Final Report

Task XII - "Heavy-duty hybrid vehicles"

2007 – 2010

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Remark

Task XII “Heavy-duty Hybrid Vehicles” of the "Implementing Agreement for Hybrid and Electric Vehicles” (IA-HEV), functions within a framework created by the International Energy Agency (IEA). Views, findings and publications of Task XII do not necessarily represent the views or policies of the IEA Secretariat or of all its individual member countries.

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1 General Introduction Task XII

1.1 Participating countries

Heavy-duty vehicles encompass a wide diversity of applications and have specific technical requirements and economic boundary conditions compared to the passenger car market. Therefore, some members of the IA-HEV felt the need for setting up a specific Task on this topic.

Task XII focusing on heavy-duty hybrid vehicles was initiated and approved at the IA-HEV Executive Committee meeting in October 2006 and ran from January 1st, 2007 until November 30th, 2010.

Belgium, Canada, the Netherlands, and the United States have been participating in Task XII since 2007. Finland and Switzerland joined Task XII respectively in 2008 and 2010.

Figure 1: IEA-IA-HEV-Task XII : Participating Countries

1.2 Objectives and structure

Task XII reports on the current status of the heavy-duty hybrid vehicles "playing field." This status report will focus on the available and emerging hybrid vehicle technologies and on the current and expected state of the market of heavy-duty hybrid vehicles.

Task XII has been structured in three subtasks to collect and organize the required information.

The first -technology oriented- subtask aimed at structuring the information on heavy-duty hybrid vehicle components, systems and configurations. This subtask identifies and illustrates the technical requirements, especially highlighting where they are different from light-duty requirements, the available technologies and their characteristics, and the system integration requirements. Additionally, there is a focus on powertrain configurations (topologies) and powertrain strategies for high efficiency and low emissions.

The second -market oriented- subtask collects market information on heavy-duty hybrid vehicles. The current market of existing hybrid prototypes and standard vehicles needs to be investigated. The information gathering focused on the applied technology, as well as the costs and its merits in meeting customer expectations. In this way it complements the first subtask. This subtask will increase the insights into the applications where heavy-duty hybrids have been an effective solution and can thus provide essential information for future hybrid vehicle deployment projects. To address the potential of heavy-duty hybrid vehicles it is useful to identify niche applications that may benefit to a great extent from hybridization.

The third -dissemination oriented- subtask involves collecting and disseminating general information and promoting the Task XII objectives and results to a broad range of stakeholders. This has been done by setting up a dedicated website (http://ieahev.vito.be), preparing papers (e.g. EVS25), giving presentations at relevant conferences, and keeping up contact with relevant platforms by sharing information on heavy-duty hybrid developments.

All collected information has been organized in reports for the different subtasks and has been aggregated in this final end report. The end report has been presented to the IA-HEV Executive Committee in November 2011 at its 35rd meeting in Lisbon (Portugal).

1.3 Contact details of the Operating Agent

Research institute VITO is the Operating Agent of Task XII. Organizations that are interested in the work on heavy-duty hybrid vehicles are invited to contact the Operating Agent:

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2 Technologies

The end report is structured in such a way that it gives an overview on the status of heavy-duty hybrid vehicles, by starting to explain the existing or expected technologies available on the market.

This chapter will describe in detail the various types of advanced vehicle power trains available or being considered for use in heavy vehicles, the components of those power trains, the commercial systems available today as well as the tools and methods used to assess them, and, finally, some of the challenges associated with heavy hybrid technologies.

Following chapters will describe more in detail the market developments, the different applications and the potential benefits and barriers. But it is obvious that heavy duty vehicles play a critically important role in many nations around the world. In the United States, the trucking industry, for example, moves nearly 70% of all freight tonnage and nearly 75% of total freight value; in addition, this industry delivers products and services to 80% of communities (ATA 2009, Singh 2007, BTS 2009). Trucking businesses run on tight margins, and fuel costs directly affect their economics. Thus, advanced heavy vehicle technologies - such as hybrid electric vehicles that can reduce fuel consumption without compromising the utility of the vehicle - are of great interest. Furthermore, as nations address such issues as sustainability and global warming, or consider eliminating the use of certain vehicles in city centers, heavy trucks with clean, advanced power trains may become more prevalent. Companies may also find value in the green image that these technologies convey to the public.

If advanced vehicle technologies are to be used in the commercial sector, there must also be a value proposition. Some technologies are already penetrating the market, especially the transit bus and package delivery markets of the United States and some other countries. Commercial-grade electric vehicles have made inroads in Europe recently, as well. Plug-in hybrid and pure electric vehicles are making inroads in niche heavy truck markets and will be discussed in this report.

But before we look into the value proposition of hybrid technology in the different heavy-duty vehicles applications, we will describe the various types of advanced vehicle power trains available or being considered for use in heavy vehicles, the components of those power trains, the commercial systems available today as well as the tools and methods used to assess them, and, finally, some of the challenges associated with heavy hybrid technologies.

2.1 Configurations

There are many different types of advanced technology power trains. Some of the major types are all-electric, hybrid electric, plug-in hybrid electric, accessory electrification, and hydraulic hybrid power trains. These and other power trains are briefly discussed in the following sections.

2.1.1 All-Electric

In an electric vehicle (EV), an electrical energy storage system such as a battery pack provides power to an electric traction drive to move the vehicle and power accessory loads. System components include the energy storage unit, which stores electrical energy; an inverter for power

conversion between the battery and the electric motor; a converter to condition the power sent to low-voltage accessory loads; power electronics, for charging the energy storage system; and an electric motor for traction power. One option is a fast-charging system for accelerated charging of the vehicle. Advantages of the all-electric vehicle include its low emissions (zero emissions at the vehicle) and its ability to use electricity generated from diverse primary sources, including renewable energy.
All-electric power trains can also be designed to provide electric power to run off-vehicle equipment such as work tools. However, the high cost of batteries and long recharging times have made large-scale deployment of this technology difficult to achieve.

A successful example of an all electric vehicle is the trolleybus. Every day thousands of trolleybuses around the world transport millions of people and are reducing noise and emissions in the streets. As a consequence the local carbon footprint is extremely low. The electrical traction of a trolleybus gets it's energy from the electrical lines. While breaking the electrical driveline can recuperate energy back to the lines or use it on board for other users as heating, AC, etc. The recuperation depends on the topography and the characteristics of a line but is normally between 15 and 35%. Therefore the lines can be considered as an electrical storage system. As a new development in the industry we see that ultracapacitors are integrated in the line system to avoid peaks in the consumption of the electrical energy. Trolleybuses can have a length of 12 to 25m and carry up to 220 passengers in one vehicle.

Figure 2 : Trolleybus

2.1.2 Hybrid

Hybrid systems use two sources of power to propel the vehicle. The hybrid system uses the advantages of the two power sources to attain lower fuel consumption. Typically, the two power sources are a petroleum-fueled internal combustion engine and an electric motor and battery system. However, other systems that combine a petroleum-fueled internal combustion engine with hydraulic accumulators have also gained popularity. Specifically, increased efficiency is gained by the following:

1. Unloading harsh transient operations (e.g., launch acceleration and passing maneuvers) from the internal combustion engine

2. Augmenting the engine torque for transient maneuvers (e.g., short accelerations) with the secondary power system, which allows designers to downsize the internal combustion engine so it can operate at higher average loading and higher average efficiency
3. Recapturing a portion of the vehicle's kinetic energy during deceleration, which is known as *regenerative braking*
4. Meeting the accessory (or auxiliary) power demand when stopped by using the secondary power system, which allows the internal combustion engine to turn off.

In addition, some hybrid vehicles (and some plug-in hybrid electric vehicles, or PHEVs) are capable of all-electric driving. This capability can be useful for vehicles needing to operate in zero-emission zones.

There are three major hybrid vehicle configuration subtypes:

- series hybrids,
- parallel hybrids,
- series/parallel (power-split) hybrids

The major differences between these subtypes relates to how energy flows from the power sources to the wheels. In a series hybrid, energy flows from one power source through all of the components in series (that is, one after another). In a parallel hybrid, each of the on-board power sources can provide energy directly to the wheels. A series/parallel or power-split hybrid can take on aspects of both the series and parallel system. Although hybrids are normally discussed in the context of hybrid *electric* vehicles, or HEVs, the same designations described above can be used for other hybrid systems, such as hydraulic hybrids.

2.1.2.1 Hybrid Electric

The primary power source in a hybrid electric system - whether it is a series, parallel, or power-split system - is almost always an internal combustion engine, although other options such as fuel cells or gas micro-turbines have been used in transit buses.

The secondary power source is typically an electric motor connected to a battery system. Lead acid batteries have been used in the past, although more recent hybrids use both nickel metal hydride and lithium ion battery chemistries. Ultracapacitors have been used successfully in some hybrid applications, as well. Although ultracapacitor systems do not have high energy density, they are ideally suited for some hybrid applications. For example, they have been successfully demonstrated in refuse hauling applications in the United States (Business Wire 2006). A refuse hauler makes about one thousand stops per day. In these cases, the ultracapacitor's high cycle life and high power absorption capability are advantages that make it preferable to a battery.

A similar application for ultracapacitors we see today on hybrid city buses. Very often the distance between bus stops in a city bus application is between 300 and 500 meter. The permanent stop-and-go between the bus stops is producing a lot of breaking energy and has to be stored in very short time, something a battery never can do. Today's hybrid buses with ultracapacitors can drive zero emission for approximately 800m. If this range has to be extended batteries could be combined.

Hybrid energy storage systems that combine batteries with ultracapacitors achieve the benefits of both: the ultracapacitor's cycle life and power density and the battery's high energy density. However, successful commercial deployments of that technology have not been demonstrated yet.

One advantage of a hybrid electric system is its ability to provide electric power to off-vehicle electrical equipment - effectively working as a separate generator unit. This capability is of interest to military and commercial buyers. Commercial trucks demonstrating this capability are already being sold (Eisenstein 2005). Providing power for off-vehicle equipment such as water pumps has been demonstrated for emergency situations such as when Hurricane Katrina struck New Orleans, Louisiana, in 2005 (Shachtman 2006).

According to the 2008 Vehicle Technologies Market Report issued by the U.S. Department of Energy (DOE), the first diesel-electric hybrid was produced in 2007 in the United States (Ward and Davis 2009). The vehicle was a class 6 medium-duty International DuraStar (Navistar 2009). As of July 2009, approximately 1000 units have been sold around the world. The incremental price of these diesel hybrid electric medium-size trucks ranged from $45,000 to $60,000 (U.S. dollars) in 2008 although the base price for the vehicle itself was not listed.

- ***Series***

In a series configuration, the internal combustion engine or other prime mover is mechanically decoupled from the road. All power is generated and transmitted to an electric or hydraulic drive to power the wheels. Figure 2 shows a schematic of a series hybrid electric vehicle power train. In a series hybrid electric system, chemical energy contained within the fuel (e.g., diesel, hydrogen, ethanol, gasoline, etc.) is released as a result of a chemical reaction such as combustion or that of a fuel cell. This reaction occurs in the power unit, which runs a generator to create electricity.

A commercial application of that principle we see since many years on dual mode trolleybuses. These are trolleybuses which have an extra strong diesel generator on board to produce the electricity on board, which allows to run the electrical driven buses also where no electrical lines are existing.

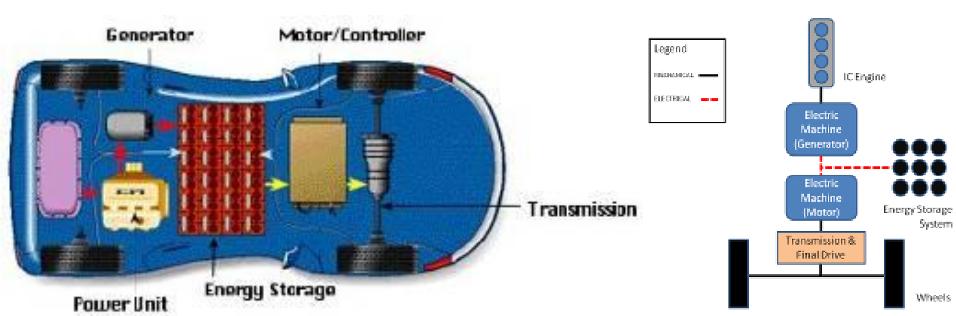


Figure 3. Series hybrid electric vehicle

- ***Parallel***

In a parallel hybrid system (Figure 3), each power source follows a direct path to supply energy to the wheels. In an electric hybrid, one path would be through an electric traction motor and another through the internal combustion engine. In a hydraulic hybrid, the two paths correspond to an engine and a hydraulic accumulator. Parallel systems are commonly used with "power assist" and "micro/mild" hybrid systems.

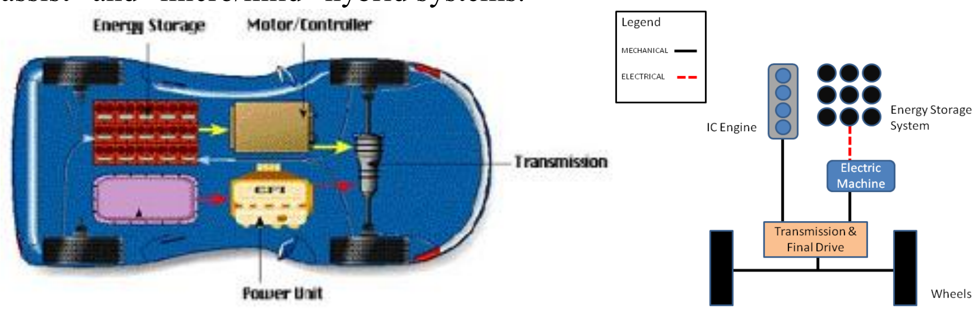


Figure 4. Parallel hybrid electric vehicle

2.1.2.2 <u>Power Split</u>

The series/parallel or power-split hybrid system has the advantages of both the parallel and series configurations, but the price is higher due to more complexity. Power-split hybrids use sophisticated planetary gear systems along with electric machines to form an "electric continually variable transmission," or e-CVT. The electric machines play the role of both motors and generators, depending on which way the power is flowing. Figure 5 shows the component setup of two common power-split systems. The system with one planetary gear set is known as an *input split system*. The system with two planetary gear sets is a *compound split system*, sometimes also called a *two-mode system*.

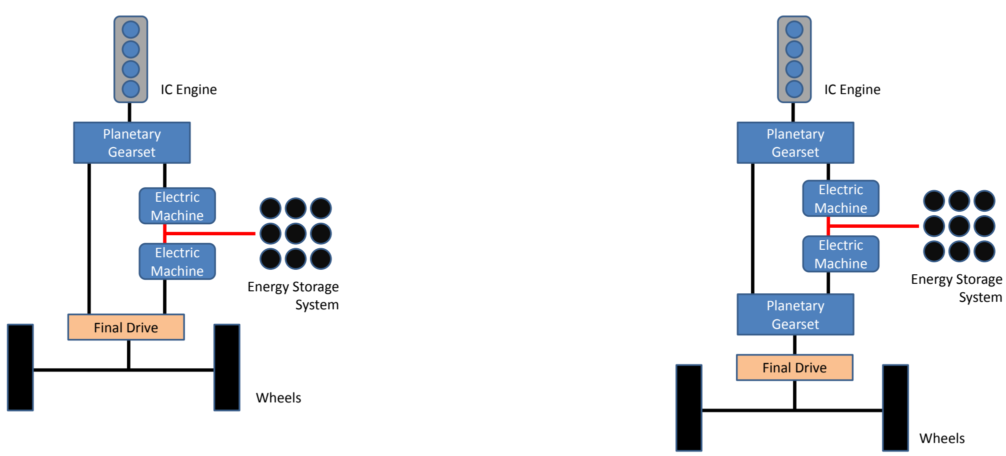


Figure 5. Types of power-split hybrid systems. Left: an input split system; right: a compound split system (also known as a *two-mode system*)

2.1.2.3 Hydraulic Hybrid

Hydraulic hybrid systems fit well into the hybrid classifications already described. Thus, we have series and parallel hybrid hydraulic systems, just as we have series and parallel hybrid electric systems.

The basic premise behind energy management for hydraulic hybrids is common to all hybrids. That is, recapture braking energy and use it to accelerate the vehicle, remove transient operations from the engine to load-level the engine’s operation over the cycle, allow component (engine) downsizing by reducing peaks, and finally, enable engine idling to be turned off during stops.

Hydraulic hybrid technology is characterized by a high power density, but hydraulic accumulators have a relatively low energy density. The high power density of the hydraulic hybrid system allows a great amount of regenerative braking energy to be captured. A study by the U.S. Environmental Protection Agency (EPA) showed that 70% of braking energy can be captured and returned to the wheels to accelerate the vehicle (Ogando 2008, Kargul 2007). The high power density and the high rate of brake energy recovery, combined with the relatively bulky accumulators, makes heavy-duty vehicles that operate in stop-and-go driving cycles very suitable for hydraulic hybrid drive technology. Therefore the first applications are in package delivery and refuse hauler trucks, although there is talk of using the technology in light-duty vehicles as well.

Hydraulic hybrids are still in the development phase and are not yet commercially available (Ward and Davis 2009). However, a number of pilot projects with hydraulic hybrids are currently running to demonstrate fuel savings when used in practice. Since 2008 for example, the city of Denver (CO, USA) is operating a refuse truck equipped with an Eaton HLA parallel hydraulic hybrid drive. Compared to non-hybrid refuse trucks fuel savings of 25% are reported (Denver 2010). Another example is a refuse truck equipped with a Parker RunWise series hydraulic hybrid system that showed even 72% improvement in fuel efficiency during a month of testing in South Florida (Parker 2009).

Additional advantages of the hydraulic hybrid drive, as reported by Bosch Rexroth for example, are a reduction in brake wear and dust and the ability to retrofit the system into existing commercial vehicles (Bosch 2008). However, according to Worcester Polytechnic mechanical engineering professor James Van de Ven, new pump-motors with high efficiency, even at low displacement, are needed to further advance automotive application of hydraulic hybrid technology (Ogando 2008).

Hydraulic hybrid systems have also been proposed for off-road heavy-duty machinery. Achten discusses ways to use concepts from hydraulic hybrids in off-road systems to improve fuel economy (Achten 2008).

2.1.3 Plug-In Hybrid Electric Drive

A plug-in hybrid electric vehicle is a cross between a full-electric vehicle and a hybrid electric vehicle. The basic premise is to allow all-electric or *blended* electric driving during the majority of short trips and the use of hybrid electric mode during long trips. Blended electric driving is the opposite of what occurs in a conventional hybrid electric vehicle. In other words, instead of using the internal combustion engine as the dominant power source, with an occasional assist from the electric traction motor, blended electric driving focuses on using the electric traction motor for primary power and brings on the internal combustion engine only for high acceleration or hill climbing maneuvers. The electricity to charge the battery comes from the electric utility grid - ideally from charging overnight when electric demand is low.

