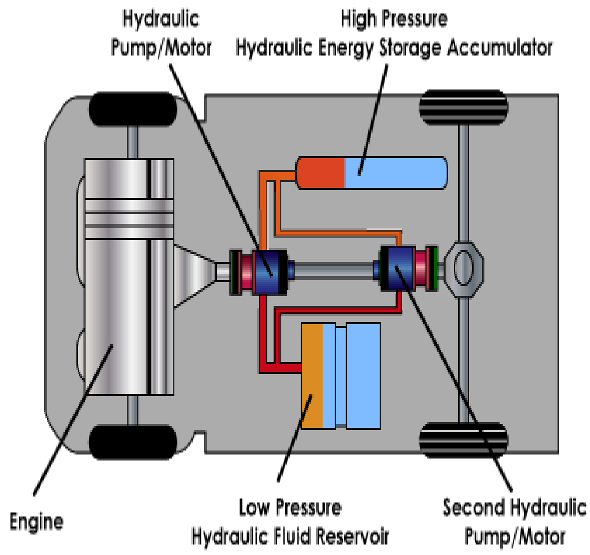

Figure 4 – Storing and realising energy in Serie Hydraulic Hybrid

Series hydraulic hybrids are already on the road today. In 2005, the EPA announced that it had partnered with UPS and Eaton Corporation - Fluid Power to create a number of series hydraulic hybrid-powered trucks for UPS. The trucks look like regular UPS delivery vans, but have a series hydraulic hybrid propulsion system.

6. Hydraulic Launch Assist™

The Hydraulic Launch Assist™ or HLA® System [4,5], is a parallel hybrid hydraulic regenerative braking system developed by EATON.

This system is capable of recovery the majority of the energy normally wasted as heat during braking and uses it to supplement the engine's power during acceleration.

The HLA returns more benefits when applied to vehicles that have cycles of driving with lots of stops and go's.

EATON offers two types of HLA depending of the type of duty applications the vehicle is destiny to do:

-Light & Medium Duty Applications

-Heavy Duty Applications

The major difference between then in components aspect is that the HLA for Heavy Duty Applications don't have a low and a high reservoir, instead he only have a high pressure reservoir, and a second reservoir.

Light & Medium Duty Applications

The HLA for Light & Medium Duty Applications was design for city transit bus, shuttle bus, and package delivery vehicles.

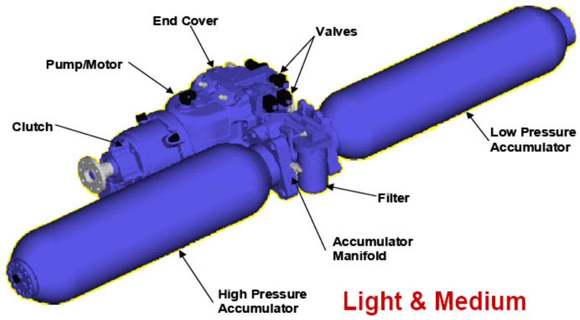

Figure 5 – HLA for Light & Medium Duty Applications

The HLA have two distinct stages, the regeneration stage, when the system accumulates energy and the Launch Assist Mode stage, when this energy is used.

Regeneration Mode

During braking, the vehicle's kinetic energy drives the pump/motor as a pump, transferring hydraulic fluid from the low pressure reservoir to the high pressure accumulator. The fluid compresses nitrogen gas in the accumulator and pressurizes the system

Launch Assist Mode

During acceleration, fluid in the high pressure accumulator is metered out to drive the pump/motor as a motor. The system propels the vehicle by transmitting torque to the driveshaft.

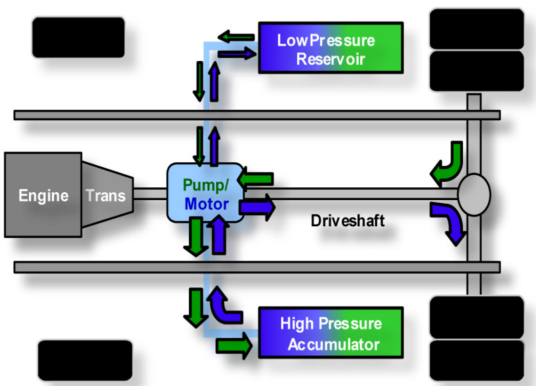

Figure 6 – HLA cycle

This system presents as major advantages the:

Fuel Economy: The HLA system delivers 17-28% better fuel economy during refuse collection

Environment: Reduces emissions of NO_x, particulates, and CO_2

Performance: Provides more torque for quicker acceleration and shorter cycle times

Maintenance: Greatly increases brake life and extends service intervals for engine and transmission.

