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SESSION
“TRANSPORT. SAFETY AND ECOLOGY. LOGISTICS AND MANAGEMENT

SESSION
“TRANSPORT TECHNIQUES. INVESTIGATION OF ELEMENTS. VEHICLE ENGINES”

Fuel economy of off-road vehicles in respect to recuperation of vehicle's kinetic energy

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Abstract: *Since the fuel-saving idea was introduced in the 20th century, energy efficiency has gained attention in the transport industry. Ground vehicles (military, agricultural, and construction) usually operate on unprepared ground and need to overcome very complex and difficult ground obstacles, such as steep grade and very soft ground. The electrification of conventional vehicles, ranging from passenger vehicles and trucks to ground vehicles such as agricultural tractors, construction equipment and military vehicles, can potentially offer improvements in fuel economy and emissions. Applied new systems reduce the amount of mechanical energy needed by the thermal engine by recovering the vehicle kinetic energy during braking and then assisting torque requirements. Energy management strategies for off-road vehicles are studied in this paper. With heavily fluctuating fuel prices, the total cost of ownership of loaders, excavators, and other classes of ground vehicles is nowadays strongly influenced by the fuel costs and there is growing concern about* CO_2 *emissions as well as about the long-term availability of fossil fuels.*

Keywords*: ENERGY EFFICIENCY, REGENERATIVE BRAKING, ELECTRIFIED, HYDRAULIC, BRAKING SYSTEM*

1. Introduction

The global energy landscape is changing. Traditional centers of demand are being overtaken by fast growing emerging markets. The energy mix is shifting, driven by technological improvements and environmental concerns. A central feature of the energy transition is the continued gradual decarbonization of the fuel mix. Rapid improvements in the competitiveness of renewable energy mean that increases in renewables, together with nuclear and hydro energy, provide around half of the increase in global energy out to 2035. Natural gas is expected to grow faster than oil or coal, helped by the rapid growth of liquefied natural gas increasing the accessibility of gas across the globe. Oil demand continues to increase, although the pace of growth is likely to slow as vehicles become more efficient and technological improvements, such as electric vehicles, autonomous driving and car sharing, potentially herald a mobility revolution.

The Fig. 1 shows the pattern of oil discovery, listing all of the major plays that have dominated oil production. Hybrid vehicles are just one of a number of solutions suggested by the transport industry to reduce dependency on oil and harmful GHG emissions. "Hybrid" has its origin in the Greek language and means: "Mixture or combination of two things." The most common hybrid technologies are electric and hydraulic hybrids. The number of electric cars rises significantly, from 1.2 million in 2015 to around 100 million by 2035 (6% of the global fleet). Around a quarter of these electric vehicles (EVs) are Plug-In Hybrids (PHEVs), which run on a mix of electric power and oil, and three quarters are pure Battery Electric Vehicles (BEVs) [1].

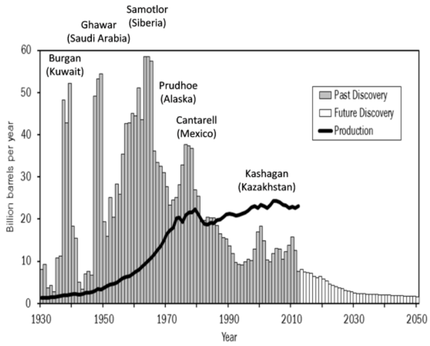

Fig. 1 *Actual and projected worldwide discovery, extraction and demand for conventional oil (From 1930 to 2050 in billions of barrels)[2].*