The PHEV fills a nice niche market for consumer vehicles that are parked during most of their lifetime and have driving profiles featuring a large number of short trips and an occasional long trip. For heavy vehicles, not all vocations may be commercially viable for a PHEV power train. One vocation that is being developed for commercial truck PHEVs is that of the utility bucket truck or aerial lift truck (Blanco 2007). Conventional utility bucket trucks currently require an idling engine to power the hydraulic lift bucket while working on a job. The PHEV power train would allow this energy to be supplied electrically through on-board electric energy storage, thus saving fuel, lowering emissions, and reducing noise (CalCars 2007).

2.1.4 *Externally Powered Drives*

A significant drawback to vehicles that use electrical power as a primary fuel source is the energy density of batteries. The energy density for lithium ion battery technology, one of the most energy dense of the available battery chemistries, is said to be around 0.5 megajoules (MJ) per kilogram (kg) (about 140 watt-hours (Wh)/kg), with a theoretical energy density limit of 2 MJ/kg (560 Wh/kg) as currently designed. Even 3 MJ/kg (830 Wh/kg) might be possible with design modifications to the anodes (House and Johnson 2009). However, when compared with the lower heating value of diesel fuel at about 42.8 MJ/kg (11,900 Wh/kg), this is at best only about 7% of the energy density of diesel fuel (Pacific Northwest National Laboratory 2008).

There are a few subtleties in this energy comparison, however. Batteries cannot be fully charged and discharged without severely lowering their cycle lives. Therefore, the full energy capacity of the battery is seldom used. On the other hand, the electrical energy in the batteries can power the wheels more efficiently than diesel fuel can through an internal combustion engine. However, if we stick with our 7% calculation, to go the same distance, batteries weighing at least 15 times the mass of diesel fuel would be required; for current state-of-the-art lithium technology, this could be more than 85 times. Thus, the main message is that it takes quite a few batteries to provide power on a par with fossil fuels.

One possible way around this limit is to use fewer batteries, and this is the strategy used in hybrid electric and plug-in hybrid electric vehicles. One other potential enabler to reduce the battery size of a vehicle is using “external vehicle power”. Such systems have been demonstrated in working commercial vehicles.

Technologies such as all-electric and dual-power train trolleybuses with overhead catenary lines to supply electrical power have been used with some success in various parts of the world. Independently from the local situation, the weather conditions, etc. the overhead lines supply always reliable the required energy. And additional advantage is that the energy source is outside the vehicle and therefore the empty weight can be reduced.

In Shanghai a new concept is in test where storage systems on city buses are recharged on every approx. 3rd bus stop while the passengers are boarding. As a typical stop takes not more than 30 seconds, batteries would be to slow to charge and therefore ultracapacitors are in use. To allow the transfer of the energy also in the required time the system is made on the roof via a conductive solution.

Additionally, inductive power transfer has been demonstrated recently for a transit bus operating in Japan (Hino Motors 2008). Also in Belgium a demonstration project on inductive charging has been set up. The project examines the feasibility, efficiency and practical applicability of inductive charging for electric vehicles, focusing both on stationary applications for cars (parked charging) and dynamic applications for buses (charging while driving). Departing from an existing inductive system developed for charging trams, the project will fit out a hybrid bus (and in a later stage a fully electric bus) with inductive components. Next to the integration of this technology in vehicles and infrastructure, the project will also examine the communication interface between both.

Battery swapping is another form of "external power" that has been announced by at least one company (O'Dell 2010). Mitsubishi Heavy Industries announced in April 2010 that they would be running a swappable-battery electric bus program in 2011.

2.1.5 Retrofit Systems

The expected median lifetime for a 1990 model year heavy truck is 29 years in the United States (Davis et al. 2008). Thus, it takes a long time for the heavy-duty fleet to turn over or be completely replaced.

Therefore, some companies have proposed systems that can be retrofit on existing vehicles to make the existing fleet more efficient (Connaught Engineering 2009). These types of systems have been proposed for both hybrid electric and hybrid hydraulic vehicles (Leech 2008).

2.1.6 Ancillary Hybridization

Traditionally, drivers of long-haul trucks in both warm and cold areas of the United States have left their engines on during stops for security, convenience, or comfort, for example in order to provide power for heating, ventilation, and air conditioning (HVAC). Because the engine is extremely oversized for these relatively small "hotel loads" - personal loads for the driver's comfort and for small appliances - the efficiency of energy generation is low. Furthermore, there are concerns about the environmental impact of emissions from idling.

Various technologies are available to eliminate the need to idle the engine. These include battery-powered auxiliary power systems, fuel-fired heaters, diesel-fueled auxiliary power systems, and shore power, which is power from a stationary source plugged into the truck (California Air Resources Board 2008).

Truck stop electrification has received some attention in the United States as a means of reducing emissions and energy use (and energy costs) associated with idling a heavy vehicle engine to provide power for hotel loads and other electric accessories. The EPA has estimated that the cost savings for diesel fuel could be as high as $3,240 per parking space per year (Ward and Davis 2009).

There are two types of systems for truck stop electrification: single-system electrification and shore power systems. Single-system electrification involves mounting a unit onto the window of a truck to provide power for HVAC and an electrical outlet. These are stand-alone units that do not require any equipment on the truck other than a window mounting template. In contrast, shore power systems provide electrical outlets for trucks to plug into, and they require trucks to have a 120 volt (V) inverter. It is estimated that 60,000 class 8 trucks with sleeper cabs are capable of using shore power, and 50% of all new class 8 trucks come equipped with the 120 V alternating current (AC) connections for block heaters, oil pan heaters, fuel-water separators, and battery chargers. As of 2008, 136 truck parking spaces across the United States were electrified, of an estimated total of 5,000 spaces. The Society of Automotive Engineers (SAE) and the Electric Power Research Institute have established J2698 as a standard for the 120 V AC electrification of trucks (Ward and Davis 2009).

2.2 Components

Hybrid electric vehicle systems require an electric traction system to operate. That system is composed of an energy storage system, a motor, and an inverter. The motor provides power to turn the vehicle wheels and is sometimes referred to as an electric traction motor. The inverter converts electric power (using direct current, DC) between the energy storage system (usually batteries) and the electric traction motor (which usually uses alternating current). A power-conditioning DC/DC converter is used to step down the bus voltage to suitable levels (e.g., 14 V for conventional vehicle accessories). Vehicles such as the Toyota Prius also include a bidirectional buck/boost DC/DC converter to increase or decrease the voltage differences between the battery pack and the high-voltage bus to the inverter. In PHEVs, an on-board charger may also be present. Hydraulic accumulators and hydraulic pump/motors are needed for hydraulic hybrids.

This section provides a brief overview of the various components needed for advanced vehicle power trains and the current state of the technologies.

2.2.1 Energy Storage Devices: Batteries, Capacitors, and Hydraulic Accumulators

Energy storage devices, which include batteries and ultracapacitors, are a critically important enabling technology for advanced, fuel-efficient, electrified power train vehicles.

2.2.1.1 Lithium Ion Battery Technology

Of all the battery chemistries, lithium ion battery technology comes the closest to meeting the energy and power requirements of vehicles, and many experts expect them to be the battery chemistry of choice for future HEVs, PHEVs, and EVs (Voelcker 2007; Howell 2008). Lithium ion batteries have been used with great success in the consumer power tool and portable device industry, and more money is being spent on lithium ion R&D than on all of the other battery chemistries combined (Voelcker 2007; Economist 2008). The advantages of lithium ion batteries in comparison to other battery chemistries are that they are lightweight, lack a “memory effect” (i.e., the loss of capacity when the battery is recharged without being fully depleted), and have the potential to be cheaper than nickel metal hydride batteries at production volumes (Economist 2008). Although not yet commonplace, lithium ion battery technology already appears in electric vehicles, such as Tesla's luxury sports car, the Roadster (Economist 2008). However, many challenges must be addressed by the R&D community before lithium ion will become common in vehicle applications; these challenges include cost, performance, abuse tolerance, and lifetime. Lithium ion cells for all-electric applications are currently three to five times too high in cost (for hybrid applications, two times too high) compared to industry targets set by the United States Advanced Battery Consortium (USABC) for light duty vehicles. In addition, lithium ion chemistries may not be able to last the desired life goal set by the USABC under EV/HEV cycling (Howell 2008).

Some people consider safety to be the key issue that must be addressed for lithium ion batteries to approach deployment. Some lithium ion chemistries can go into thermal runaway conditions, which could result in fires or explosions (rapid disassembly). In 2006, Sony had problems with lithium ion safety in the company's laptop batteries, and these resulted in fires in certain cases. Sony had to rectify the problem through a massive recall (Economist 2008). Safety issues for automotive-sized battery packs are even greater than those of laptop batteries. Safety can be addressed by isolating individual cells or by working on the fundamental chemistry (Voelcker 2007). But looking at the safety results of lithium ion batteries in the quickly developing passenger cars market, we can expect the safety aspects to be under control.

Lithium ion cells, like all electrochemical batteries, are composed of an anode (a negative electrode typically made of graphite), a cathode (a positive electrode made of various materials), and an electrolyte. A polymer film separator prevents the anode and cathode from coming in contact and starting a short circuit. Lithium ions from the anode pass through the separator and electrolyte to the cathode, which enables electrons to flow through an electrical circuit and deliver power. The cathode composition and, specifically, the rate at which the cathode can absorb and emit free lithium ions affect the battery power density. Materials based on cobalt (cobalt dioxide), nickel (nickel-cobalt-manganese, nickel-cobalt-aluminum), manganese (manganese oxide spinel), and others are being considered for the cathode (Voelcker 2007).

In terms of expected lifetime, both usage and calendar life can be degradation pathways for lithium ion technology. Calendar life degradation is particularly challenging in light of a vehicle's typical life of around 15 years in the United States. Currently, battery technology is oversized to allow for degradation and to increase the battery's life. However, oversizing adversely affects cost, weight, and volume (Voelcker 2007; PESA 2006).

With regard to cost, lithium ion cells are believed to cost around $450/kWh at the cell level. However, the cost of these devices when outfitted as a rugged automotive pack may be much higher and more in the range of $700-$1.000/kWh (Voelcker 2007).

Although concerns have been raised about the availability of lithium, they appear to be unfounded - at least in the near term. More availability issues may be associated with nickel, a key ingredient of nickel metal hydride batteries (Voelcker 2007; Romero 2009). Most lithium comes from Chile and Argentina today, and Bolivia and China have large reserves. Depending on lithium availability, price, production volumes, legislation, … the recycling of lithium will become a reality. At the moment it is not yet economically interesting to start recycling lithium from automotive batteries, but companies like Umicore in Belgium are already prepared for this (see recycling factory in Hoboken, Belgium).

Several lithium chemistries exist. The lithium battery chemistries currently being researched by groups such as the United States Department of Energy include graphite/nickelate, graphite/iron phosphate, graphite/manganese spinel, lithitum-titanate/high voltage nickelate, lithium/sulfur, and lithium metal/lithium-ion polymer (Howell, Barnes, et. al. 2009).

2.2.1.2 NiMH Battery Technology

Nickel/metal hydride (NiMH) batteries have been used in the majority of light-duty hybrid applications over the past ten years. For example, this battery chemistry has appeared in all versions of the Toyota's Prius, the most popular selling hybrid car to date. For heavy duty applications, NiMH has made some significant appearances, as well, such as on the GM Allison Hybrid System Two Mode Parallel Hybrid Electric Transit Bus (Vehicle Technology 2007).

The future dominance of NiMH is less clear with Li-Ion being the anticipated contender. In an interview with EV World, Professor Andy Frank of University of California, Davis, someone with decades of experience building electric vehicles with his students, commented that, if both NiMH and Lithium Ion were to be mass produced, their costs per kWh would be similar, but Li-Ion would weigh half as much. NiMH may continue to play a roll, however, due to its demonstrated durability/reliability in the field (Bagatelle-Black 2007).

Some providers of hybrid and electric vehicles from both light and heavy duty already appear to be switching to lithium-ion technology. For example, JB Straubel of Tesla Motors and Tom Gage of AC Propulsion were reported as saying that NiMH battery technology was already obsolete, at least for pure EVs (Bagatelle-Black 2007). In the medium duty hybrid world, Eaton appears to be offering Lithium Ion battery technology for at least some of their medium duty hybrid electric vehicles (Eaton 2009).

2.2.1.3 Lead Acid Battery Technologies

Lead acid battery technology was the earliest battery chemistry to be used in vehicles, and most if not all battery-powered vehicles in the late 19th and early 20th centuries used that technology. Early electric vehicle prototypes from the 1990s, such as GM's EV1, also initially used the technology. In the late 1990s and early 2000s, several heavy hybrid electric vehicle manufacturers, such as BAE Systems and ISE Research, produced vehicles using lead acid batteries. In fact, lead acid technology has been used longer in the commercial heavy vehicle area than in the light vehicle area. This is likely due to the lower up-front costs associated with lead acid technology, as well as to the fact that heavy vehicles are less sensitive to packaging concerns than light-duty vehicles. Lead acid is used exclusively in conventional vehicles for starting, lighting, and ignition; is the mainstay of small electrified vehicles such as neighborhood EVs and golf carts; and is the technology used to power the electric scooters and e-bikes still popular in Asia.

However, the future of lead acid for use in advanced electrified vehicles is less clear, especially in plug-in hybrid and pure battery electric vehicle applications. Although companies such as

Axion Power and Firefly Energy are working on advanced lead acid battery designs that may be used in micro and mild hybrid electric cars, the low energy density and limited life of lead acid chemistries make them a poor match for full HEVs, PHEVs, and EVs, which rely heavily on energy storage. As the costs of other battery technologies come down and experience with them goes up, it may become harder to justify staying with lead acid technology.

2.2.1.4 Ultracapacitors

The term "ultracapacitor" is a common term for an electrochemical double-layer capacitor (EDLC). EDLCs have much higher energy density than that of traditional capacitors. In comparison to batteries, ultracapacitors have a higher power density but much lower energy density.

Although most of the heavy hybrid electric vehicle systems in use today use batteries, some systems are based on ultracapacitors (see, for example, Nishikawa et al. 2003; ISE Corp 2008; Shachtman 2006). Other systems have been proposed that consist of both a battery and ultracapacitor (see, for example, Power Management Design Line 2008). Such a system could potentially offer the dual benefits of the high energy density of batteries with the high power density and cycle life of ultracapacitors.

Figure 6 : lighTram®Hybrid with ultracapacitors (photo courtesy of HESS AG)

A typical application for ultracapacitors are the city buses. The permanent stop-and-go application requires the fastest possible energy recharging. The combination with batteries makes only sense if the required distance for a zero emission drive has to be increased.

2.2.1.5 Hydraulic Accumulators

Hydraulic accumulators store energy as a pressurized gas (such as Nitrogen) in excess of 20 megapascal (MPa) (equivalent to 200 bar). The gas is separated from the hydraulic oil by a membrane or a piston. The accumulator energy density is low in comparison to that of batteries. Mr. Karl-Erik Rydberg of the Linköping University in Sweden mentions 4-11 kJ/kg for hydraulic accumulators versus 125 kJ/kg for Lithium ion batteries (Rydberg 2009).

Although design concepts for hydraulic hybrids vary, a hydraulic hybrid system might require the following components: two hydraulic pump-motors, power electronics and controllers for the motors, a high-pressure accumulator, and a second, lower pressure accumulator (needed to complete the hydraulic circuit). During braking, the pump-motors capture regenerative braking energy and store that energy as pressurized fluid in the high-pressure accumulator.

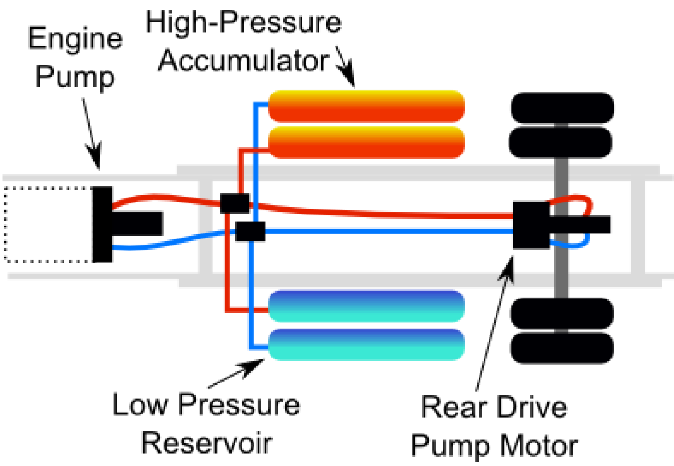


Figure 7 : Main components of a hydraulic hybrid system for heavy vehicles

Ogando (2008) states that work is needed to make accumulators lighter, smaller, and less expensive for automotive applications.

2.2.1.6 Other Energy Storage Systems

Although other battery technologies exist, their use in future electrified vehicles seems limited. Despite that, they are worth mentioning. Some of the major alternative battery chemistries that have been used or are considered for use in vehicle applications include zinc air batteries, nickel cadmium batteries, and sodium-nickel-chloride and other molten salt batteries.

In addition to batteries, flywheel systems are seen by some as having potential viability (Ricardo 2009). Flywheel systems store energy in the rotational inertia of a rotating mass. New generations of flywheels using composite materials are thought to be safer than previous generations. Power electronics and motors can be used to transform mechanical energy into electrical energy again if needed.

2.2.2 Internal Combustion Engines

Compression ignition internal combustion engines are the workhorse of most commercial trucks. These engines typically run on diesel fuel.

Spark ignition engines that run on gasoline are sometimes used in heavy vehicle applications, as well. In California, 23-foot gasoline-electric hybrid buses have been deployed (Calstart 2009). In addition, internal combustion engines have been created for heavy vehicles that run on a myriad of alternative fuels, such as compressed natural gas, liquefied natural gas, hydrogen, biodiesel, electricity, and propane (AFAVDC 2009).

2.2.3 *Auxiliary Power Units*

Auxiliary power units provide supplementary power for auxiliary systems at higher efficiencies than those of the main engine. For example, Sunline Transit in California worked with the U.S. Army's National Automotive Center in Michigan to install Hydrogenics' proton exchange membrane fuel cells in a Peterbilt truck (Fuel Cell Bulletin 2004). The 20 kW fuel cell powered auxiliary devices that had been converted from mechanical engine belt-driven devices to 42 V electrically powered devices. The advantage of an electronic accessory device is that it can be shut off when not in use and run at optimal load when in use. Accessories used in the vehicle include a water pump, radiator cooling fan, air compressor, air conditioning (A/C) compressor and condenser fan, and an air brake scroll compressor. Southwest Research Institute evaluated the vehicle in the laboratory and determined that a 13% increase in fuel economy was possible (see Fuel Cell Bulletin 2004; MAE 2005; Sunline 2005; and Show Times 2005 for details).

Researchers at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) conducted a study in 2002 to assess the potential fuel economy benefit of accessory electrification in heavy trucks (Hendricks and O'Keefe 2002). These studies predicted a maximum increase in fuel economy for a class 8 tractor trailer of 9% to 15% in urban driving and 5% to 8% in constant-speed highway driving, depending on the engine type, accessory duty cycle, baseline accessories being replaced, and the like. Note that the improvement predictions are only for the diesel fuel consumption of the ICE. That is, the energy consumption of the auxiliary power unit, or APU, is not taken into account.