This advantages was proven on test done to a class 2 truck [8].

EPA City Cycle	HC	NOx	CO	CO_2	FE
4.0L V8, 4R70W trans. (no HLA)	0.139	3.31	2.59	650	13.6
4.0L V8, 4R70W trans. (w/HLA)	0.11	2.33	1.75	528	16.8
Improvement	21%	30%	32%	19%	23.5%
OEM City Cycle					
4.0L V8, 4R70W trans. (no HLA)	0.17	4.68	3.69	801	11.0
4.0L V8, 4R70W trans. (w/HLA)	0.147	2.79	2.07	594.8	14.9
Improvement	14%	40%	44%	26%	35.5%

Figure 7 – Results of Class 2 Truck tests

This test demonstrated decreases in the gases release to the atmosphere and an increase in the fuel efficiency.

Heavy Duty Applications

The HLA for Heavy Duty Applications was develop is focusing on solid waste compaction (refuse) trucks.

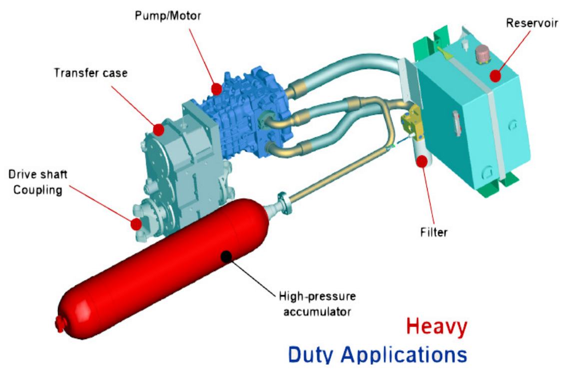

Figure 8 – HLA for heavy Duty Applications

The system for heavy duty application works similar to the previous one. We have still a Regeneration mode and a launch assist mode that works almost the same with the difference refer before, we don't have a low pressure reservoir.

In the regeneration stage when the vehicle brake , the kinetic energy drives the pump/motor as a pump introducing hydraulic fluid that is in the reservoir to the high pressure accumulator The fluid compresses nitrogen gas in the accumulator and pressurizes the system.

When the vehicle accelerates (Launch Assist Mode) the fluid in the high pressure accumulator is metered out to drive the pump/motor as a motor. The system propels the vehicle by transmitting torque to the driveshaft.

Is important to refer that the HLA, for heavy Duty Applications, have two modes of working, an economy mode and a performance mode.

The economy mode prefers the fuel economy to acceleration and productivity.

The performance mode increases the vehicle acceleration and the productivity butt reduces the fuel economy.

EATON developed a test on a Class 8 Refuse Truck and the results are presented next. [11]

	Actual Results 100ft Stops
Economy Mode	
Fuel Economy Improvement	28%
Vehicle Acceleration	2%
Productivity (Cycle Time Improvement)	NA
Brake Savings	51% (J)
Performance Mode	
Fuel Economy Improvement	17%
Vehicle Acceleration	26%
Productivity (Cycle Time Improvement)	11.50%
Brake Savings	51% (J)

Figure 9 – Class 8 Refuse Truck Test Data

The results show for a test that the truck have to stop 30m on 30m we can save a lot of fuel in both modes and we can save 51% of the brakes, or in another words the breaks last two times more.

7. A REAL CASE: THE UPS HYDRAULIC HYBRID

As we said in chapter before, in 2005 EPA made a partnership with the delivering company UPS. The benefits of this partnership are demonstrated in this chapter.

As we explained before, the hydraulic hybrid system gets its power through regenerative braking. That means that, flying down the highway, a hydraulic hybrid isn't much different than a regular car. But in traffic, particularly stop and go traffic, a series hydraulic hybrid can shut its engine off and use hydraulic power alone. Stopping and starting is the key to saving fuel with a hydraulic hybrid.

The system used in this truck is a series hydraulic hybrid.

In this type of system the driveline is replaced by the hybrid system. The transmission is removed and energy is transferred from the engine to the drive wheels through fluid power.