Hybrid vehicles are called hybrids because they use both an internal combustion engine (ICE) and an electric motor to obtain maximum power and fuel economy with minimum emissions. What all hybrids have in common is the ability to generate electric current, store it in a large battery, and use that current to help drive the car. Hybrids have regenerative braking systems that generate electric power to help keep the batteries charged. When the driver applies the brakes, the electric motor turns into a generator, and the magnetic drag slows the vehicle down. For safety, however, there is also a normal hydraulic braking system that can stop the car when regenerative braking isn't sufficient. There's no difference in maintenance or repair except that the brake pads tend to last much longer because they don't get used as much. The big difference is that regenerative brakes capture energy and turn it into electricity to charge the battery that provides power to an electric motor. Hybrids can also conserve energy by shutting down the ICE when the vehicle is in Park, idling at a light, or stopped in traffic, or when the electric motor's energy is sufficient to drive the vehicle without assistance from the ICE [3].

Regenerative braking has many advantages: emission of carbon dioxide is reduced in the environment; overall performance of the system is increased; during braking most of the heat is converted into useful mechanical energy; engine life enhances; wear of engine is reduced; due to reduction in brake wear, the life span of the friction braking system increases, but has also limitations: regenerative braking system is more complexes; overall weight of the vehicles increases due to the assemble of extra components; higher maintenance is required; for safety purpose friction brake is necessary, in case failure of the regenerative brake system; the size of energy stores mainly depend upon size of vehicles.

It is important to analyze the efficiency of power trains of electric and hybrid electric powered land vehicles to compare them with canonical combustion engines, both in a tank-to-wheels basis and a well-to-wheels basis. One of the question formulations is if an electric or plug-in hybrid electric vehicle charged by public electricity generated by a fossil plant will result in any environmental alleviation at all, in excess of reducing the local tailpipe pollution [4].

An off-road vehicle is any ground vehicle which does not, in general, use normal roads for its operation. Examples of such vehicles include predominantly construction vehicles and equipment, mining vehicles, agricultural vehicles like tractors, and so on. Some military vehicles also fall into this category. Off-road vehicles to be discussed in this section have quite different drive cycles and speed–torque demands, compared to a regular automobile [2].

With heavily fluctuating fuel prices, the total cost of ownership of loaders, excavators, and other classes of ground vehicles is nowadays strongly influenced by the fuel costs. Moreover, there is growing concern about CO_2-emissions caused by the burning of fossil fuels as well as about the long-term availability of these fuels. The fuel economy and efficiencies of the drive train and the hydraulic implements have therefore become extremely important parameters in the design of future ground vehicles. Hybrid transmissions are now considered to be a solution for ground vehicles. Furthermore, hybrid electric vehicles need sophisticated electric transmissions with delicate and expensive inverters, converters, and batteries. Taking the extreme power transients in mobile machinery and the rough operational conditions of off-road drive trains into account, it is questionable whether the delicate hybrid electric drive trains can be considered a viable, inexpensive, and robust option for ground applications. Yet, there is still the alternative of the hydraulic hybrid drive train-a full series hybrid system with an in-wheel motor in each wheel and hydraulic transformers for efficient power control. For military vehicles, the drivers for hybrid electric vehicles are quite different; although the fuel economy remains a desirable feature for both the commercial and military sectors. The military needs for hybrid electric reside in their ability to generate significant level of electric power onboard the vehicles to meet the demand of the warfighter thus expanding his mission capabilities in terms of mobility, survivability and lethality. However, the fielding of hybrid electric military vehicles has been much slower than the commercial vehicles due to the technical challenges that must be overcome before the hybrid technology can be considered viable for military applications [5].

EVs have penetrated the market of off-road vehicles successfully over the years for clean air as well as for cost advantages. Examples of such applications are airport vehicles for passenger and ground support; recreational vehicles as in golf carts and for theme parks, plant operation vehicles like forklifts and loader trucks; vehicles for disabled persons; utility vehicles for ground transportation in closed but large compounds; etc. There are also EVs that run on tracks for material haulage in mines. There is potential for EV use for construction vehicles. The locomotives that run on tracks with electricity supplied from transmission lines are theoretically no different from other EVs, the major difference being in the way energy is fed for the propulsion motors [6].