2.2.4 *Electric Machines (Motors and Generators)*

Three motor topologies are in common use in heavy hybrid electric vehicles today:

- the permanent magnet synchronous (PSM) motor (also sometimes called a brushless DC motor or synchronous AC motor)
- an induction motor (sometimes called an asynchronous motor or AC induction machine).
- switched reluctance machines

In most light-duty HEVs and some heavy-duty HEVs, the internal permanent magnet (IPM) motor is used. The IPM provides the best balance of high efficiency, small size, and low weight. Both Cho (2004) and Husain (2003) state that the cost of the IPM motor tends to be higher than that of other electric machines. Therefore, the benefits of the IPM motor in terms of packaging and efficiency could ultimately earn it a place in hybrid systems - especially in parallel hybrid and power-split hybrid electric vehicle systems in which the motor's peak power is less than half the peak vehicle power and continuous operation is limited.

For applications that require high continuous (and peak) power - such as full electric vehicles, fuel cell vehicles, and series hybrid applications - there seems to be a preference for induction machines. For example, the GM-Allison hybrid bus system uses an induction machine (Allison Transmission 2008). This preference may have to do with a change in system cost trade-offs and could be related to the limitations of an IPM motor's continuous high power usage, particularly because demagnetization of the permanent magnets is possible at higher temperatures.

Currently, R&D focuses on new motor designs that eliminate the need for permanent magnets, new configurations, new magnet materials, and new manufacturing methods.

2.2.5 Power Electronics

Power electronics are required to process and control the (potentially two-way) electric power flow between the energy storage units and the electric machines (i.e., electric motors). Power electronics also serve to control the operation of motors as part of the overall hybrid control system. Power conditioning DC/DC converters play an important role in stepping down the voltage from the high-voltage hybrid system to the low-voltage vehicle accessory loads. Additionally, bidirectional DC to DC buck/boost converters can be used to step up or step down the voltage between the energy storage system and the inverter.

A power electronics module for an electric traction drive requires semiconductor switches, capacitors, gate drivers, and a multi-material package to work together in harmony over harsh conditions. One of the biggest challenges arising from power electronics is thermal management of the heat generated by switching losses. Heat can cause the switch junction temperature to rise to unacceptable levels and destroy the switch. Similarly, the transient nature of the heat loading can cause thermal cycling of the package, and because of the thermal expansion of dissimilar joined materials, that thermal cycling can in turn cause fatigue in bonded joints or in the flexural fatigue of wire bonds (or both). As more and more heat goes through an increasingly smaller volume of material while being subjected to harsh conditions, including vibration, both cooling and reliability must be carefully understood. A cross section of a power inverter - the "work horse" of a power module - is shown in the figure below.

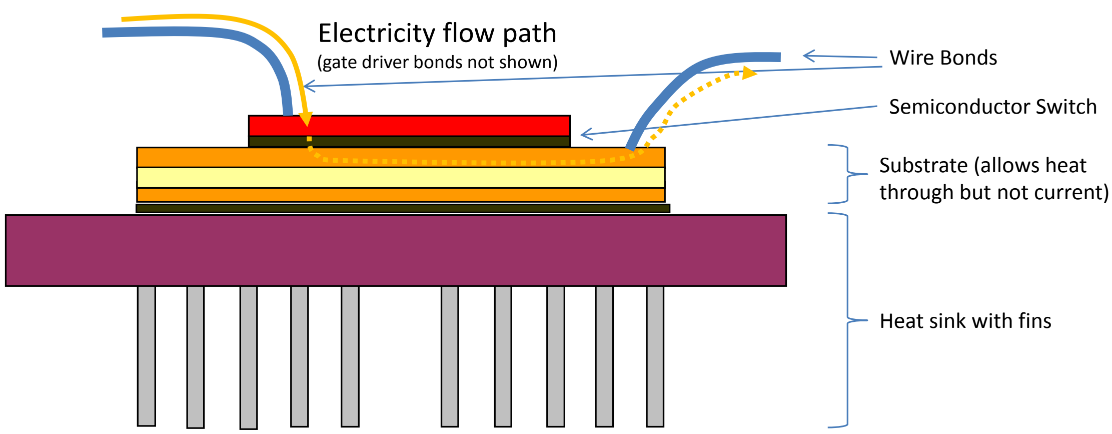


Figure 8 : Side view of a power inverter for hybrid vehicle applications.

The semiconductor switch is periodically activated using a gate driver circuit (not shown) that allows electrical current to periodically flow through the switch. The substrate allows heat conduction but prevents current from flowing through the rest of the package (figure is not to scale).

Depending on the amount of heat and heat flux to be dissipated, the technology used to cool a power module varies. Conventional forced air cooling can be used for some systems. However, the majority of hybrid power modules today use forced liquid cooling with a finned heat exchanger. Advanced techniques being developed include jet impingement cooling, advanced air cooling, and novel package designs to allow for double-sided cooling. An overview of advanced power electronics cooling technologies is available (see, for example Kelly et al. 2008). Three heat exchanger designs for power electronics are shown in the figure below.

Figure 9 : Heat exchanger designs for power electronics : (left) Flat fins used in a Toyota Camry; (center) elliptical pin fin heat exchanger; (right) jet impingement cooling

Today's vehicular power electronics systems grew out of industrial drive technology. A significant improvement occurred when the vehicle industry moved away from an industrial drive mind-set to one in which systems are optimized for the vehicle (see, for instance, Staunton et al. 2006 and Burress et al. 2008). Still, cost reports show that power electronics represent a large part of the system cost of hybridization. For example, the incremental cost of hybridization for the Toyota Prius and the Toyota Camry can be broken down into approximately three areas of equal cost: batteries, power electronics, and electric machines (see, for example, EEA 2007). Cost reduction without a sacrifice in performance is a current goal of power electronics research (see, for instance, EETT 2006).

2.2.6 Transmissions

Transmissions serve to match the torque and rotational speed of drive components to the wheels of a vehicle. Advanced power-split transmissions that use planetary gear sets can act like a full continuously variable transmission capable of taking any combination of engine speed and torque to be matched to a given wheel speed (see Allison Transmission 2008a). This offers unprecedented opportunities for control optimization for fuel efficiency.

The electric traction drives currently available for heavy vehicles are typically packaged as a single transmission unit, and power electronics and energy storage are separate modules (see, for example, Allison Transmission 2008b or Eaton Transmission 2009).

In his article on hydraulic hybrids, Ogando notes that some radical series hybrid designs can operate without a mechanical transmission (Ogando 2008). Although Ogando's article applies to light-duty vehicles, the same opportunity may exist for heavy-duty hydraulic hybrids as well.

Full-electric drive technologies offer the same opportunity to eliminate the mechanical transmission from the vehicle (see, for example, Oshkosh Truck 2009). In some hybrid drive units, the engine generates electricity and the electricity powers the traction motor to move the wheels. There are no direct mechanical linkages between the engine and the wheels. This gives many possibilities for the design of an electrical vehicle. A lot of trolleybuses use this drive line technology to drive two axels and guarantees in every weather condition a stable traction and a reliable transport. As a consequence the electrical torque per axle can be much lower and the mechanical use is significantly less.

2.2.7 Control Systems

The hybrid control system that coordinates the operating strategy of each component in the hybrid system is both integral and necessary. Some advanced concepts are being considered to further increase the fuel efficiency of vehicles by intelligently combining information about the vehicle's route with the hybrid system control strategy. Since many heavy vehicles often repeat the same or similar routes (e.g., transit buses, refuse haulers, parcel delivery trucks), they are good candidates for route-based controls.

A stand-alone hybrid control system does not provide optimum fuel savings over all driving profiles. However, if a control strategy had advance knowledge of the vehicle's route, it could provide higher fuel savings without any change in the cost of the hybrid components. In a modeling study conducted by the NREL, researchers found that a 2% to 4% increase in fuel savings could be obtained using route-based controls (Gonder 2008). Such a system would use advance knowledge of the terrain and expected speeds to most effectively schedule the timing of charges and discharges of the energy storage system.

2.3 Systems

This section discusses a selection of commercial systems in use around the world. This is not a comprehensive list but highlights some commercial systems where data was available.

2.3.1 Commercial Systems

2.3.1.1 BAE Systems' HybriDrive™

BAE Systems' HybriDrive™, a hybrid electric vehicle propulsion system, has been successfully used in Orion buses that have been deployed in New York City Transit's (NYCT) fleet since 1998 (NAVC et al. 2000). NREL has been tracking the performance of these vehicles in the field periodically since the first 10 buses were sent to NYCT in 1998. NREL conducted an evaluation of the Orion VII low-floor bus over the 12-month period from October 2004 to September 2005 (see Figure 10). The hybrid buses were part of a larger order of 125 vehicles that included Orion VII hybrid buses with BAE Systems' HybriDrive™ installed. These buses cost $385,000 each. For comparison, during the same years, equivalent CNG and diesel buses were $313,000 and $290,000 each, respectively (Barnitt 2008). The hybrid buses traveled about 5000 miles between road calls, which is better than the minimum 4000 miles required by NYCT. The hybrid electric transit buses had an average fuel economy of 3.19 miles per gallon over the 12-month period. This was 34% to 40% higher than the fuel economy of diesel buses without exhaust gas recirculation units that were operating under similar driving conditions from two different depots over the same period. Figure 11 shows the fuel economy of the HEV buses over the year in comparison to that of the diesel buses at the same stations.

Figure 10 : Orion VII bus with BAE Systems HybriDrive hybrid propulsion system

A distinct drop in fuel economy was observed during the summer months; it was believed to be due to the use of the air conditioning system. Maintenance costs were tracked for the hybrid system at $0.367 (U.S. dollars) per mile. Unfortunately, there were no new diesel baseline buses to compare this figure with over the same period. For details on this study, see Barnitt and Chandler (2006).

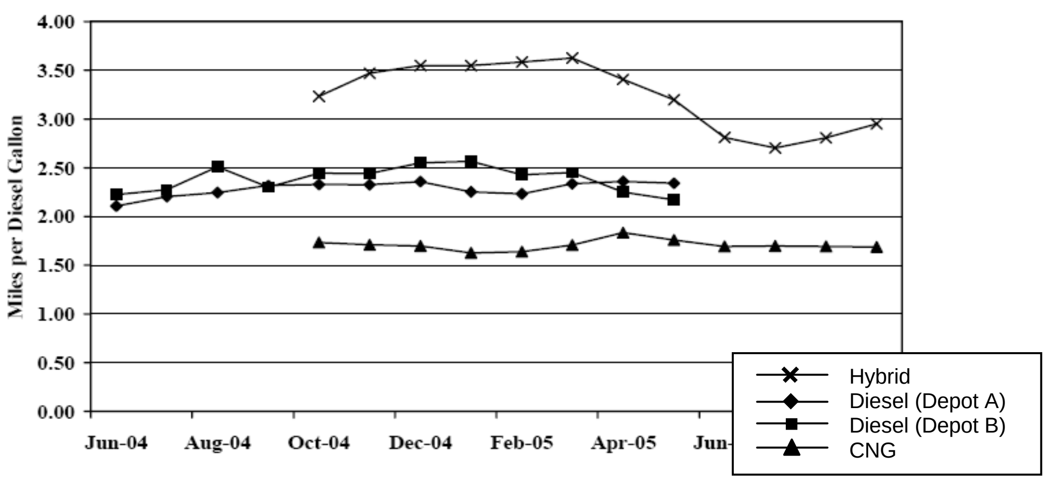


Figure 11 : Performance of the BAE Systems HybriDrive on the Orion VII transit bus

BAE Systems is supplying drive systems to many bus manufacturers, including Alexander Dennis Ltd of London (delivery accepted in October/November 2008; see *Fleets & Fuels* 2008-11-10).

2.3.1.2 Eaton Hybrid Electric Package Delivery Truck

The Eaton hybrid electric drive system consists of an automated manual transmission integrated with an electric drive motor. The use of an automated manual transmission reduces overall weight by eliminating the 127 kg torque converter typically be found in a baseline system (Eaton 2008).

Figure 12 : Eaton hybrid system being tested at NREL's Chassis Dynamometer Facility

One of the selling points of Eaton's system is its ability to generate auxiliary electrical power (120/240 V AC) drive all-electric for short periods (see Eaton 2008 for details).

Component Property	Value
Transmission type	Automated manual
Torque (Nm)	895 to 1166
Weight (kg)	426 (includes hybrid drive system, clutch, batteries, cables, etc.; does not include the auxiliary power unit)
Electric motor power	44 peak/26 continuous
Battery system voltage and type	340 V DC lithium ion

Table 1: System specification for the Eaton hybrid system (Eaton 2008)

2.3.1.3 Eaton Hydraulic Hybrid Package Delivery Truck

Eaton offers both series and parallel hydraulic hybrid systems. The parallel system is referred to as a hydraulic launch assist (HLA). The parallel hydraulic hybrid system is said to be capable of 25% to 35% better fuel economy than a conventional baseline vehicle for travel involving frequent starts and stops (Eaton 2008).

The Eaton series hydraulic hybrid drive system was developed in cooperation with the EPA under a cooperative research and development agreement that started in October 2001. A hydraulic hybrid vehicle was unveiled to United Parcel Service (UPS) in conjunction with International Truck and Engine (Eaton 2008). In 2008 UPS announced the purchase of seven series hydraulic hybrid package delivery trucks from International-Navistar equipped with Eaton hydraulic hybrid systems. The first two of these trucks were scheduled for delivery in the first quarter of 2009. Early tests with a prototype vehicle showed a 45% to 50% improvement in fuel economy over that of conventional diesel delivery trucks in real-world driving. UPS believes that a 30% reduction in carbon dioxide (CO_2) and similar fuel economy improvements are possible in real-world driving (Fleets and Fuels, November 10, 2008; UPS 2008).

2.3.1.4 Allison Transmission/Hybrid 60-foot Articulated Transit Bus

The Allison EV Drive (The E[P] System[TM]) is a 2-mode power-split hybrid power train currently being sold in 60-foot articulated transit buses. The table below lists the specifications of the system (Allison Transmission 2008).

Component Specification	Value
EV drive weight (kg)	417 (dry) and 428 (wet)
Output power (kW)	261
Dual power inverter module (DPIM) continuous power (kW) DPIM weight (kg)	150 75

Table 2: Specifications for the Allison EV Drive (Allison Transmission 2008)

In a study conducted at NREL, two 60-foot articulated transit buses (one conventional and the other a hybrid system) were tested at NREL's ReFUEL heavy vehicle chassis dynamometer test facility (Hayes et al. 2006). The hybrid bus was part of a 235 hybrid bus order by King County Metro, which operates bus service in a 2,134-square-mile area in and around Seattle, Washington (Chandler and Walkowicz 2006).

Figure 13: GM-Allison hybrid transit bus at the NREL ReFUEL Chassis Dynamometer Test Facility

Both vehicles were 2004 New Flyer buses powered by Caterpillar C9 8.8 liter engines. The hybrid used the GM-Allison hybrid power train. Four driving cycles, ranging from extreme stop-and-go to more high-speed driving, were used to evaluate the vehicles. The hybrid bus demonstrated a fuel economy improvement of 30% to 75%, depending on the driving cycle.

2.3.1.5 Oshkosh ProPulse Hybrid Electric Drive

Oshkosh Truck Corporation of Oshkosh, Wisconsin, offers a hybrid electric system called the ProPulse. The benefits of the system include lower fuel consumption, reduced emissions, and better life-cycle costs than those of conventional vehicles, as well as the ability to provide on-board AC power generation. The system is a series hybrid configuration that allows for a high degree of modularity. Ultracapacitors are used for energy storage, and the motor is an AC induction motor (see Oshkosh Truck 2008 for details).

Figure 14: Oshkosh hybrid refuse hauler tested at NREL's ReFUEL Heavy Vehicle Chassis Dynamometer Facility

The system has been suggested for use in defense, refuse hauling, fire, and emergency applications, among others.

2.3.1.6 Fuel Cell and/or Hydrogen-Powered Buses

A recent report describes the status of fuel cell transit bus technology as well as the progress of various fuel cell bus demonstrations across the United States (Eudy et al. 2008). Figure 15 is a montage of photographs of the various buses studied. Ten fuel cell buses from six different demonstration projects are highlighted in the study. The technologies highlighted include fuel cell systems from Ballard and UTC Power coupled with hybrid drive systems from ISE and Ebus. The ISE/UTC Power buses use a sodium nickel chloride ZEBRA battery. The report also mentions hydrogen-fueled transit bus technologies with internal combustion engines.

Figure 15: Fuel Cell Bus Demonstrations

According to the report, fuel cell technology is still undergoing field testing and final design refinements. In the next few years, two major programs are expected to increase the number of fuel cell bus demonstrations in the United States: the Federal Transit Administration's National Fuel Cell Bus Program and the California Air Resources Board (CARB) Zero Emissions Bus Demonstration Program. These programs will include eight demonstration projects and will place a total of 23 new fuel cell buses on the road.

Also Europe still strongly supports the importance of hydrogen. Therefore, the Joint Undertaking on Fuel Cells and Hydrogen (JU-FCH) has been launched, with the purpose of bundling the forces/efforts of the European industry, knowledge centres and regions (e.g. through the realization of demonstration projects). Europe has unlocked 470 million euros to this end, which implies that, with the public/private approach, there is a total budget of about 1 billion euro for 2008 – 2013.

Figure 16: New-generation fuel cell hybrid electric bus. (Photo courtesy of Van Hool)

Also the region of Flanders – Southern Netherlands has the potential to grow into a trend-setting hydrogen region within Europe, because the region is home to a number of important and promising players and end-users (markets) for hydrogen. Therefore the project "Hydrogen regio Flanders-South-Netherlands" has been set up.

2.3.1.7 Volvo system

Volvo is offering 12m hybrid buses with a parallel system. One axle is driven and batteries are used on the roof. The concept is mainly designed for a regional transport.

2.3.1.8 Siemens system

Siemens is offering a serial system and uses batteries to store the energy. One axle is driven. The system is e.g. used by the bus builder Van Hool in 12m and 18m buses.

2.3.1.9 HESS system

The HESS buses have two axle electrical driven, which is a result of the serial hybrid system which is using ultracapacitors to store on a short term base the generated energy. The energy management can be adapted to the local route. The buses are 18 or 25m long and have an electrical operated AC.

Figure 17: Hybrid bus in Luxembourg (photo courtesy of HESS)

2.3.1.10 <u>ZF system</u>

ZF is offering a serial system with batteries to store the energy. The traction is made on one or two axels with wheel hub engines. ZF has designed an extra version of their standard low floor axle AV 132.

2.3.1.11 <u>Voith system</u>

Voith is offering a parallel system with batteries. The traction is made on one axel and in use in the 12m buses from Gillig in the USA and Solaris in Poland.

2.3.1.12 <u>Other Commercial Vehicles</u>

Hino Truck, part of the Toyota Group, announced its plans to release Class 4 and 5 hybrid trucks in the United States on April 2011 (*Fleets & Fuels*, December 2008). Nice Vermet, senior vice president for sales and customer support with Hino Trucks in Michigan, was quoted by *Fleets and Fuels* as saying, “We need to provide cost-effective business solutions. Today, cost-effectiveness is nowhere near what it needs to be. We want this next system to stand on its own two legs.” *Fleets and Fuels* remarked that the current Hino systems are able to work in Japan because of government support. Hino is reportedly looking for a 5-year payback on its trucks.