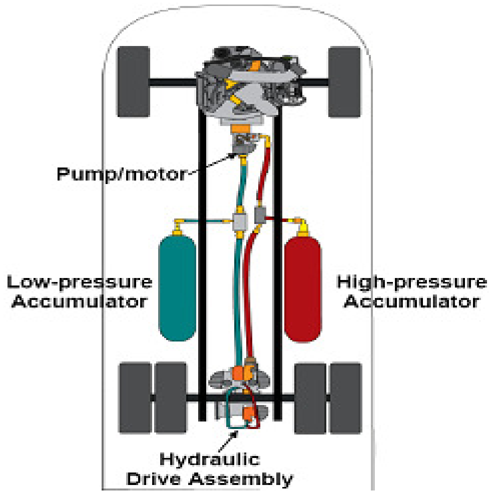

Figure 10 – Series Hydraulic Hybrid UPS Truck

The value proposition is provided by operating the engine at a “sweet spot” of best fuel consumption facilitated by the CVT functionality of the hybrid system

-regeneration of braking energy

-shutting the engine off when not needed

-Fuel economy improvements with this technology are significantly higher than those attainable by the HLA system.

Figure 11 – An example of a UPS Hydraulic Hybrid truck

UPS trucks go from one stop to the next, often in urban traffic, and are rarely used on the highway.

This vehicle was first shown publicly in June 2006.

The series hybrid hydraulic UPS truck demonstrated 50-70% better fuel economy than a standard UPS truck over the EPA City Cycle with no degradation in performance.

A UPS truck equipped with the series hybrid hydraulic drivetrain was placed in service in the Detroit area and achieved 45-50% better fuel economy in "real world" use.

The EPA estimates that CO2 emissions from hydraulic hybrid UPS trucks are 40 percent lower than conventional UPS trucks, and a fleet of trucks could save 3785 liters of fuel a year. The EPA also estimates that with less maintenance than a gas/electric hybrid and less fuel then a conventional truck, UPS could save up to $50,000 over the lifespan of each hydraulic hybrid truck.

8. INVESTIGATION WORK

Bin Wu, Chan-Chiao Lin, Zoran Filipi, Huei Peng and Dennis Assanis developed a methodology for developing a power management strategy tailored specifically to a parallel Hydraulic Hybrid Vehicle (HHV) configured for a medium-size delivery truck. [1]

An International 4700 series, Class VI 4x2 truck is selected as the baseline for this work. The conventional truck has a mass of 7340 kg when fully loaded.

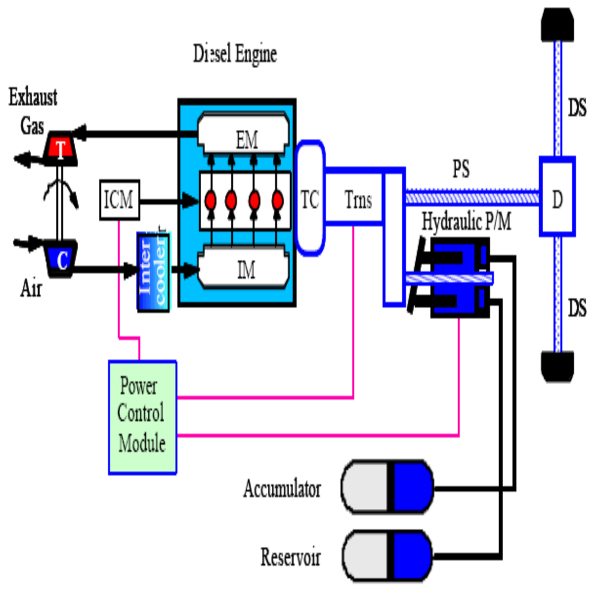

Figure 12 –Schematic of the developed system

This rear-wheel-drive hydraulic hybrid truck has two power sources. The primary power source is the same diesel engine used in the conventional truck, which is a turbocharged, intercooled.

The Torque Converter (TC), Transmission (Trns), Propeller Shaft (PS), Differential (D) and Driving Shaft (DS) are the same as those in the conventional truck. The hydraulic pump/motor is located behind the transmission for more effective regeneration during braking. The hydraulic pump/motor is coupled to a propeller shaft via a transfer case with the gear ratio of two.