This paper presents different configurations of hybrid vehicles to improve the braking energy regenerated potential and engine work efficiency. From the results obtained we try to draw a conclusion on the difference in energy recuperation level in the major strategies with consistent pedal feel in mind.

2. Fuel savings for ground vehicles

Ground vehicles (military, agricultural, and construction) usually operate on unprepared ground and need to overcome very complex and difficult ground obstacles, such as steep grade and very soft ground. Depending on the functional requirements, different criteria are used to evaluate the performance of various types of ground vehicles. For tractors, their main function is to provide adequate draft to pull various types of implement and machinery: drawbar performance is of primary interest. This may be characterized by the ratio of drawbar pull to vehicle weight, drawbar power, and drawbar efficiency. For ground transport vehicles, the transport productivity and efficiency are often used as basic criteria for evaluating their performance. For military vehicles, the maximum feasible operating speed at two specific points in a given area may be employed as a criterion for evaluation of their agility [7].

2.1. Mechanical regenerative braking

Improvements of truck fuel economy are being considered using a flywheel energy storage system concept (KERS-Kinetic Energy Recovery System). This system reduces the amount of mechanical energy needed by the thermal engine by recovering the vehicle kinetic energy during braking and then assisting torque requirements. The benefits of flywheel based KERS are similar to hydraulic regenerative braking but with the advantage of reduced complexity, less space needed and simpler construction and operation. The cost as well as the packaging and weight of a KERS for truck are not an issue as in passenger car applications. Two counter rotating flywheels could possibly solve the stability issue due to the increased rotating mass required for braking vehicles of considerable weight.

The energy boost by KERS may be beneficial more to help trucks climbing hills rather than for engine downsizing, also providing a better road safety. KERS will also collect considerable energy braking down hills reducing the need for engine brakes and thus noise. Boretti [8] summarizes the computed fuel economy benefits of KERS.

2.2. Hybrid-electric ground vehicles

The idea of hybrid-electric drive is based on maximizing the energy efficiency of fuel. In the classical drive the energy disappears by transforming into the heat in all drive components from the fuel tank to the drive wheels of vehicles, and most in the internal combustion engine that converts chemical energy of fuel into useful work. The causes of this are numerous, but one of the biggest is that the engine is running in a very wide range of number of revolutions and loads while working with varying degrees of efficiency ratio.

Fig. 2 *Diagram of the relative fuel consumption of a typical internal combustion engine and the paths of energy through a typical gas-powered vehicle in city driving [9].*

Figure 2 shows the relative fuel consumption of a typical ICE and the paths of energy through a typical gas-powered vehicle in city driving. If, for example, the engine delivers 100 kWh of energy from areas of least fuel consumption, it will be spent 22 liters of fuel, and if that same energy draws out from the area of the engine works at low load, it will be spent up to two or even three times more fuel. If the engine could keep the regimes of minimum consumption, which means a load of more than 50% and the number of rotation around the maximum torque, then you could save a considerable amount of fuel for the same usable energy. This is not possible in a classical drive chain (motor-transmission-wheels). It is necessary, therefore, to separate the engine physically from the drive wheels and to establish a completely different structure of the propulsion system, in order to achieve full control of engine operating modes according to the number of rotation and load [9].

There are three basic types of hybrid-electric drive: serial, parallel and plug-in (Fig. 3). A series hybrid uses a gasoline or diesel ICE, coupled with a generator, to generate electricity but not to drive the car. The engine can send the electric current directly to the electric motor or charge a large battery that stores the electricity and delivers it to an electric motor on-demand. The electric motor propels the vehicle, using its power to rotate a driveshaft or a set of drive axles that turn the wheels.