UPS has purchased 12 electric vehicles from Modec, an electric truck manufacturer in the United Kingdom. The UPS trucks will be used in fleet service in both the UK and Germany (*Fleets & Fuels*, 2008-12-08). This British bus manufacturer provides several electric drive vehicles using components from Southern California’s Enova Systems and Valence Li-Ion batteries. A full-electric, plug-in hybrid electric, and parallel hybrid system are available. The parallel hybrid system uses Allison’s EP40 drive system with NiMH batteries. Battery charging systems are integrated onboard the vehicle. The electric drive motor is an induction machine for the Enova system and an interior permanent magnet machine for the Allison system (*Fleets and Fuels*, 2008-11-10).

Smith Electric Vehicles is an electric truck manufacturer in the United Kingdom. The company sells 2.3 to 12-tonne capacity electric vehicles. Vehicles can travel at speeds up to 70 miles per hour, and ranges are said to be up to 150 miles on a full charge (Smith Electric 2008).

Azure Dynamics, a developer of hybrid electric and electric power trains for commercial vehicles, has signed agreements with Ford dealerships for the sale of Azure's Balance™ Hybrid Electric drive system integrated into the Ford E450 Cutaway and Strip Chassis commercial van. Additionally, Azure has signed a supply agreement with Johnson Controls/SAFT for the supply of advanced lithium ion battery packs to be used in these vehicles, according to Azure press releases.

Also, FedEx recently released results from an ongoing trial of 10 hybrid diesel electric delivery vans from Iveco, a Fiat Group company. Results to date show a 26.5% reduction in fuel consumption in comparison to that of their diesel baselines over a 6-month trial being conducted in Milan and Turin, Italy (Logistics manager.com 04-2009; Greenbiz 04-2009).

2.3.2 *Benefits of Hybridizing Heavy Vehicle Vocations/Applications*

2.3.2.1 General Benefits

The overall benefits of hybridization include the following:

1. Reduction in the amount of fuel consumed per unit of distance per unit of mass hauled
2. Reduction in emissions per unit distance per unit mass hauled
3. Integrated electrical power generation to run ancillary systems and auxiliary loads as well as the ability to provide off-vehicle power in some applications
4. Ability of hybrid electric systems to be tuned for performance (at the expense of the fuel economy benefit, however)
5. Ability to run using only electricity, in some instances.

Additionally, researchers have observed reductions in the wear of some system components, such as brake pads and braking systems (Barnitt and Chandler 2006).

In addition to fuel savings, heavy hybrid electric vehicles offer other values to the customer. These include noise reduction, reduced emissions, export power capability to use the power train to power off-board systems, and zero-emission capability. Unfortunately, these are not necessarily known to or valued by potential customers. Also, because of the way engines are certified, no additional credit is given to a heavy hybrid electric vehicle over the credit for the engine at component certification time.

A zero-emissions range could be quite valuable in some applications. For example, a zero-emissions capability would allow the engine to turn off when coming to a school bus stop and any other time when children are outside the vehicle. Additionally, a zero-emissions capability can be used in entering areas designated by authorities for zero emissions for pollution mitigation or safety reasons. For example, conventional vehicles cannot typically enter an enclosed space because toxic carbon monoxide emissions could build up. However, if niche applications such as those described here are the only ones for which this technology has value, it may be difficult to achieve the economies of scale needed to justify adding zero-emissions range capability to hybrid technology.

2.3.2.2 Examples

- ***Transit Buses USA***

Several studies of transit bus hybridization have been conducted both in simulation (Vertin and O'Keefe 2002) and in testing (Chandler and Walkowicz 2006; Barnitt and Chandler 2006; Hayes et al. 2006; TCRP-59 2000; NAVC 2000).

In one study (Hayes et al. 2006), a 60-foot long articulated transit bus was tested on a vehicle chassis dynamometer over four driving profiles representing a range from urban to highway driving. One bus was a conventional diesel bus; the other used the GM-Allison advanced hybrid electric drivetrain. The hybrid demonstrated an improvement of 30% to 75% in fuel economy compared with that of the baseline vehicle, depending on the driving profile used for testing. In addition, the effect of air conditioning on the results was tested and found to be significant.

- ***Transit Buses Europe***

Various governmental and regional programs support cities to buy electrical driven buses. These programs are often followed by technical institutes to measure the benefits of reduced noise and emissions.

As an example the German government is supporting the region of Saxen by taking over the additional costs to buy hybrid buses. These buses are in use in the city center as well as in the regional transport. The Fraunhofer Institute is following the program closely. An other example is the region of Nordrhein Westfalen, which supports on a regional level the use of hybrid buses. The various suppliers participate in a program to compare the results of the tests.

Figure 18: Brake-energy recovery on hybrid buses using ultracapacitors (inset) (Photo courtesy of Van Hool).

In Belgium, public transport has increased its fleet of hybrid buses since 2009. In Brussels and Genk, the first full-electric buses have been put in service and in other cities (Brugge, Gent, Leuven, etc.) public transport company "De Lijn" has been rolling out an extra fleet of 79 hybrid buses. At the moment hybrid busses already make up 3,5% of their total bus fleet.

In the Netherlands the city of Utrecht has decided to change a big part of their fleet to hybrid buses and bought 219 hybrid buses which have to be operational from December 2011.
As European transit buses are up to 2 tonnes lighter than transit buses from the USA, systems from USA had not the same fuel savings in Europe as expected.

The first reliable results which are known can report of fuel saving between 12 and 20%. But a major advantage for the city centers is the increase of living quality as a result of the reduced noise.

- ***Class 8 Over-the-Road Tractor Trailers***

In the United States, although Class 8 trucks make up only 42% of the heavy vehicle fleet, they use 78% of heavy vehicle fuel as a result of their long annual travel distances – nearly 100,000 miles annually (Ward and Davis 2009).

In following study (Brooker et al. 2007), researchers from NREL worked with data provided by Oak Ridge National Laboratory (ORNL) to explore the question, "Can a significant fuel economy benefit be obtained through hybridization of class 8 over-the-road tractor trailers?"

Two key factors affect the ability of class 8 heavy hybrid trucks to make significant fuel economy improvements: duty cycle and component power requirements. Duty cycle refers to the vehicle's representative usage for both the driving profile and powering of accessory loads such as refrigeration units for cold storage, cabin climate control, other hotel loads, and other auxiliary systems. In the NREL study, only on-road driving profiles were examined. A high-level model was used, in which a parallel hybrid electric configuration was assumed and the heavy vehicle was modeled using drive cycle, coefficient of drag, mass, rolling resistance, power train efficiency, energy storage capacity, and percentage of regenerative braking energy captured. In addition, assumptions were made about the efficiency of the various power train components.
Three driving profiles were examined: an urban, a regional, and a long-haul driving profile. Two energy storage systems of different sizes were examined: a small one with 322 Wh usable capacity and a peak power of 30 kW, and a larger system with a capacity of 3000 Wh and 100 kW.

The results are shown in Figure 19. Based strictly on the driving profile opportunities, trucks fitting the "urban" and "regional" driving profiles showed a 4% to 14% decrease in fuel consumption. In contrast, trucks performing only "long-haul" driving showed negligible decreases in fuel consumption.

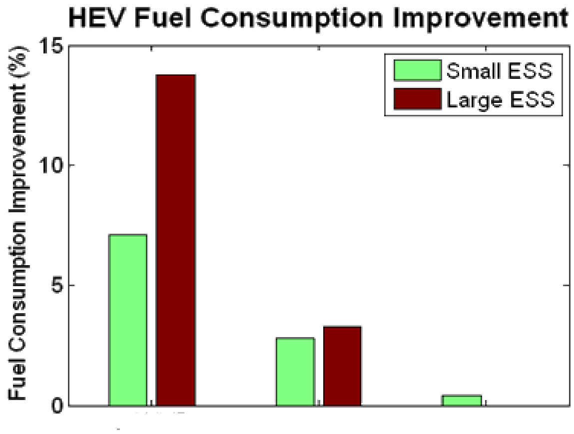


Figure 19: Fuel consumption reduction for HEV compared with the baseline

This study highlights the importance of understanding duty cycles in hybrid vehicle applications.

2.3.3 Modeling Tools for Hybrid Vehicle Simulation

Modeling tools can be of benefit for OEMs to reduce the cost of designing systems and to optimize system usage prior to investing in hardware. For government agencies, modeling tools can be used to assess the benefit of various advanced heavy truck powertrains and, perhaps, in the future could be used as a means of extrapolating component emissions performance to vehicle performance without using a chassis dynamometer test.

Several modeling tools are available for simulating vehicle fuel efficiency as a function of driving pattern. The U.S. Department of Energy has sponsored the development of some vehicle simulation tools such as ADVISOR (Markel et al. 2002; AVL 2009) and PSAT (ANL 2007). NREL first developed ADVISOR in 1994 as part of DOE's hybrid vehicle program. Between 1998 and 2003, more than 7,000 individuals, corporations, or universities around the world downloaded the program. In 2004, AVL was awarded the exclusive rights to license and distribute ADVISOR worldwide (AVL 2009). PSAT is a similar code developed by Argonne National Laboratory (ANL) that can be used for more extensive hardware-in-the-loop testing.
Other agencies of the U.S. Government offer other specialty modeling tools. For emissions, the EPA offers MOVES (Motor Vehicle Emission Simulator) (EPA 2009). ANL has a tool for calculating the energy and emissions of various vehicles; it is called the GREET (the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Model (ANL 2009).

In recent years, several good commercial products have also arisen. The Mathworks offers several packages for development on its MATLAB/Simulink product (Mathworks 2009). ADVISOR, PSAT, and RAPTOR, a software tool created by Southwest Research Institute (SwRI 2009), are built on the MATLAB/Simulink framework. In addition to ADVISOR, AVL offers a product for vehicle simulation called CRUISE (AVL-b 2009). MSC Software offers Easy5. In addition, languages such as MODELICA, which have compilers available in both open-source and commercial packages, can also be used for vehicle power train simulations, and libraries relevant to automotive simulation are available.

For dynamics testing, Mechanical Simulations Corporation offers TruckSim (MSC 2009). MSC Software offers ADAMS for vehicle dynamics analysis and Easy5 for multi-domain dynamic systems modeling (MSC 2009).

Also companies like LMS International brings innovative simulation software, testing systems and engineering services to the market (like LMS Imagine.Lab) to be able to search for multi-domain solutions for thermal, fluid dynamics, electrical and mechanical system behavior.

In summary, it seems that most equipment manufacturing companies inevitably develop and validate their own vehicle simulation software using a general purpose modeling environment such as MATLAB. Specialty software does play a role in some special topic areas (for example, ADAMS for vehicle dynamics). However, the general tools available from the government may provide the quickest way for university and policy makers to conduct some modeling and simulations as part of their assessments.

2.3.4 Drive Cycle Analysis

The benefits of hybrid technology vary significantly according to a vehicle's duty cycle. However, the hybrid value equation often depends on reduced in-use fuel consumption in order to justify the added purchase cost over that of a conventional vehicle. Thus, it is often critically important that hybrid vehicles be deployed over duty cycles where they will show a clear benefit.

A wide variety of heavy vehicle vocations are suitable for hybridization, including refuse haulers, transit buses, pickup and delivery vehicles, utility trucks, and military applications. Many other vocations have been considered for hybridization, as well. There is significant variation among heavy vehicle vocations and in usage within a given vocation. Thus, it is important for hybrid manufacturers and potential purchasers to understand the duty cycle in order to understand the benefit of hybridizing a vehicle for a given application.

NREL researchers, working in conjunction with staff at Oshkosh Truck Corporation, have developed several metrics for use in duty cycle characterization (O'Keefe et al. 2007). See that paper for the mathematical derivation of the duty cycle metrics, which can be used to associate hybrid advantage (i.e., the percentage reduction in fuel consumption of a hybrid over a baseline vehicle) to driving cycle.

Figure 20 shows how the hybrid advantage, the reduction in fuel consumption of a hybrid over a baseline vehicle, varies with one of the driving cycle metrics, kinetic intensity, in actual test data for the 60-foot articulated conventional and hybrid electric transit buses tested on the chassis dynamometer. Kinetic intensity is a metric used to quantify the ratio of drive cycle inertial effects (determined by an equivalent acceleration) to speed effects (determined by the speed required to yield the same average aerodynamic load). As can be seen, a relationship exists between the type of driving (characterized by kinetic intensity) and the hybrid advantage.

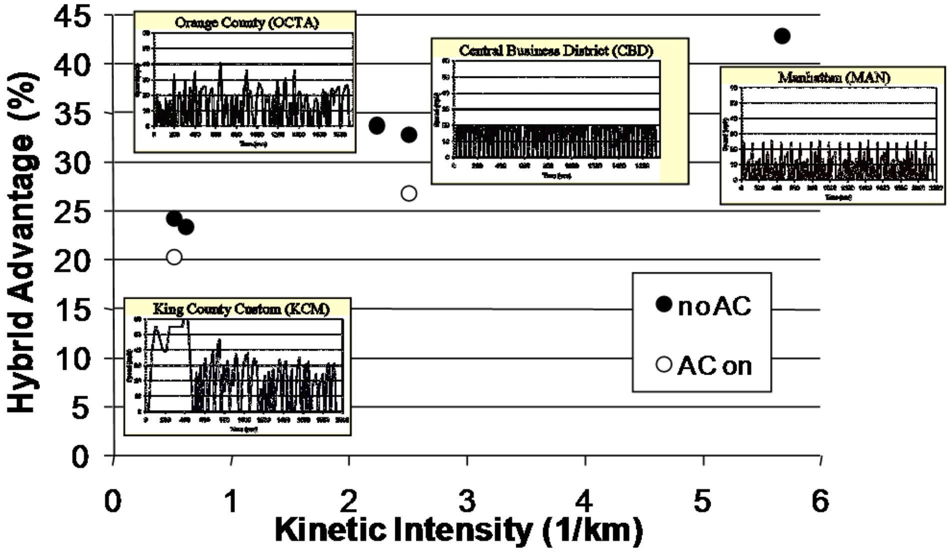


Figure 20: Variation in hybrid advantage with kinetic intensity

Although more work is needed, it may be possible to use metrics such as those presented here in the testing and analysis of HEV duty cycles as well as in the process of duty cycle selection and creation. NREL has successfully used the techniques and metrics presented here, in the creation of a refuse hauler duty cycle for EPA's SmartWay Fuel Efficiency Test Protocol (see Figure 6 of EPA 2007).

2.3.5 Component Sizing

As a general rule, the larger the difference between peak power requirements and average power requirements that a single component must satisfy, the lower the overall efficiency.

In applications in which peak *transient* power dictates engine size, hybridization can make it possible to downsize the internal combustion engine to the peak *continuous* power requirement. That is, you can have a hybrid with a smaller engine that performs the same as a conventional vehicle with a larger engine. This can be done by allowing the electric traction drive of the hybrid systems to supply the *transient* peak power to meet transitional loads, such as quick bursts of vehicle acceleration. Unfortunately, the large variation in vehicle payload and continuous power requirements for pulling a load up a grade tend to size heavy vehicle components. Thus, depending on the specific system or vocation involved, downsizing may or may not be an option. We have also seen that aerodynamic considerations can affect the ability to downsize components. For example, consider a boxy vehicle that has a hill-climbing performance requirement of 55 miles per hour on a 6.5% grade. If the engine size is dictated by this requirement, improvements to the aerodynamic drag of the vehicle may help to reduce engine size requirements. Note that this type of engine downsizing could apply to both hybrid and conventional vehicles.

Fleet maintenance considerations can also make downsizing difficult for heavy hybrid vehicles. For example, a hybrid transit bus may be able to use a smaller engine and thus gain higher overall fuel economy. However, if all of the other buses in the fleet use the larger engine, a transit operator may opt to stay with the larger engine in the interest of standardization and fleet maintainability.

When possible, however, downsizing the internal combustion engine can be an effective strategy to realize more fuel savings from the use of a hybrid system. As an example, in a recent cooperative research and development effort conducted by Anheuser-Busch and the National Renewable Energy Laboratory, various Anheuser-Busch fleet vehicles were instrumented with global positioning system units to estimate their typical daily driving patterns. The vehicles were Navistar 4400s, 4900s, and a T-800 model operated out of the Anheuser-Busch's distribution center in Denver, CO. Modeling and simulation were used to estimate the benefit of replacing the conventional vehicles with various technology options. It was found that an engine downsizing of 20% (that is, 20% reduction in peak power) could yield almost a 15% increase in average fuel economy (Walkowicz, 2010).

2.4 Challenges

Heavy vehicles are the backbone of the economy in many countries. For example, in the United States, 75% of the value of all goods are shipped via truck (21CTP 2009). Heavy vehicles transport people and goods across the country; play a critical role in the construction and maintenance of buildings and infrastructure; and provide critical services such as refuse pick-up and disposal, firefighting, emergency medical services, and military support.

As concerns about environmental issues and energy security continue to grow, heavy truck manufacturers have been challenged to reduce fuel consumption and emissions while also reducing vehicle costs. Operators of heavy vehicles are finding their margins becoming tighter as their operating costs increase as fuel costs rise. Advanced power train technologies such as hybrid electric drives can play a very important role in meeting these challenges if the business case is viable. In this section, we look at the specific challenges associated with advanced power train technologies for heavy vehicles.

2.4.1 Engine Certification

Several challenges related to engine certification for heavy hybrid electric vehicles are worth mentioning:

- harmonization of worldwide standards for engines
- availability of smaller certified engines for optimal downsizing
- lack of vehicle-level tests to certify these engines.

With regard to harmonizing worldwide standards, work on this is being conducted through the United Nations Economic Commission for Europe - Working Party 29, an informal working group on harmonized worldwide heavy-duty vehicle certification procedures (UNECE 2009). Harmonized standards allow companies to reduce the costs required to certify their products in different areas of the globe.

With regard to the second item, hybridization provides the possibility of downsizing the internal combustion engine in some instances to better match the required load. However, there are not always enough certified engine options for a company to realistically use. Policy options that make it easier to use smaller engines in hybrid systems could also increase fuel savings.

Regarding the final point, heavy vehicle engines are currently certified apart from the vehicles themselves. A vehicle certification standard could make it possible for hybrid systems to achieve emissions compliance using the best engine for the design. Although some initial work has been carried out in this area (see, for example, EPA 2007), more work is needed.

3 Applications and market situation

3.1 Introduction

Transportation of goods is a basic economic activity of the logistical chain from source of materials to production of end products and from place of production to place of consumption. Transportation of persons or a group of persons is part of the public transportation system in a region, country or city. These activities of transportation are part of the total industrial and economic system in a country.

3.2 Overview Vehicle Categories

A classification of heavy-duty hybrid vehicles according to purpose or operational application has been agreed upon to focus the study.