The assistant power source is an axial piston pump/motor (P/M) with variable displacement. The hydraulic displacement per revolution can be adjusted via inclination of the swash plate to absorb or to produce desired torque. When pumping, hydraulic fluid flows from the low -pressure reservoir to the high-pressure accumulator; when motoring, hydraulic fluid flows in the reverse direction.

The accumulator contains the hydraulic fluid, and inert gas such as Nitrogen (N2), separated by a piston. When hydraulic fluid flows in, the gas is compressed, and its internal energy is increased. When discharging, fluid flows out through the motor and into the reservoir. The reservoir can be regarded as an accumulator working at much lower pressure (e.g. 8.5 bar to 12.5 bar). The State of Charge (SOC) is defined here as the ratio of instantaneous fluid volume in the accumulator over the maximum fluid capacity, thus SOC=0 corresponds to accumulator being empty, and SOC=1 to accumulator being full.

The foundation for modeling the HHV system was the simulation of the conventional truck, previously developed at the University of Michigan Automotive Research Center. The model is implemented in the MATLAB/SIMULINK and named Vehicle-Engine SIMulation (VESIM). It has been validated against vehicle data measured on the proving ground.

For development of this methodology it was been utilized the Dynamic Programming (DP). DP is a numerical methodology developed for solving sequential or multi-stage decision problems. The algorithm searches for optimal decisions at discrete points in a time sequence. It has been shown to be a powerful tool for optimal control in various application areas.

The results of forward-looking DP optimization are used to extract sub-optimal rules for power splitting and gearshifting, implementable in the practical controller. The new rules differ significantly compared t o typical strategies for hybrid electric vehicles, and enable frequent use of the hydraulic motor as the sole power source during acceleration. This forces its operation at high-loads/moderate-speeds, a combination providing highest efficiency. In addition, aggressive use of the motor for vehicle acceleration often depletes the accumulator charge, thus preparing the system for the next regeneration event. Depending on the efficiency of the particular hydraulic pump/motor, the practical control strategy derived from DP results enables fuel economy increase of the HHV truck over the conventional counterpart between ~28% and ~48%.[9]

9. Conclusion

In spite of the major benefits of the Hydraulic Hybrid systems, we won't see them in our cars soon, at least with series Hydraulic Hybrid. No major automaker has plans to build hydraulic hybrid passenger cars. The reason for that is the electrical system in a car. Modern cars have a number of electrical systems to power things like the radio or air conditioner. Those systems are powered by a conventional car's battery which gets charged by the car's gasoline engine. If the engine shuts off and the electronics stay on, the battery gets drained.

In gas/electric hybrids, the extra batteries can keep the electrical components running while the engine is shut off at a stop. Hydraulic hybrids, however, lack the extra batteries needed to power electrical systems when the engine turns off. While that's not a big deal for parallel hydraulic hybrids, since their engines don't shut off when the vehicle stops, it is a big deal for series hydraulic hybrids. While they offer the best fuel efficiency, they can't power a radio or air conditioner when the vehicle stops.

And to introduce an maximum fuel economy the vehicle applications have to do a lots of stop and go’s, the graphic shown next demonstrate the best applications for the regeneration system[10].

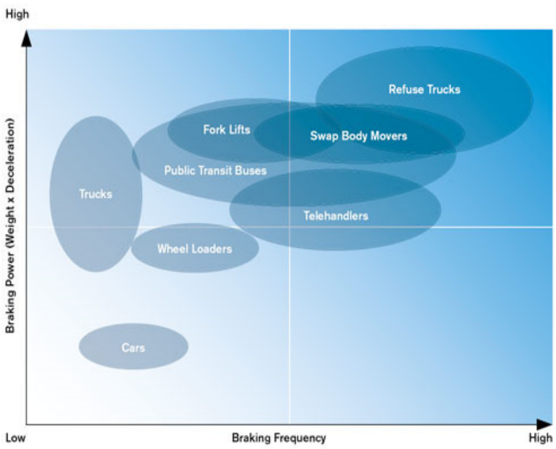

Figure 13 –Ideal application

This is one of the main reasons that this system is not in our cars this days, the price we have to pay is high for a slow increase of fuel economy, but for a refusal truck then we can have 2 /3 Year Payback of the money invested [11] and that’s the main reason that company’s who use a lot of refuse trucks have introduce this system in their trucks.

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