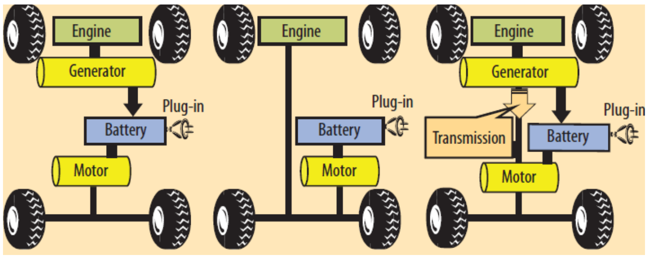

Fig. 3 *The basic structure of serial, parallel and plug-in hybrid-electric drive.*

A parallel hybrid uses both an electric motor and an ICE for propulsion. They can run in tandem, or one can be used as the primary power source with the other kicking in to assist when extra power is needed for starting off, climbing hills, and accelerating to pass other vehicles. Because both are connected to the drive train, they're said to run "in parallel." Because plug-in hybrids feature larger batteries that can be charged at any ordinary electrical socket, they have the capacity to extend the ability of the electric motor to drive the car farther without the need for starting the ICE and therefore substantially increase the vehicle's fuel efficiency. Estimates have ranged as high as 100 mpg!

2.3. Hydraulic hybrid ground vehicles

Hydraulic hybrid technology has the advantage of high power density and the ability to accept the high rates/high frequencies of charging and discharging, therefore it is well suited for off-road vehicles and heavy-duty trucks. Relatively lower energy density and complicated coordinating operation between two power sources require a special energy control strategy to maximize the fuel saving potential. Kumar [10] has presented a new configuration of parallel hydraulic regenerative vehicle (PHRBV) to improve the braking energy regenerated potential and engine work efficiency. Based on the analysis of optimal energy distribution for the proposed PHRBV over a representative urban driving cycle, a fuzzy torque control strategy based on the vehicle load changes is developed to real-time control the energy distribution for the proposed PHRBV.

The HRB Hydrostatic Regenerative Braking System helps meet increasingly strict environmental regulations and reduces operating costs by saving fuel. The HRB system will provide superior return on investment. The HRB stores a vehicle's kinetic energy, which would otherwise be lost during mechanical braking operation. This energy is then available for powering the vehicle and reducing primary energy use. HRB, the hydraulic hybrid of Rexroth, reduces fuel consumption and CO_2 emissions from heavy commercial vehicles with a high stop & go frequency by up to 25 percent and brake wear by up to 50 percent. This helps to reduce environmental pollution and the total cost of ownership for the operator.

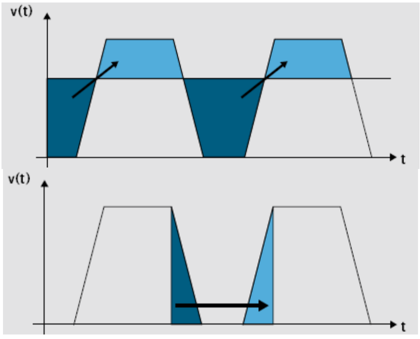

Fig. 4 *Characteristics of an electric hybrid and hydraulic hybrid [11].*

Characteristics of electric hybrid: Excess motor power is continuously accumulated in a battery over a longer time period (blue) and accessed as needed (light blue); High energy density and low power density: The battery can absorb a great deal of energy, but the charge time is relatively long, so it is not possible to fully recapture the braking energy; Energy is stored in batteries; Typically found in passenger cars.