Main categories	Sub categories
Bus	• City transportation • Regional transportation • Long distance transportation
Truck	• City distribution/delivery of goods • Regional distribution • National and international transportation • Niche applications, e.g. garbage collection
Non-road mobile machinery	• Construction, mining, and earth moving: loaders, excavators, dumpers, bulldozers, etc. • Agriculture and forestry: tractors and their accessories, harvesters, forwarders, etc. • Transportation of goods and material handling: forklifts, straddle carriers, Rubber Tyred Gantry Cranes, terminal tractors, etc. • Municipal or janitorial machines: gardening, cleaning, etc.

Table 3: Main categories of heavy duty vehicles

Commercial goods vehicles in Europe have been classified as follows:

- LCV / LDV : Light Commercial/Duty Vehicle, any vehicle up to 3.5t GVW [1]
- HGV : Heavy Goods Vehicle, goods transport vehicles above 3.5t GVW
  - MDV : Medium Duty Vehicle, 3.5-15t GVW, including both rigid and drawbar trailer vehicles. Vehicles in this segment tend to be predominantly used as delivery vehicles with majority urban driving and frequent stop/start activity.
  - HDV : Heavy Duty Vehicle, above 15t GVW, including both rigid and articulated vehicles. Vehicles in this segment tend to be used for regional and long haul distribution with largely continuous high speed driving and infrequent stop/start activity.

[1] GVW : Gross Vehicle Weight. In case of an articulated vehicle : GCW : Gross Combination Weight.

In the USA commercial goods vehicles are classified according to the class categories, class 3 up to class 8 (http://en.wikipedia.org/wiki/Truck_classification) :

- MDV : Medium Duty Vehicle : class 4, 5 and 6
- HDV : Heavy Duty Vehicle : class 7 and 8

3.3 Overview Vehicle Applications

In Table 4 an overview is presented about vehicle category, application and regional characteristics. This table shows some of the differences in the used vehicles in any application in a category.

The procurement process for goods vehicles in Europe shows some difference from the USA.In Europe the basic vehicle chassis is chosen from a catalogue (a list of complete vehicle chassis configurations) of the vehicle manufacturer and various options can be added. The required body will be fixed to the chassis by the body manufacturer. In the USA the transportation company selects a set of basic components (e.g. cab, engine, transmission, axles, options) and the vehicle manufacturer will assemble the vehicle and then the required body will be added to the chassis by a vehicle body manufacturer.

These differences in the buying process influences the demand for hybridization of the drive lines of the purchased vehicles and also the hybridization of components of the vehicles, such as electrification of the systems for the hotel loads in the cab of the vehicle and subcomponents of the engine such as air conditioning, water pumps, cooling fans, and oil pumps.

Vehicle category	**Application**	**North Americas**	**Europe**	**Asia**
Truck				
	Delivery of goods in cities and urban areas	Class 4, 5, 6; Parcel delivery vehicle	Up to 20 ton GVW single truck, up to 32 ton GCW combination vehicle	Small delivery vans, single delivery truck
	Regional distribution	Class 5, 6, 7	Up to 40 ton GCW combination vehicle	Single truck (2- and 3-axle)
	Inter- and national transportation	Class 7 and 8	Up to 40 ton GCW combination vehicle	
Bus				
	City transportation	Hotel shuttle bus, city bus, transit bus, coach	Taxi bus (up to 9 persons), city bus (up to 50 persons), articulated bus	Small bus (up to 12 persons)

	Regional transport	Schoolbus (2 axle), transit bus	Regional bus(2 axle)	Regional bus (2 axle)
	Long distance travel	Long distance bus (2- and 3 axle), coach	Touring bus (2- and 3 axle)	Touring bus, coach
Niche Application				
	Refuse collection	Garbage truck (2 axle, 3 axle)	Garbage truck (2 axle, 3 axle)	Garbage truck (2 axle, 3 axle)
	Lift tractor in ports, terminal tractor	Single tractor, 2 axle (lift truck for moving trailers)	Single tractor, 2 axle	Single tractor, 2 axle
	Non-road mobile machinery : construction, earth moving, agriculture, forestry, material handling, municipal machines	2-, 3-, 4-, 5-axle single truck, dump trucks , bulldozers, crane trucks, straddle carrier, excavator.	2-, 3-, 4-, 5-axle single truck, dump trucks , bulldozers, crane trucks, straddle carrier, excavator	
	Others, Specials	Fire engines	Fire engines	

Table 4: Heavy Duty Vehicles – Vehicle Category, application and regional characteristics

3.4 Vehicle supply, Vehicle manufacturers

Due to the fact that the heavy-duty vehicle market is so widespread with so many different applications, it is impossible to give a complete overview of the vehicle manufacturers in this chapter. Specialized databases or reports are available for every vehicle application and in this chapter we just want to show an example related to truck manufacturers.

For applications in the Medium Duty Vehicle segment most truck manufacturers are using a parallel hybrid configuration using Li-Ion battery technology as seen in Figure 21 (this is a non-exhaustive list of course).

Examples

Truck Manufacturer	GVW / Usage	HEV Type	Energy Storage	System Configuration	Claimed FC Improvement
Daimler (Atego BlueTec)	12.0 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4 cylinder 44kW electrical machines +60kg weight increase (total vehicle)	20%
MAN (TGL 12.220)	12.0 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4.6L 4 cylinder 2 and 6kWh battery options 60kW electrical machine (425Nm) +100kg weight (reduced payload)	15%
DAF (LF 45)	7.5 Tonne (Distribution)	Parallel (P2)	Li-ion Batteries	Engine downsized to 4.5L 4 cylinder 44kW electrical machine (420Nm) 2km full EV range (fully charged)	30%
Kenworth (T270 / T370)	11.5/15.0 Tonne (Distribution)	Parallel (P1)	Li-ion Batteries	Paccar PX-6 engine with ISG Eaton 6-spd ultrashift transmission 340volt Li-ion battery pack 44kW electrical macine +200kg weight (50kg battery)	20%
Peterbilt (330)	12.0 Tonne (Distribution)	Parallel (P1)	Li-ion Batteries		30%
Hino (Ranger)	13.0 Tonne (Distribution)	Parallel (P1)	NiMH Batteries	Hino J05D engine 4.7L 36kW electrical machine (350Nm) 288volt NiMH battery pack	20%

Source: OEM websites and public information

Figure 21: Examples Hybrid Truck Manufacturers

In the Heavy Duty Vehicle segment, applications such as refuse trucks with hybrid drive systems are now coming to the market. Other niche applications are investigated for hybridisation.

Volvo Trucks started as one of the first with the mass production of hybrid trucks. In June 2010, the first series of about 100 hybrid trucks was scheduled to be produced in the Volvo Trucks plant in Ghent, Belgium. They will be used primarily for distribution applications and garbage collection in urban environments.

Figure 22: Volvo FE Hybrid

The hybrid technique is particularly appropriate for operating cycles involving repeated stops and starts and a period of intensive field testing has shown that fuel savings of more than 30% can be achieved.

Hybridisation of heavy duty vehicles for long haul transportation is less valuable because of the low economic value of the reductions of the operational costs, such as reduced fuel usage, for the transport company.

The benefits of a hybrid system are dependent on the application of the vehicle and best suited to lower duty cycles and frequent acceleration/deceleration :

- Simple parallel HEV configuration appears suited to most commercial vehicles
- "electrification" cost challenge may provide opportunities for cheaper mechanical systems like engine cooling systems and power steering systems
- However, electrification of heavy duty drive systems can lead to a higher increase in system efficiency

3.5 Heavy Duty Hybrid Vehicle Activities Around the World

3.5.1 North America

This section will cover the various activities happening in the United States.

In the United States, the 21st Century Truck Partnership (21CTP) is a collaborative effort between the U.S. Government and the heavy-duty vehicle industry. The vision of the partnership is to promote a trucking and bus industry that will move freight and passengers safely and cost effectively with little or no pollution while drastically reducing industry's dependence on imported oil. Some specific R&D efforts related to advanced heavy-duty hybrid propulsion systems are part of this partnership.

The purpose of the advanced heavy-duty hybrid propulsion systems work under 21CTP is to "promote research focused on advanced heavy-duty hybrid propulsion systems that will reduce energy consumption and pollutant emissions" (21CT 2006). The top-priority R&D areas being addressed include these:

- reliability of the hybrid drive unit
- system cost
- energy storage system reliability
- energy storage system cost
- demonstrated ability to meet 2007 heavy-duty vehicle emissions requirements
- a target 60% improvement in fuel economy when compared with that of today's conventional non-hybridized heavy-duty vehicles.

In addition, as part of the American Recovery and Reinvestment Act (ARRA), 48 new projects were announced in August 2009 in the area of U.S. Batteries and Electric Vehicles; the total award was $2.4billion (U.S. dollars). Award projects relevant to advanced heavy vehicles include the following:

- A $229 million award was given for battery production in Holland, Michigan, to Johnson Controls, a lithium ion battery producer; Johnson Controls will be supplying batteries to Azure Dynamics, a maker of commercial hybrid vehicles. Other major battery manufacturers also received funding, and their batteries may be used in other heavy vehicle projects.

- Navistar, Inc., was awarded $39.2 million to develop and deploy 400 electric vehicle delivery trucks with a 100-mile range.
- Smith Electric Vehicles received $10 million to develop and deploy 100 electric vehicle light- and medium-duty trucks and vans.
- Allison-Transmission received $62.8 million for increasing the capacity to manufacture hybrid systems for the commercial truck market.
- Delphi Automotive Systems received $89.3 million to expand manufacturing of existing electric drive power electronics components for both passenger and commercial vehicles.

In addition, a new effort announced in May of 2010 directs the US Government in conjunction with Canada to include heavy duty trucks in fuel economy standards in an effort to reduce pollution (including green house gas emissions) and reduce oil imports. A goal of July 30, 2011 has been set for the determination of the new targets for fuel efficiency for heavy trucks (Runningen and Hughes 2010, Lee 2010).

In addition to the government programs mentioned above, various groups exist in the United States with the purpose of assisting with the deployment of advanced powertrain technologies for heavy trucks. One such organization is the Hybrid Truck User's Forum (HTUF). It is a national, multi-year, user-driven program to speed the commercialization of medium- and heavy-duty hybrid and high-efficiency technologies. HTUF is operated by CALSTART with project support and sponsorship from the U.S. Department of Energy, the U.S. Army's National Automotive Center (NAC) and the Hewlett Foundation.

More information : http://www.calstart.org/projects/hybrid-truck-users-forum.aspx

3.5.2 Europe

This section will cover the various activities happening in Europe.

Besides activities initiated by national or regional governments in the EU countries, most important driver on European level to stimulate developments and demonstrations of heavy-duty hybrid vehicles in Europe is the **European Green Cars Initiative (EGCI)** (www.green-cars-initiative.eu).

It is one of the three Public Private Partnerships (PPP) launched by the European Economic Recovery Plan, which was announced by the President of the European Commission on the 26th of November 2008. The automotive sector was selected with the building and manufacturing sectors because of the severe impact of the crisis on their activities, combined with high opportunities for green growth. The objective of the PPP EGCI is to support Research & Development on technologies and systems that are able to bring breakthroughs in the goal of Europe to achieve a green Road Transport System, safe and reliable, and using renewable energy sources. Apart from loans provided through the European Investment Bank, the PPP European Green Cars Initiative makes available on the period 2010-2013 a total of one billion EURO through R&D projects set up jointly by the European Commission, industry and research partners, and the EU Member States.

In 2010, the support for European research projects under the EGCI started with the first calls for proposals (with a total indicative EC budget of 108 Million EURO) published in July 2009. Thirty projects were selected for funding, with a focus on electrification of road transport, including research on electric vehicles, batteries, hybrid technologies, and integration of electric vehicles into smart electricity grids. In July 2010, a second round of calls was published, covering three major R&D pillars: research on electric and hybrid vehicles, research for heavy duty vehicles based on internal combustion engines, and research on logistics and co-modality.

In addition to this funding of research projects, the European Investment Bank continues the implementation of the European Clean Transport Facility as a contribution to the European Green Cars Initiative. Until now, 8.2 Billion EURO of loans have been approved for the automotive sector under this scheme.

While the electrification of passenger cars and light-duty vehicles is predicted to increase over the next decade and to be implemented progressively in our cities, the powertrains of heavy-duty vehicles necessary for long distance transport are expected to remain based on the internal combustion engines. Although the powertrains of the commercial vehicles are already very optimized towards fuel efficiency, the predicted increase in goods transport demand requests that new technologies are investigated in order to compensate the overall increase of fuel consumption and its effect on the carbon footprint of freight transport. These efforts towards more energy efficient trucks must cover three main areas of R&D:

- vehicle efficiency
- driveline efficiency
- driver efficiency

And such as for electrification, timely developments are also necessary in the view of demonstrations, production, market introduction, and regulatory frameworks. At the same time, CO2 emissions from freight transport can be further reduced through measures to optimize the use patterns of vehicles and the logistics schemes in general. City logistics are a crucial part of the overall picture. Usually hubs at the city periphery are used as switching points for the goods. In the longer term it should be possible to convert large trucks into smaller vehicles, and vice verse, and to use electric propulsion while moving within the city provided an adequate infrastructure is available (e.g. for battery charging, etc).

The EGCI calls generated lot's of new heavy-duty hybrid vehicle projects. One of them is the **Hybrid Commercial Vehicle (HCV) project** (http://www.hcv-project.eu/overview.shtml) for reducing the emission of climate gases and other emissions in urban areas. Commercial vehicles stand for a not insignificant part of pollution in todays city environments and hybridisation of said applications can to a large degree decrease the emitted substances. Electric hybrids have so far shown a large potential, however the commercial success is heavily dependant on both the cost and benefits.

Figure 23: Demonstrators HCV Project

The different hybrid technologies will be demonstrated in four vehicles from four different manufacturers throughout large parts of Europe and evaluated in real life situations. The project consists of 18 partners and includes both large vehicle manufacturers and large companies in the vehicle industry, as well as institutes, universities and smaller companies.

The HCV project aims to enhance the further reduce fuel consumption and to decrease the cost of a hybrid system. Test methods, certification procedures and subsystems will be further developed and the market opportunities and barriers for hybrid commercial vehicles will be evaluated in conjunction with commercial vehicle operators in a user forum.

In order to ensure that the vehicles meet the needs of potential users and that new technology can be smoothly and appropriately implemented, input from users and potential users of hybrid commercial vehicles is needed. This **Hybrid User Forum** (http://hybriduserforum.eu/) was established to facilitate exchange among users – including public transport operators, trucking firms, waste removal services, delivery and courier companies, public authorities, network representatives and others – to help set frameworks for operating hybrid commercial vehicles (e.g. air quality management, CO2 reduction, noise abatement) to ensure that the needs of (potential) users are represented and that communication between researchers and practitioners is fostered.

Another platform is **HyER "Hydrogen Fuel Cells and Electromobility in European Regions"** in which thirty-two European Regions and Municipalities agreed to work together to accelerate the deployment of electric battery and electric fuel cell vehicles and their required infrastructure in local transport systems. More information : http://www.hy-ramp.eu/

CHIC, the Clean Hydrogen In European Cities Project, is the essential next step leading to the full market commercialization of Fuel Cell Hydrogen powered (FCH) buses. The project involves integrating 26 FCH buses in daily public transport operations and bus routes in five locations across Europe – Aargau (Switzerland), Bolzano/Bozen (Italy), London (UK), Milan (Italy), and Oslo (Norway).

The CHIC project is supported by the European Union Joint Undertaking for Fuel Cells and Hydrogen (FCH JU) with funding of 26 million Euros, and has 25 partners from across Europe, which include industrial partners for vehicle supply and refuelling infrastructure. The project is based on a staged introduction and build-up of FCH bus fleets, the supporting hydrogen refuelling stations and infrastructure in order to facilitate the smooth integration of the FCH buses in Europe's public transport system. An important part of the project will be to assess the environmental, economic and social impacts of the use of hydrogen powered buses. The objective of CHIC is to move these demonstration vehicles towards full commercialization starting in 2015.

On national level, we also see projects on hybrid buses in e.g. Belgium and the Netherlands. In Belgium, the public transportation company De Lijn is putting 79 hybrid buses (from midi buses up to articulated buses) into service in 2010 in different cities.

Figure 24: Hybrid diesel-electric bus in Bruges, Belgium (De Lijn – Public Transportation Company)

In the Netherlands, the company APTS has developed the Phileas concept. The concept is a public transportation system with high frequency on dedicated bus lanes with special buses with a parallel hybrid propulsion.

Figure 25: Phileas bus in Eindhoven, the Netherlands (Courtesy of APTS)

3.6 Market deployment and barriers

Nowadays the transportation sector is a marginal profitable business, especially due to the economic situation in the world during 2009 and 2010. Investments in new equipment are delayed. In the EU sales of HDV in 2009 were 48% less than 2008, and during the first half of 2010 HDV sales fell 16% compared to the first half of 2009 (http://www.acea.be/images/uploads/files/20100709_ER_1006_2010_II_Q1.pdf).

In Europe there are indications that the transportation sector is slowly recovering and that could result in new investments by the end of 2010.

Key issue for commercial hybrid vehicles remains the aspects in the business case : savings in fuel costs must be greater than extra purchase/lease and other operational costs of hybrids compared with conventional vehicles**.**

Other aspects for purchasing commercial hybrid vehicles besides economics also play a significant role, such as risk aversion to adopting new technology and concern for required changes to driver habits.

Though in cities and urban areas hybrid vehicles contribute to the emission reductions, to improve the local air quality, quieter traffic and thus cleaner transportation in general. In several cities and urban regions in Europe and the USA so called “environmental zones” are valid and required by the local governments. Only vehicles with special labels are allowed to enter these environmental zones.

Market studies predict a future market share for Hybrid Light Duty and Medium Duty Trucks in Europe and the USA :

- For light duty trucks, hybrid diesel will gain market share, while diesel ICE share will fall
- For medium duty trucks, diesel ICE will remain the most prevalent technology, with a limited tendency towards hybrid
- For heavy duty trucks, diesel ICE will remain the most prevalent technology

In the case of hybrid buses, we can see more and more demonstration projects on city buses but some kind of government support is still needed to make the demonstration projects economically possible.

Because the type of applications in non-road mobile machinery are even more diverse than those in trucks and buses, we will focus on this topic more in detail in next chapter.

4 Non-road mobile machinery (NRMM)

4.1 Introduction

Like in automotive industry hybridization and electric power transmission is a trend in off-road working machines. This chapter reviews the existing situation and future trends in the field of non-road mobile machinery. Different types of machines are presented and the overall market is estimated. The differences between road and off-road vehicles are evaluated both from the motivation and technical point of view. Real examples of existing commercial and prototype vehicles are presented. The future trends are analyzed based on own research and state-of-the-art review.

Reduction of fuel consumption and emissions are key issues in the design of today's cars. Downsized turbocharged gasoline and diesel engines provide smaller consumption and emissions without any downscaling in the performance. Engine start and stop automatics and electric auxiliaries will minimize the idle state consumption especially in the urban environments. Alongside with the improvement of the traditional technology the electric power trains have sneaked back to the cars after being "forgotten" almost 100 years. Electric motor has a superb efficiency through the operational area compared to the ICE and the unique possibility to regenerate energy while braking. Bottleneck has been the poor energy density of electric storages. With hybrid technology the energy storage problem can be handled and the benefits of ICE and the electric transmission combined. Putting the two technologies together will increase the manufacturing cost but Japanese manufacturers Toyota and Honda have shown that hybrid transmission in personnel cars is already successful business. The development of battery technology – especially Li-Ion type of batteries - has made it possible to develop plug in hybrids and even full electric cars for urban traffic.

Non-road mobile machinery (NRMM) is less familiar to the general public than the road vehicles but despite their numeric inferiority NRMM's part of the overall diesel consumption and emissions is remarkable due to the professional usage. These vehicles work in different specific tasks typically 8 hours per day or in some applications such as mines and harbors often 24 hours per day. Traditionally the performance in the specific task has been the nominating factor in the design and efficiency has not been the highest priority. The increasing fuel price and tightening emission regulations has increased the importance of efficiency and the electric or hybrid electric transmission is seen as most promising technology due to the fact that it will also generate other side benefits such as better controllability/operator comfort and more freedom in the machine structure.

It has to be emphasized that in NRMM the consumption has to be calculated relative to the productivity. In most cases the hybridization affects to performance, thus it's not fuel consumption as liter-per-hour but in terms of productivity such as liter-per-tons.

In NRMM the electric transmission is not as new issue as it is among the road vehicles. In certain application areas there have already a long time been used electric transmission mostly with full electric architecture. In all applications where net power is feasible it has been always utilized. The most typical area is different type of rail based vehicles such as mobile cranes. In indoor or partially indoor applications such as pallet transportation in warehouses the use of ICE is a problem due to the exhaust gases. Therefore the forklifts and automatically guided vehicles (AGV) are today the biggest existing group of battery powered mobile machinery. They utilize the traditional lead-acid battery technology and quite often the limited energy capacity is solved with changeable battery packs. Diesel electric power trains with high efficiency and easy controllability are also attractive when machine size and/or power is big enough. Typical examples of diesel electric vehicles are rubber tired gantry cranes and straddle carriers both having a complicated structure and high power as well as gigantic dumpers power up to several megawatts.

From power and energy point of view, most of the NRMMs are similar to the heavy duty road vehicles. The mobility doesn't allow net or trolley supply and the work cycle/shift requires the vehicle to carry enough energy onboard for operation of several hours. Additionally the refueling should be performed in few minutes. The biggest difference to the road vehicles, which affects to the hybridization, is the duty cycles. Road cycles are typically divided to city and highway ones. City cycles include continuous acceleration and deceleration generating a peaky load and regenerative parts whereas highway cycles include mainly continuous relatively high loads. Road vehicles typically utilize both cycles during their normal operation. However, quite often – depending on the vehicle and the user - most of the vehicle's operational time only the other cycle is applied. Mobile machines don't have any common cycles but each machine type has an own cycle depending also on the prevailing task properties.

4.2 Machines and application areas

Non-road mobile machinery (NRMM) include – mainly wheeled or tracked – machines targeted for a specific tasks in off-road conditions. Traditionally NRMMs are divided by the application area. The biggest area is construction machines or earth-moving machines including all kinds of loaders, dumpers, excavators, land rollers, bulldozers, etc. Transportation of goods or material handling equipment includes forklifts, AGVs, mobile cranes, RTGs, straddle carriers etc. The municipal or janitorial machines include different type of gardening and cleaning machines often targeted also for on-road operations. A big but clearly own group is tractors and other agricultural (and forestry) machines. There is some overlapping in this classification. Agricultural tractors are used a lot in janitorial applications as well as some loaders are used both in janitorial and construction applications. However, it seems that today's trend is specialization. Machines are more and more designed for relatively niche application area and the variety of their size is widening: there will come even bigger and at the same time smaller ones.

As the application areas also the power varies a lot. Power of small loaders and utility vehicles starts from 10kW and the gigantic dumpers have power range up to 3 MW.

From the hybridization and electrification point of view it's more informative to classify machines based on their work tasks. In hybrid system development the work cycle is very important (as discussed in chapter 2.3.4 - Drive Cycle Analysis) and therefore the task is more informative than the application area. Work tasks vary a lot but in general they can be divided in three main classes: transportation, manipulation and continuous high load tasks. Transportation tasks include acceleration and deceleration transients and nearly constant load transportation part. Loading of transported material – either bulk or parceled – is done in most cases by the machine itself with an own manipulator. This manipulative part takes only a short part from the cycle and the overall energy. Non-manipulative transporting machines are typically different type of dumpers – often being similar to standard trucks. They are loaded by another machine and unloading is done by dumping the whole load. Parcel transportation machines and their manipulators are designed based on the parcel. Most typical examples are forklifts, AGVs and different types of container handling machines.

Figure 26: Transportation machines

From left to right:
- Amman Yanmar small dumper C30R-1 http://www.kh-koneet.fi/
- Sandvik TH320 underground truck http://mediabase.sandvik.com/smc/
- Kalmar DRF Reach Stacker, http://www.kalmarind.com/
- Caterpillar forklift GC20-33N, http://www.catlifttruck.com/

Manipulative machines have a manipulator for a certain work task, which can vary a lot. The most of the cycle is spent to the manipulation. Most common manipulative machines are different size excavators and loaders. Loaders can also be transportation machines. The relation between manipulation and transportation during the cycle makes the change. Mine loaders (LHD) for example are typically transporting more than manipulating. Additionally there are plenty of special manipulative machines such as harvesters, bulldozers, road graders, etc. Parcel transportation machines having a manipulator for a certain type of parcel don't typically spend very much time for the manipulation but the cycle is clearly transportation.

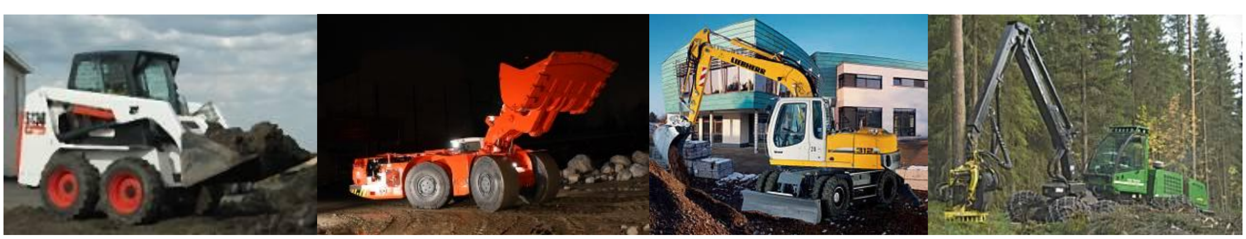


Figure 27: Manipulative machines

From left to right:
- Bobcat S130 small loader
- Sandvik LH514 undergound loader, http://www.sandvik.com/
- Liebherr excavator A312 http://www.liebherr.com/
- John Deere 1270D Harvester http://www.deere.com

An agricultural tractor is undoubtedly a NRMM but difficult to classify. It's mainly a mobility and power source for different kind of transportation and manipulative tools called implements. Without any tools it can only transport its driver. Agricultural and janitorial devices may also differ in terms of working hours. In agriculture even very low (few hundreds) working hours per year are normal compared to classical non-road mobile working machinery thousands of hour per year. Therefore it's easier to keep it as an own class.

Machines which are mainly targeted for recreational purposes and human transport such as ATVs snow mobiles, etc. are left out of this study. However, one must remember, that they can be used as work machines also. Military machines especially armored personnel carriers/system vehicles are targeted to off-road with demand of high speed capability on road. They have so many similarities with the work machines thus they are included. There have also been a lot of hybridization activities among these vehicles, making them even more interesting.

Important requirement in this study is also that machines are able to navigate freely. Machines moving on rails such as cranes and rail gantries are excluded despite they clearly are considered as work machines. Trains are their own genre, however there is a term hybrid presented while meaning a locomotive capable of operating under contact line or independent operation in diesel-electric mode (possibly with limited performance).

4.3 Traditional powertrains for non-road mobile machinery

Today's work machines generate their energy almost totally with energy efficient diesel engines. The power is transmitted further either mechanically or hydraulically. Hydraulic power transmission is de-facto in all high force/torque manipulators such as buckets and booms due to the fact that at the moment there is no replaceable technology available. In small sized and/or slowly moving (<20km/h) machines the hydro-static transmission is used quite much for traction also. Hydraulic transmission provides in-built continuous variable speed transmission and high torque. At higher speeds the efficiency of hydraulic transmission decreases rapidly and mechanical transmission is more attractive. Mechanical transmission can be realized with traditional manual clutch and gear box combination but today most of the machines have a combination of mechanical gear box and hydro dynamic torque converter or CVT-transmission or a variable speed planetary gear controlled with hydro-static actuator.

4.4 Market

Due to the very different application areas, it's relatively difficult to get accurate fleet or market information covering the whole area of work machines. The presented rough figures are based on several sources.

Construction machines/earth moving machines are the biggest single group in this area and agricultural machines are the second biggest group. The size of construction machine market (sold new machines) 2008 is roughly 110 – 130 BUSD/year worldwide [freedonia], [Construction market]. The agricultural machine market is 93 BUSD/year respectively [Agricultural market]. In EU overall mobile work machine market is 60 BUSD [market survey] and the construction machine and agricultural machine markets are 20 BUSD each. Thus the other groups (janitorial and material handling) are roughly 20 BUSD. If the EU ratio is the same all over the world, it can be estimated that worldwide market is 300 BUSD. From the hybridization point of view the interesting part is machine powertrain, which is typically 20% from the manufacturing cost.

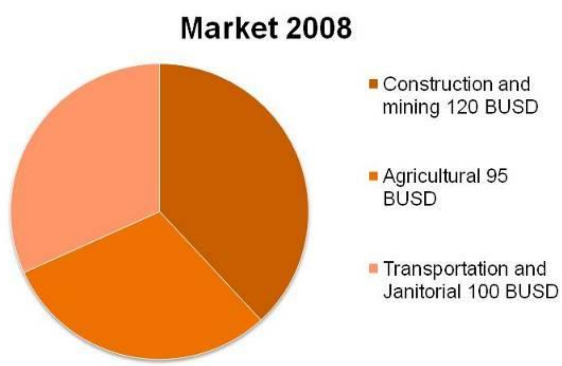


Figure 28: NMRR worldwide market 2008

It's difficult to give a average price for a "generic" machine but even the average price would be as high as 300.000 USD there would be 1.000.000 machines sold worldwide each year. Due to the fact that smaller sized machines have bigger volumes the total amount is clearly higher. When these machines are in professional use, their daily operation hours are 8 and lifetime between 5 and 10 years.

According to [Kunze, G.] the total diesel consumption in Germany was 29,0 million tons on 2007. Construction and agricultural machinery part from the overall consumption was 3,67 Mt, which is 12,7%. One must remember that amount of diesel powered personnel cars is relatively high in Germany. During last 10 years the share of diesel cars of new registrations has been between 30% and 40%.

Despite these machines are a niche group comparing to the road vehicles they provide a remarkable potential to reduce energy consumption and emissions worldwide.

4.5 Trends in the non-road mobile machine industry

As part of heavy metal industry the mobile machine industry has not generally been considered to be a high tech industry. However, it has already a long time been very advanced in using electronics, advanced materials and embedded control systems. Today most of the manufacturers use more resources to software development than mechanical design. The most advanced examples are automatic multi machine transport systems such as Sandvik's Automine [Automine] and Cargotec's Autostrad [Autostrad].

Automine is a semiautonomous loading and hauling system for underground mines. It includes LHDs and dumpers, which both are capable to navigate autonomously without any additional infrastructure. Only loading and exceptional situations need the help of operator, who supervises - and occasionally operates - several machines from a control room.

Figure 29: Automine control room

Autostrad - autonomous straddle carrier system is based on a conventional straddle carrier. This vehicle can autonomously pick up, carry and place shipping containers, allowing movement of containers from land-side vehicles, to holding yards, to quay cranes and back.

Figure 30: Autostrad straddle carrier

From the technology point of view the clear trend is to improve the productivity, operator comfort and machine safety by improving the smooth control of the machine traction and actuators. Additionally the increasing automation level provides different measurements such as load sensing, actuator positioning, etc. and enhanced support for task execution and data transfer.

Machine types are evolving to two opposite directions. The need for improving productivity promotes more and more task specific machines when the very close construction sites in city centers and cost efficient one man contractors drive towards multipurpose machines.

From the market point of view the megatrend is increasing renting and leasing business, which is driven both from financial and taxation reasons. This is especially typical for construction machines due to the bid and build project nature of the construction industry. [Freedonia].

4.6 Existing commercial (H)EV work machines

Among the existing electric work machines the size really matters. Machines with electric power transmission are found from the smallest and the biggest classes of machines.

In the low power machines battery operation is technically and commercially feasible. Especially in applications where the environment requires zero emissions or low noise level, electric vehicles have a market. The largest application with no doubt is indoor forklifts both human operated and AGVs. Small utility vehicles used in janitorial and gardening services are also available as battery powered versions.

Figure 31: Commercial low power, electric driven vehicles

From left to right:

- AGV by Rocla
- Electric utility vehicle Gator TE by John Deere
- Polaris Ranger EV by Polaris

In the mid-power class from 50-200kW the amount of commercial (H)EVs is small but when the power increases, increases also the attractiveness of electric transmission.

The biggest machines are more often driven electrically. Rail machines such as different types of cranes are naturally electric due to the easy power supply by cable or trolley but also freely navigating machines such as gigantic dump trucks, straddle carriers and even LHDs (Load Haul Dump machines) are often electrically driven. Big size and power provides a very good starting point for (diesel) electric power train. First of all, in the high power systems the energy efficiency is more crucial. Especially in the megawatt-class the control of an electric transmission is much easier than control of a diesel mechanical system and finally in diesel electric systems the big size allows space for the needed additional hardware. The availability of traditional power transmission systems with megawatt power is also almost nil.

Figure 32: Commercial high power, electric driven work machines

From left to right:

- Liebherr T282B Dump Truck 2,7MW
- Kalmar ESW Straddle Carrier 400kW
- Sandvik Load Haul Dump (LHD) Toro 2500E 315kW

The three machines above are a good example how different the machines and the electrification motivation can be. Load Haul Dump (LHD) is supplied by a tether cable and the main motivation is the zero emission, which decreases the need of the ventilation in underground mines. In certain mines this is seen more cost efficient despite of limited driving distance of the cable machines and short MTBF of the cable. These cable supplied LHD machines are available in all power classes.

Dump truck and straddle carrier are both diesel electric. In a dump truck the diesel electric system saves fuel and reduces emissions due to the constant speed diesel. The electric drives provide better controllability, possibility to use trolley supply and electric braking with regeneration. Also the maintenance costs are smaller than with a traditional machine with mechanical transmission.

Due to the complicated structure of the straddle carrier the electric transmission is easier to build than conventional one but the main motivation is to decrease fuel consumption and maintenance costs. According to discussions with the manufacturer, the diesel electric straddle carrier is 20-30% more expensive comparing to diesel mechanic but smaller fuel consumption and lower maintenance costs give payback time of couple of years. While writing this the hybrid version with of the diesel electric straddle carrier has just been announced. The fuel consumption of the hybrid one is 16 l/h while diesel electric one is 21l/h and the conventional one 25l/h. Hybrid system is implemented with super capacitor buffer.

Figure 33: Cargotec (Kalmar) Hybrid Straddle Carrier

Commercial work machines with hybrid transmission are difficult to find. As mentioned, diesel-electric and battery electric machines are available but hybrids are yet very rare. One of the first is the mentioned Cargotec's (Kalmar) hybrid straddle carrier, which was presented in June 2008. The first commercial machines have already been supplied to the customers.

4.7 Drivers towards hybridization

Drivers towards hybridization are partly similar as in the car industry. The main drivers are the increasing oil price and tightening emission regulations, which both require better efficiency from the system. Requirement of smooth continuously variable transmission and actuator control are also promoting the use of electric transmission. Existing electric machines have proved that electric transmission needs less maintenance comparing to the traditional ones. Together with better efficiency this decreases the lifetime costs remarkably. Green imago, which is important in consumer market, is a plus in the work machine market but only very few customers – mainly in the municipal machine area – are willing to pay extra from the imago. Free placement of system components connected with flexible cables is important in complex structured machines. However, this can be solved with hydrostatic transmission also.

Compulsion is always the most effective driver. In work machines the compulsion driver are the emission regulations. The EU limits for emissions of variable-speed diesel engines to be installed in non-road mobile machinery according to [EC-directive] are illustrated in Figure 34. The type-approval dates for the engines are one year earlier. The emission limits of the US EPA Tier regulations go in line with the EU limits. As can be seen from the figure, the emission limits are tightening tremendously in near future for engines bigger than 37 kW. For example, the introduction of Stage IIIB will cut the PT emission limit of engines in the power range of 37–75 kW by 94 %, and the introduction of Stage IV will cut the NOx limit of 56–130 kW engines by 88 % and 130–560 kW engines by 94 %, respectively.

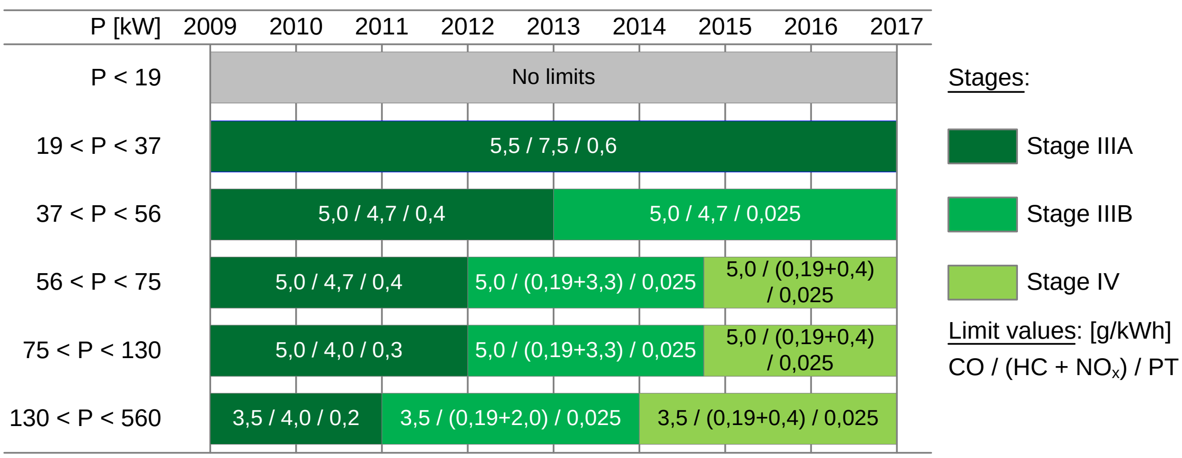


Figure 34: EU regulations for emission standards for diesel engines other than constant-speed engines to be installed in non-road mobile machinery

The internal combustion engine (ICE) of a conventional work machine is dimensioned to supply the peak power during the anticipated work cycle. Depending on the work machine type and its typical work cycle, the peak power demand might occur e.g. during acceleration, driving uphill with a full load, or driving against the pile when loading the bucket. The average power demand of the work cycle is often close to a half of the peak-power demand. In a hybrid electric driveline, the ICE can be downsized drastically due to the onboard energy storage that can be used during peak-power demand to provide extra power and to store regenerative braking power. With an energy storage big enough, e.g. a high power battery, the ICE can be dimensioned to provide only the average power. Thus, with hybridizing the powertrain, it is often possible to downsize the engine remarkably and thus, to achieve better fuel economy as well as less emissions. In addition, the emission limits of the downsized engine may be less tight compared to the original limits, because the downsized engine fits into smaller power class. As can be seen from Fig. 1, downsizing can be especially beneficial if the engine power can be downsized below 37 kW, since the Stages IIIB and IV do not concern engines that have net power below 37 kW.