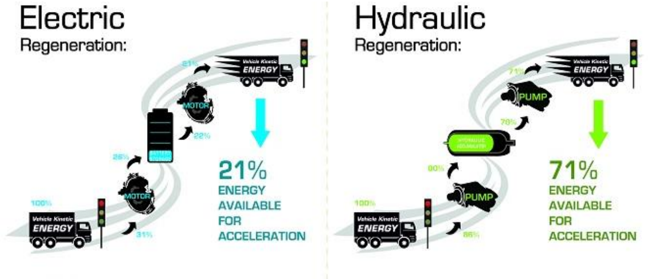

Fig. 5 *A comparison of electric and hybrid regeneration.*

Characteristics of hydraulic hybrid: The kinetic energy from braking is fed to a hydraulic accumulator (blue) and immediately reused for starting (light blue). Hydraulic hybrids are ideal for vehicles with frequent, short start-stop cycles, such as public transit buses, refuse trucks, forklifts, pneumatic tire rollers, telehandlers, swap body movers and much more; High power density and low energy density: there are limits to the amount of energy the system can accumulate. However, it takes less time to collect and store this energy, which can be called upon as needed. The full braking energy is then fed to a hydraulic accumulator and stored.

There is a common consensus that hybrid drive trains can strongly increase the efficiency of a drive train. However, the increased efficiency does not by itself result in a reduction of the fuel consumption or the cost of ownership. The electric drive train components result in an increased vehicle weight, which increases the fuel consumption of the vehicles. Moreover, the added cost for the electric components gives doubt about the cost-benefit-relationship, especially of the full hybrid drive train concepts. Nevertheless, the trend of hybrid electric transmissions has also come to the ground vehicles market. Achten & Innas [5] have proposed "Hydrid" drive and control system that enables the design of a new generation of off-road vehicles with a strongly reduced fuel consumption, while maintaining (or even improving) the productivity. The "Hydrid" completely eliminates the mechanical drive train, thereby creating extra degrees of freedom for the suspension and traction control of the vehicle. The "Hydrid" has hydraulic accumulators for energy storage and power management, hydraulic transformers for efficient power control, and highly efficient and compact in-wheel motors.

2.4. Military Applications of Hybrid Cars and Trucks

Implementing HEV technology in military vehicles offers a number of potential advantages. The possibility to generate an increased amount of electric power is one important advantage that addresses the immediate demand for ever more electric power onboard modern military vehicles. Other advantages may become equally important with time. There are, however, technical challenges related to specific subsystems (components) in a HE drivetrain and to the overall system and vehicle design.

The great interest in military HEVs suggests that it is an important technology for future military vehicles. Compared to a legacy military vehicle, a military HEV will be more complex and an increasingly multidisciplinary system. Given also the large variety of military vehicles, tracked or wheeled, from unarmed to heavy armed, and the relatively immature HE technology, no two systems are alike. It is therefore difficult to draw simple and universally valid conclusions. The relevant time frame also becomes very important. The most viable solution in the short term (5-7 years) might not be the same one as in the long term.

Model-based systems development for military ground vehicles is a key enabler for rapid prototyping and design optimization. Batteh & Tiller [12] have described flexible, modular vehicle model architecture in Modelica to support a range of systems engineering analyses of conventional and hybrid vehicle architectures throughout the product development process. The models and sample simulation results highlight the flexibility of the model architecture and the wide range of engineering analyses that can be supported.

In August 2007, the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) began full-load integration testing of the military's first hybrid electric drive propulsion system designed for combat vehicles [13]. Milner et al. [14] developed and validated a high-fidelity six-degree-of-freedom model to use in a trade study for the development of a prototype autonomous vehicle. The model was developed with extensive capabilities for evaluating both on-road and off-road vehicle performance while allowing the user to modify the components and simulation setup as desired. The model enables the user to assign any desired modifications to virtually all of the major vehicle and simulation parameters.

However, there are important technical challenges that need to be solved before we will see the successful fielding of a mass produced military HEV. A number of military HEVs have been successfully demonstrated, but there are still important limitation related to key technologies such as electric motors, power electronics and energy storage systems (e.g. batteries). The maturity of the technology depends on the vehicle type (role, weight, tracked or wheeled etc.) and the HEV drivetrain architecture opted for (series, parallel etc.) [15].