Interesting question is how regulations will react to the amount of motors onboard. With a series hybrid power train it's easy to have several small power (<19kW) diesel generators as primary power source. According to regulations these machines would have no emission limits before end of 2017.

Development towards more environmental friendly NRMMs could be also be promoted by other political means. Passenger cars have been supported by governmental initiatives like taxation, direct investment subvention, free ride, environmental zones of the cities etc. sweeten the deal from customer side. There has been seen during the last years a huge financial support for passenger car R&D activities partially due to worldwide recession and difficulties of automotive industry. These same initiatives could also be used to promote hybrid – or generally more environmental friendly - mobile machinery.

Opposite drivers are again more or less the same as in the car market. Hybridization increases the system complexity and price. The higher purchasing price will be approved only if salesman can convince the buyer that the full lifetime cost will be lower. From the technology point of view the “not yet ready battery technology” and the lack of power electronics and electric motors fulfilling at least the automotive and more likely mobile working machinery durability requirements are also retarding the development. Additionally big technological steps are naturally resisted in the very conventional application areas.

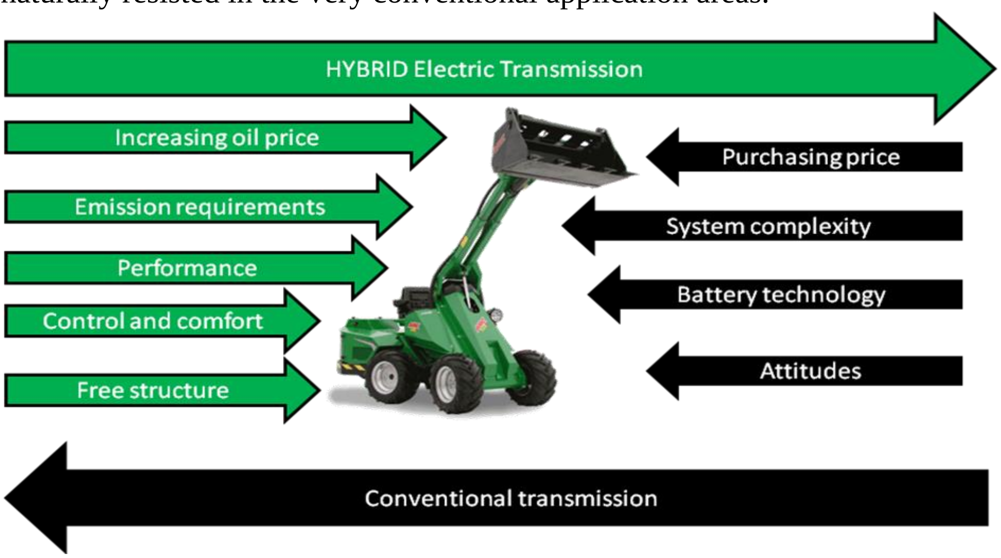


Figure 35: Drivers towards Hybrid Electric Transmission

4.8 Hybridization

4.8.1 Differences comparing to the road vehicles

From the hybridization point of view there are several differences between road vehicles and work machines. Perhaps the biggest is the huge variety in the work cycle. When road vehicles have similar cycles, each machine type has an own typical cycle. Work machines are also mainly in professional use thus the yearly operating hours are high. There is a comparison between work machines, cars and on-road heavy duty vehicles in table below.

	Car	Heavy duty vehicle	Work machine	Note
Operating hours	~ 250h/a	5000h/a	**5000h/a**	

Power	~ 100kW	100-400kW	**10kW – 3MW**	
Average operating power	20% of max.	40% of max.	**80% of max.**	depending on application
Cycle	city/highway	city/highway	**application specific**	
Speed	0-200 km/h	0-100km/h	**0-40km/h**	Many machines don't exceed 20km/h
Max. traction force/max. speed traction force	5	20	**10 - 30**	
Manufacturing series	mass	mass	**small series (10-1000/year)**	Agricultural tractors: tens of thousands/year
power transmission	mechanical	mechanical	**mechanical, hydrostatic, hydrodynamic**	
Power regeneration	city yes highway not really	city yes highway not really	**Depending on application**	
Practical lifetime	9 years	8 years	**5 – 25 years**	
Customer will pay for imago issues	yes	no	**No**	

Table 5: Comparison of work cycle of cars, heavy duty road vehicles and work machines

4.8.2 Work machine cycles

The potential benefits of hybrid electric transmission are depending strongly on the working cycle. On-road vehicles typically have very similar type of cycles. There are different types of model cycles for on-road vehicles in order to measure fuel consumption and emissions. Typical examples are Braunschweig city cycle and EPA-highway cycle. They are here used as examples of average on-road driving cycles.

Braunschweig City Cycle :

- Duration: 1740 s
- Average speed: 22.9 km/h
- Maximum speed: 58.2 km/h
- Idling time: about 22% (the first and last idle segments not included)
- Driving distance: about 11 km

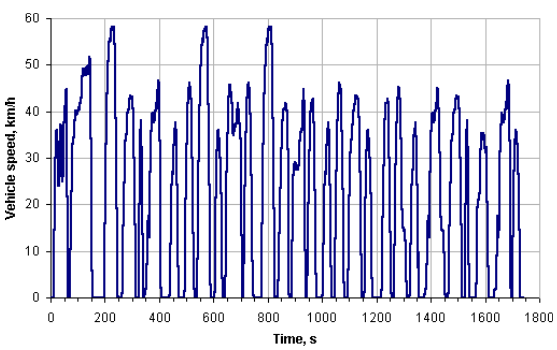


Figure 36: Braunschweig City Cycle

EPA Highway Cycle

- Duration: 765 seconds
- Total distance: 10.26 miles (16.45 km)
- Average Speed: 48.3 mi/h (77.7 km/h)

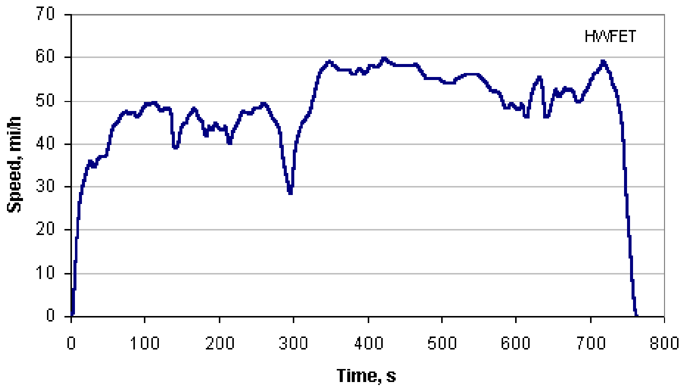


Figure 37: EPA Highway Fuel Economy Cycle

More information :

- http://www.dieselnet.com/standards/cycles/braunschweig.html
- http://www.dieselnet.com/standards/cycles/hwfet.html

As mentioned work machine cycles vary a lot depending on the application. Some of them are near car cycles when others – as the LHD cycle in Figure 38 – repeat exactly the same and very predictable cycle for a long time.

Note: work machine cycles below are presented in with power/time scaling when car cycles above with speed/time scaling.

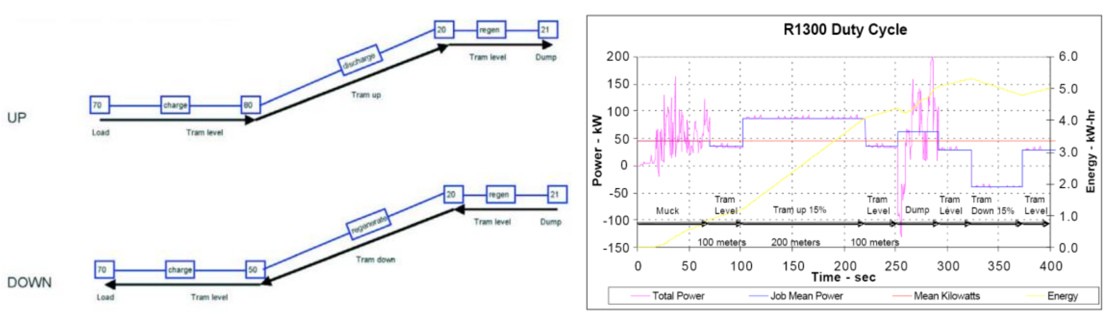


Figure 38: Load-Haul Dump cycle of a LHD machine

More information : http://www.hydrogen.energy.gov/pdfs/review04/tv_16_barnes.pdf

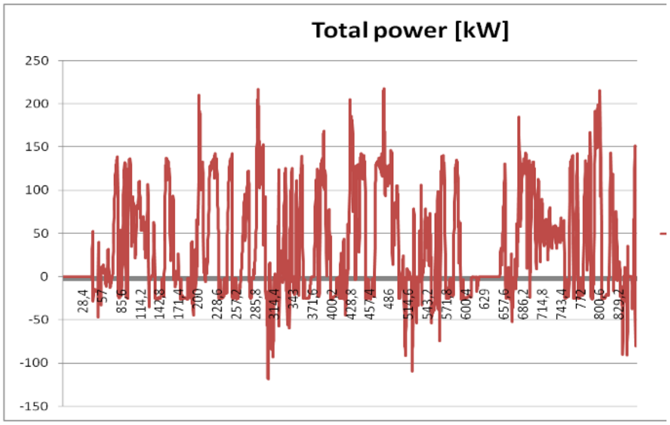


Figure 39: Duty cycle (130sec) of a straddle carrier

In both straddle carrier and LHD cycle there are subsets which set hard requirements for the energy storages. In LHD the regenerative part is long requiring a large storage in order to utilize all regenerated energy. Straddle carrier on the other hand produces short but very high power peaks requiring high power charging from the storage.

In construction machines the cycle very often includes idle periods when the machine is just standing still and waiting for a new task.

4.8.3 Hybridization trends

Work machines are typically purchased by companies for professional use. Company size varies a lot. Big corporations such as machine rental companies, harbor operators, mines, big construction companies typically have tens even hundreds of machines. In the other end are farms, small contractors (man+machine) who typically have one or few machines. In the small companies it's also possible that the machine owner drives the machine. In all cases the machine is a production facility and the purchasing is based on clear business logic: the capacity/lifecycle cost - ratio should be maximized. The lifecycle cost is the (purchasing price + all operating costs during the lifetime - possible resale value). Operating costs are mostly consisting of fuel and maintenance. Hybrid electric power train can improve the machine performance especially from the control point of view but a remarkable increase in the production capacity is difficult to increase. Also in the most cases the hybrid power train is more expensive than the traditional one. Therefore the minimization of the operation costs are only way to achieve market shares for hybrid electric machines. Only in the very limited areas such as janitorial machines the customer might be willing to pay extra for green image. In some niche areas, such as military, it's also possible to bring additional features (power for electric weapons, power station function), which can justify higher pricing.

Purchasing reasons of machinery do differ and the whole business is under evolvement. Classical ownership may be replaced more and more by leasing. In leasing there are three main types of motivation. Pure finance based are target optimize return of capital by avoiding owning the steel or seeking of taxation benefits due to different tax of leasing costs. Third reason is especially in construction business need for very large variety of machine types. For building project special machines may be needed on relatively short periods and projects do differ each to other. This leasing matter might be one instrument for governmental side to promote new technology by using taxation tools. Leasing would also be safe way for industry to explore productive benefit of new technology as well as offering limited time responsibly for machine manufactures. Leasing would offer beside a way to handle endurance risky of very new dimensioning and engineering – the cost of ownership would be more predictable.

In order to make HEV – machines competitive the operation costs are the key issue. How to increase the fuel efficiency and decrease the need of maintenance? It's clear that in most cases – depending on the cycle – the efficiency can be improved. However, the practical limit to decrease the fuel consumption is between 10 – 50%. Therefore the oil price is the limiting factor. However, we can expect that it will increase rapidly in the near future. Affect of oil price can be easily calculated. Conventional straddle carrier consumes 25l/h and hybrid one only 16l/h → savings 9l/h. The average running hours per year is 5000 and the average lifetime 5 years → 225.000 l. With existing diesel price the lifetime savings are 225.000 EUR but it increases linearly with the diesel price.

4.8.4 Hybrid architectures in NRMM

All standard automotive hybrid electric architectures – parallel, series and splitted [Ehsani 1], [Ehsani 2] - can also be used with NRMMs.

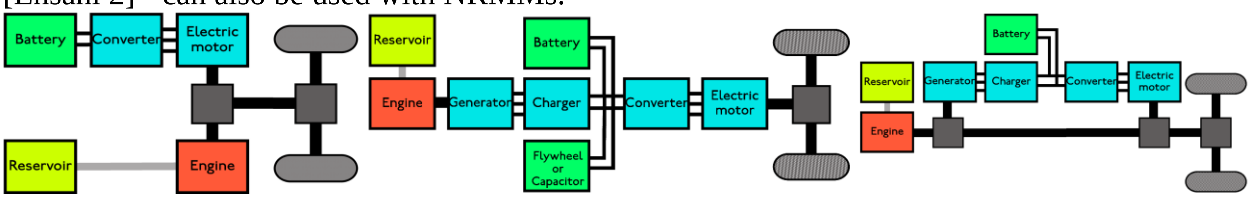


Figure 40: Hybrid topologies

Based on the existing e-machines and example prototypes presented in the next chapter it seems clear that in the big sized and power machines the series hybrid power line is the most attractive. Parallel hybrid is relevant in smaller machines and especially in the cases where hydro-static transmission is used with a cycle including high transients. Power split type of topology is the least attractive in NMRRs due to the fact that in most machines the mechanical power train is difficult or even out of question by reason of the machine structure. However, in agricultural tractors it could be feasible. Tractors are used a lot in continuous high power traction, thus the mechanical transmission has been and still is a key factor for energy efficient driving. Additionally the high manufacturing volumes make it possible to use more tailored solutions in the system.

4.8.5 Examples

4.8.5.1 Military

Hybrid electric power train has seen to be promising solution also for military vehicle platforms. Need for on board electric power has been increasing all the time. Modern armament technologies needs more and more electricity and especially in future the all electric weapons and all electric protection will need enormous amount of electric power compared to present needs. Using same electric power sources for power train and for the on onboard military systems, brings obvious synergy and increases payload capacity by reducing overlap of systems.

Fuel economics is other driving force to develop HE drive train for military vehicle platforms. Especially big armies have interest to cut costs of fuel logistics on battlefields. Also number of power source (fuels) options can give several attractive possibilities to produce effectively electricity for HE power train. Effectiveness can be effective way to use fuel itself or flexibility to use effectively local energy sources and logistics.

Electric driveline has been seen also promising way to improve off road mobility in military vehicles. This can be achieved with wheel or axle specific traction motors. Most of the military vehicle demonstrators has been based so far on wheel specific traction motors. With wheel specific traction its easier to optimize traction for different surfaces and driving conditions. Drawback in hub motors is the increase of unsprunged mass but in the speed range where military vehicles are normally used that’s not a big issue.

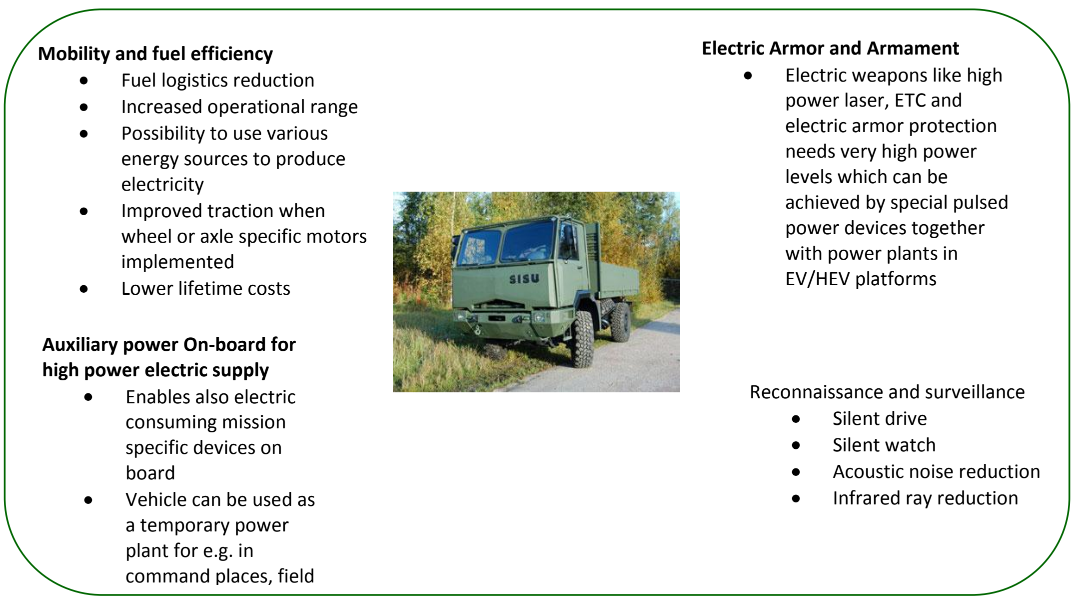


Figure 41: Why Hybrid Electric Military Vehicles ?

Number of different on board military systems which consumes electric power has been increasing all the time during last years. This has lead to situation where has been necessary to increase capacity of 24V battery system by placing more batteries in to a vehicle and also in some cases getting so called auxiliary power unit on board. Requirements for silent watch mission is challenging for conventional vehicle because electric is needed for surveillance and communication and electric production must be basically noiseless. Silent watch can last long periods especially when vehicle is unmanned.

Lower lifetime costs have been seen also one benefit of the HEV electric vehicles. Service need of electric motors and power electronics is less than ICE has and also lifetime is expected to be 2-3 times longer than 10000-15000h which is generally normal lifetime for an ICE. Also tire wearing and driveline failures are expected to be lower due to better traction controllability.

In next chapters are presented some state of the art military hybrid electric vehicles.

- ***General Dynamics – AHED***

The AHED 8x8 demonstration platform incorporates a series hybrid electric drive system. Key enabling technologies include in-hub wheel motors, pneumatic suspension, high temperature power electronics, and hybrid wheel/track steering. Figure 42 shows the power and propulsion elements. Modular wheel drives with motors provided by Magnet Motor are installed in each wheel hub. Motors are rated at 110kW each.

Motor Controllers are rated at 110 kW. Full H-bridge topography is used to allow the wheel motors to be operated as generators for regenerative braking, steering, and traction control. These controllers are packaged in modular dual channel packages that interface into a distribution manifold. The distribution manifold brings cooling; power distribution, motor conductors, and control interfaces together in a quick disconnect interface.

A 360 kW permanent magnet generator is mounted on the engine in place of a traditional flywheel. The system uses a generator controller that is both co-located and interchangeable with the motor controllers.