Combat vehicles can also have benefit from the hybrid-electric drives. Some of the most important are the following: Fuel savings- As with civilian vehicles and in combat and other vehicles for military purposes, narrowing the area of combustion engines can contribute to significant fuel savings (in some driving conditions even more than 50%). Fuel savings in military vehicles is important not only because of the fuel but also because there are other repercussions: simplifying and reducing costs of logistics, increasing the autonomy of the vehicles and so on. The issue of environmental protection is also not unimportant-lower fuel consumption means lower emissions and other toxic substances. Low acoustic signature of the vehicle-Hybrid-electric drive reduces the possibility of observing the vehicle through a lot of elements. One of the most important is that within the limits of available energy in batteries, the vehicle can be powered purely electrically powered, which means no noise, heat radiation and no emission gases. This ride can be of crucial importance in military operations. But even when the vehicle is driven in a combined operation, observing of the vehicles has been reduced because:

- IC engine runs at lower numbers of rotation, and there is no sudden changes, which means less noise,
- hydraulics for propulsion of the auxiliary systems to power the vehicle can be completely eliminated, thereby eliminating the noise of hydraulic pumps and motors, which is usually considerable,
- reduced noise from cooling fans and others.

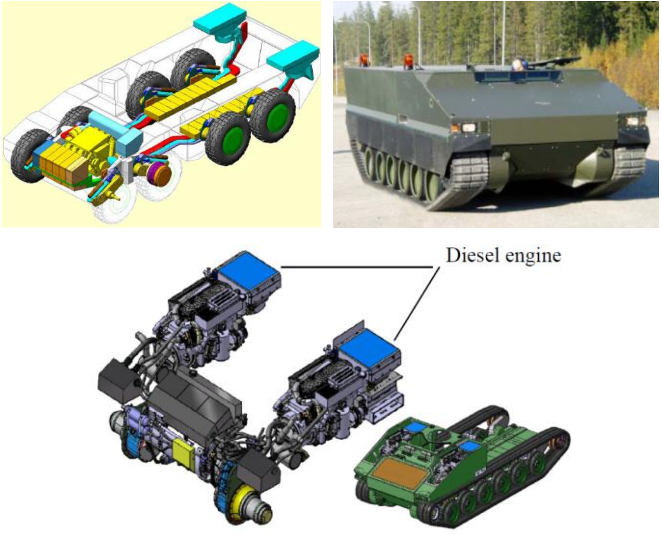

Fig. 6 *Hybrid Electric Combat Systems.*

With hybrid-electric drive, vehicle has electricity available in unlimited quantities that can be used to drive auxiliary devices, and other needs of the dome cars, and even for purposes outside the vehicle. New technologies of electric weapons and electromagnetic protection (EM shielding) are useless without a strong source of power supply. There are many other benefits of hybrid-electric drive as: modularity of the system easier to maintain, complete automation and control reduce the human factor and provide a better diagnosis, flexibility in the design of the propulsion system enables better use of space, and others [16].

3. Conclusion

Automotive engineers may be further ahead in applying hybrid technologies, but some of the most exciting hybrid innovations these days target off-road OEMs and makers of military, agricultural and construction vehicles. Regenerative braking is a major means of hybrid vehicle to reduce consumption of fuel and lower the environment pollution. Comparison of different solutions of hybrid ground vehicles in terms of the percentage of recuperated energy during the regenerative braking phase is done in this paper. The proposed hybrid drive and control system enables the design of a new generation of ground vehicles with a strongly reduced fuel consumption, while maintaining the productivity. Militaries worldwide are also interested in realizing the potential energy savings associated with hybrid vehicles. It is important to note that there are other potential payoffs associated with military hybrid vehicles: the ability to idle and possibly move without the acoustic and thermal signatures of an internal combustion engine. Regenerative braking that incorporates a hydraulic system has the advantage of high power density and the ability to accept the high rates/high frequencies of charging and discharging. This makes hydraulic regenerative braking technology well suited for off-road vehicles and heavy-duty trucks.

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