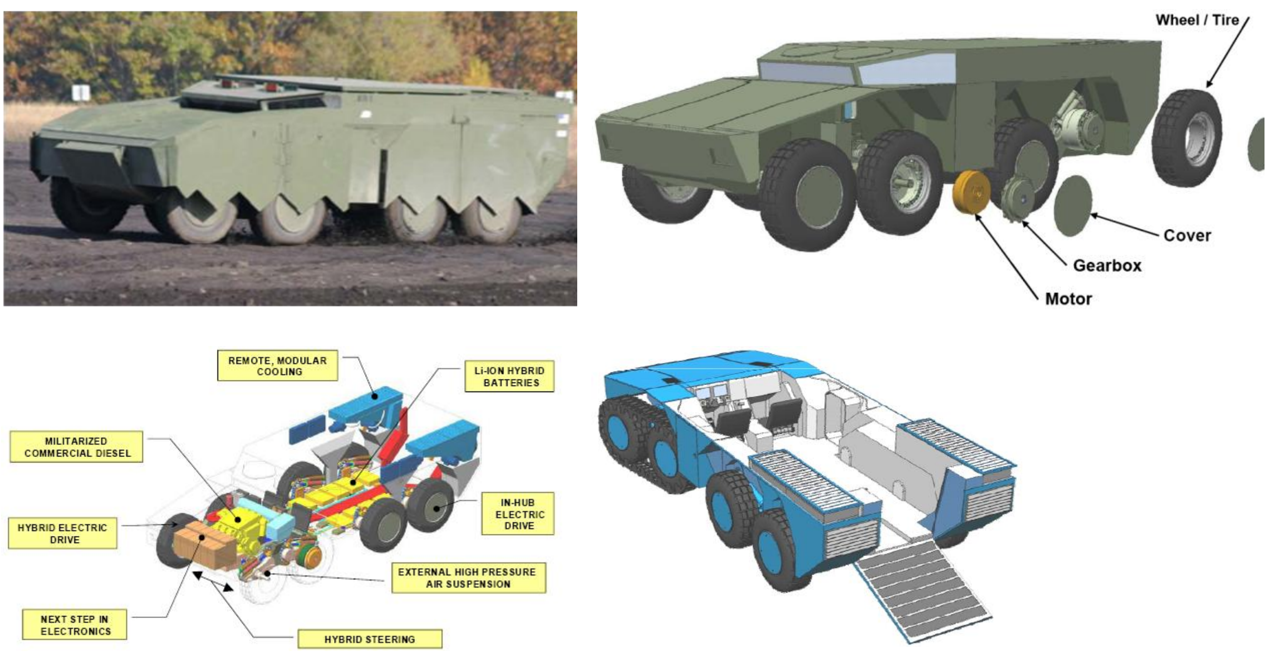


Figure 42: Advanced Hybrid Electric Drive (AHED)

The prime mover for the system is a 400kW version of the MTU 6V-199 engine. This engine is a militarized version of the Mercedes-Benz commercial truck engine and was selected due to its power density, efficiency, and favorable form factor.

Energy storage is provided through use of lithium-ion batteries. The bank developed for the demonstrator utilizes Saft HP16 cells that are packaged into modular batteries 24V, 23 kW each. Five battery packs make up the operating bank. Total bank capacity is approximately 7 kWh (C/3) at nominal bank voltage of 220 V. The platform is designed to host two parallel battery banks to allow tailoring of the power and energy per mission requirements.

Power Conversion requirements are met utilizing SatCon Technologies' DC/DC converters. For the demonstrator, two 90 kW units are being used. These bi-directional converters pass power between the fixed battery voltage and the floating (300-800V) DC Link.

The AHED 8x8 will operate in four basic modes: Hybrid (HEV), Electric Transmission (ET) Electric Vehicle (EV), and Auxiliary Power (AP). HEV mode is the basic mode of the vehicle and supplies the operator with improved fuel efficiency and significant "burst" power. Electric transmission mode is used when the hybrid energy storage system is depleted or inoperative. EV mode is used for silent or reduced signature operation. Auxiliary power mode configures the system to provide up to 300kW at 480 V DC for mission equipment or off board power requirements.

[General Dynamics - AHED] Advanced Hybrid Electric Drive (AHED) 8x8: Development Update, Mark Stephens, General Dymanics, The 6th International All Electric Vehicle Conference Bath, England, June, 13th – 16th 2005

- ***Rheinmetall Landsysteme GmbH – Gefas AVS***

The Gefas-AVS is build up out of different modules each of it consisting of a steel hull and the parts of a main assembly enclosed inside. To build up a Gefas-AVS at least two axle modules, a main module and a power module are needed. The front module and the rear module are used for completion of the vehicle.

The main components of the drive system are:

- a 4 cylinder in-line engine from the recent MTU Friedrichshafen GmbH series 890 HPD. This engine offers a performance of 410kW at about 4200rpm. It is specially designed for the use in diesel-electric drive system, uses most recent techniques like common-rail-injection or turbo chargers with variable turbine geometry and therefore offers a power to weight ratio which has not been reached before in the area of armoured military vehicles.
- a 410 kW AC-generator of the ESW GmbH that is flanged directly to the crankshaft of the diesel engine. This generator is also used to start the engine and can retransfer power from the DC-power circuit to the diesel engine. It is build to provide electric power up to 410kW at a rated speed of 4200rpm. Therefore it is possible to convert the complete output of the diesel engine into electric power.
- the power electronics, which converts the alternating current of the generator into direct current to supply the DC-power circuit and vice versa. Moreover, the power electronics controls the torque of the ACgenerator and the resulting electric power in the DC-circuit as much as the power supply of the cooling fan and the braking resistor
- an electric cooling fan motor for the cooling system of the power module including diesel engine, power electronics and generator

- a braking resistor to stabilize the DC-power circuit
- the DC-power circuit that connects the power electronics with the inverters of the drive motors
- the frequency inverters which convert the direct current of the DC-power circuit into alternating current to actuate the drive motors and vice versa
- the four single wheel drive motors of Sensor-Technik Wiedemann GmbH. Each of it has the capability to deliver a continuous mechanical power of up to 125kW
- two gear boxes connecting the drive motors to the drive shafts. By the use of the gear boxes, it is possible to shift between two different cruising ranges.
- The drive shafts and the wheel hubs with their planetary gears

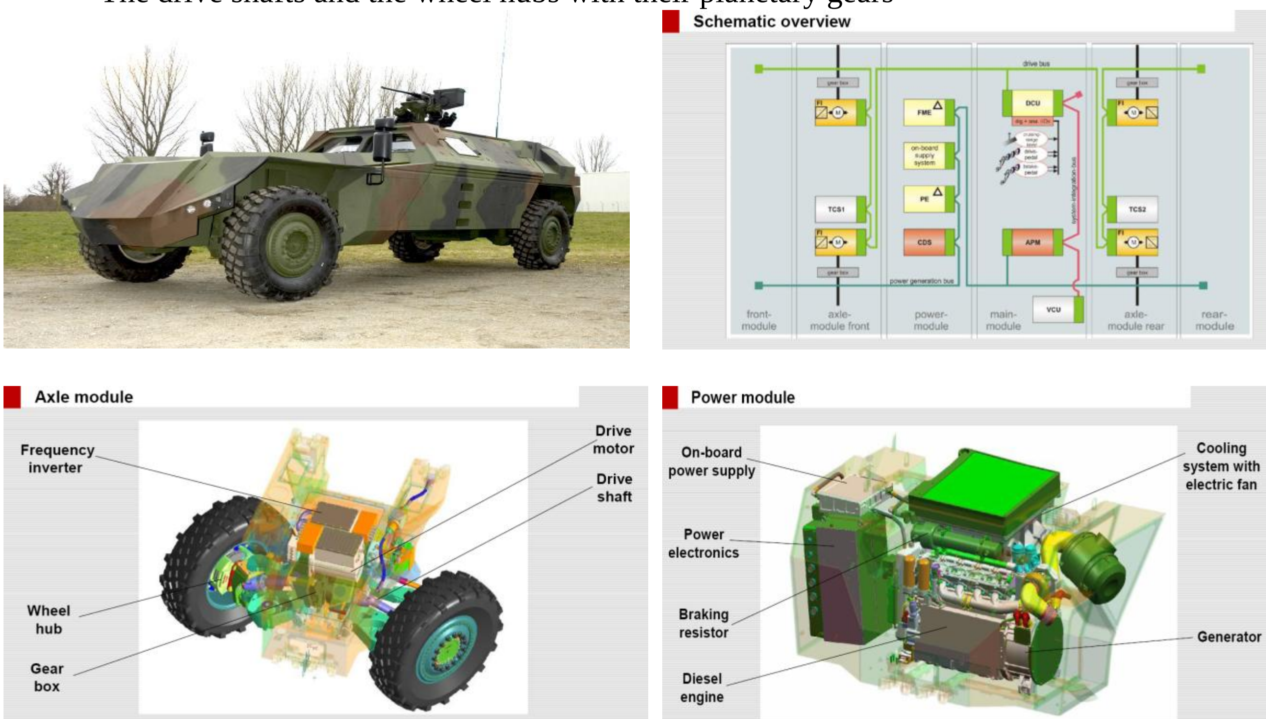


Figure 43: Gefas AVS

[Rheinmetall Defence - Gefas] Electric power transmission for a modular Advanced Vehicle System, B. Bernhard, Rheinmetall Landsysteme GmbH 7th International All Electric Vehicle Conference Stockholm, Sweden June, 11th – 13th 2007

More information : http://www.army-technology.com/projects/gefas/

- ***BAE Systems – SEP***

Originally SEP - Multi Role Armoured Platform was developed by Swedish military vehicle manufacturer Land Systems Hägglunds which is nowadays owned by BAE systems. SEP's electric driveline is based on in-hub motors in each wheel. Also tracked version is available. Even thought SEP is one of the most ready developed electric military vehicle platforms, so far no army has ordered electric version. Electric transmission is anyway offered as an option.

SEP wheeled 8x8

- Length 6 m
- Width 2.8 m
- Height 2.2 m
- Weight (empty) 14.5 tonnes
- Payload up to 12.5 tonnes
- Total combat weight 24 – 27 tonnes
- Internal volume 13 m^3
- Maximum speed < 100 km/h
- Engines 2x225 kW diesels
- Optional mechanical or **electric drive transmission**
- Steering on 3 axles, pivot turn

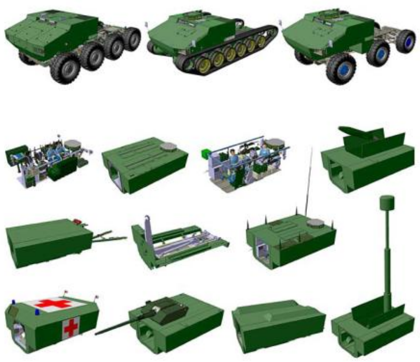


Figure 44: BAE Systems – SEP

More information :

- http://www.baesystems.com/ProductsServices/landa_hagg_product_sep.html
- http://www.army-technology.com/projects/sep/

4.8.5.2 Agriculture and forestry

Tractor is the core of agriculture. It pulls the accessory work machines and provides additional power to the machine if needed. Standardized power outputs include mechanical (rotating shaft), hydraulic and electric (trailer plug with 12V low-power output). Most of agricultural work cycles are constant load cycles where benefits of the hybrid transmission are limited. However, electric power is needed in the farm and many work machines, such as sprayers, could be powered easier with electricity than hydraulic or mechanical power. The standard add-on interface in tractors offers mechanical, hydraulic and electric supply but the 12VDC electric supply has very limited power. Therefore a high voltage and high power interface would increase the tractor versatility. The high production volumes of tractors can also enable different solutions than the in the other NRMMs.

- ***Tractors***

John Deere has developed an "electric tractor-implement interface" [Hahn, 2008] for its premium series tractors [farmers guardian].

System includes:

- Generator 20kW
- DC-bus 700VDC
- Fan drive 10kW
- A/C compressor 5kW
- DC/DC converter 4kW
- 240/400 VAC/5kW outlets for auxiliary equipment
- 5% fuel savings in normal use

Figure 45: Tractor John Deere

Deere's development is not really a hybrid but provides electric supply for onboard and external auxiliaries. These tractors are already commercially available [Deere].

Current trend is also continuous variable transmission, which is nowadays often realized with variable transmission planetary gear requiring an additional actuator to control the gear ratio. Traditionally a hydrostatic actuator is used. However, with an electric actuator, additional battery and generator the driveline can be fully hybridized. German manufacturer Fendt (part of Agco) has developed a hybrid tractor prototype utilizing this splitted hybrid solution. The 120kW electric motor enables smooth control of the mechanical transmission as well as fully electric traction.

- ***Elforest***

Elforest is a small Swedish company owned partially by Volvo Technology Transfer AB. Elforest develops and sells hybrid electric forwarders. The aim of Elforest was minimize the damages to forest floor during operation. Therefore also the body structure differs from traditional forwarders. The simple idea is that every wheel is steering and wheels of the two rearmost axles follow the same trail as the first wheel. This reduces both the damages and the energy consumption. The electric transmission is also original. Instead of today's de-facto 600-800VDC bus voltage, Elforest has only 84V. Manufacturer justifies the low voltage with safety [Elforest1], [Elforest2].

Figure 46: EL-Forest F-12 Hybrid electric forwarder

EL-Forest F-12 Hybrid electric forwarder

- Engine: 37kW diesel
- Architecture: Series hybrid
- Buffer: Lead acid batteries
- DC-bus voltage: 84 VDC
- Transmission: 6 hub motors with reduction gears

4.8.5.3 Construction machines

- ***Caterpillar D7E***

Caterpillar's bulldozer is not hybrid but diesel electric. The typical cycle of a bulldozer is constant high load, thus the hybridization would give only a minimal improvements. Diesel electric transmission provides better control of the traction optimal use of the accessories (system cooling and A/C) as well as high efficiency comparing to the traditional mechanical transmission with low efficiency hydrodynamic torque converter. Caterpillar advertises 10% improvement in productivity and 25% fuel saving comparing to the same size traditional machine.

Figure 47: Caterpillar D7E diesel electric bulldozer

Caterpillar D7E diesel electric bulldozer:

- Diesel electric 175kW
- Electric accessories
  - Cooling
  - A/C
  - DC-converter instead of 24 V DC charger
- Fuel saving 25%
- Improved productivity 10%

- Longer lifetime and smaller lifetime costs
- Improved comfort
- Less noise
- Production starts 2010

- ***Komatsu excavator***

Different size excavators are together with loaders the most numerous NRMMs worldwide. The relatively slow movements of the hydraulic boom don't promise very much from the hybridization point of view. However, in excavators roughly 40% of the energy is used to revolve the body additionally the effective excavation generates rapid peaks in the load decreasing the diesel efficiency. Komatsu [Komatsu] has equipped a traditional hydro-static excavator with electric turning motor, motor-generator parallel with the diesel and hydraulic pump and super caps as energy storage. New layout makes it possible to regenerate energy from the body turning and support the diesel during the excavation.

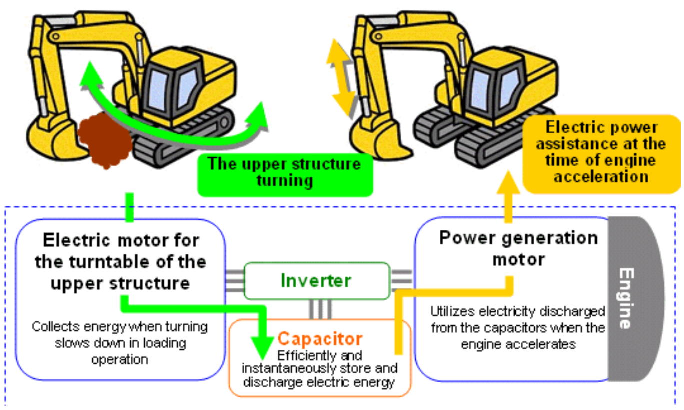


Figure 48: Komatsu hybrid excavator

Komatsu reports improved performance and 25-40% fuel savings.

- Parallel hybrid
  - Diesel+electric motor
  - Body turning with electric motor
  - Super caps
- Kinetic energy of body turning is regenerated to super caps and used to support diesel during excavating
- Fuel savings 25-40% depending on the cycle
- Improved performance
- Production 30 pcs 2009

- ***Atlas mild hybrid loader***

Atlas Ar-65 hybrid is a good example of a low-cost hybrid solution.

Figure 49: Atlas mild hybrid loader

The platform is a typical small sized loader with hydro-static transmission. By adding a motor-generator parallel to the diesel and hydraulic pumps and a battery as energy storage the diesel can be downsized with same or even improved performance. Hydro-static transmission doesn’t provide any regenerative energy but the efficiency can be improved by shaving the load peaks which are typical in the loading tasks. Small sized loaders are often used in warehouses and yards where the possibility to battery electric operation is welcome.

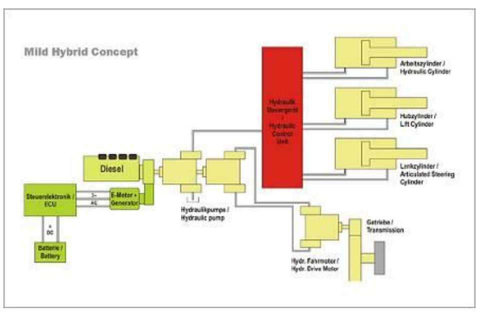


Figure 50: Atlas Mild Hybrid Concept

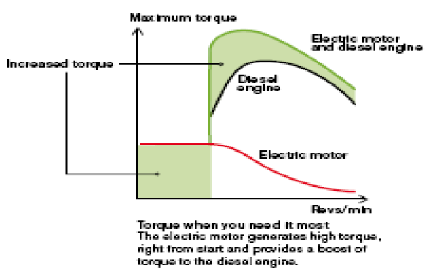
Atlas Ar-65 hybrid:

- Diesel downsized 51 -> 37 kW
- Electric motor/generator 15 kW nom./30kW max
- Li-ion-battery
- Hydrostatic transmission
- Start/stop-feature
- Fuel saving 20-30%
- Possibility to drive only with electricity
- Production starts 2012

- ***Volvo L220F hybrid loader***

Figure 51: Volvo L220F hybrid loader

The design of Volvo's parallel hybrid loader is based on the fact that loaders often have long idle times in their cycle. Typical case is the loading of a truck. When a truck is ready it typically takes some time before the following one arrives. In these cases the easiest way to improve efficiency and decrease emissions and noise is to stop the engine while being inactive. With start and stop automatics and relatively big battery – guaranteeing the driver comfort and system readiness – idling can be avoided. Additionally the parallel electric motor can support the diesel during peaks and improve performance by providing extra torque in during the work task.



Volvo L220F hybrid loader:

- Parallel hybrid
  - Diesel 259 kW
  - Electric motor 50 kW
  - Li-ion-battery
- Start/stop- for idle
- Electric accessories
  - Cooling
  - A/C
  - DC-converter instead of 24 VDC charger
- Fuel saving 10%
- Improved performance
- Lower maintenance costs

4.9 Future research challenges – problems to be solved

4.9.1 Energy storages

Mobile working machines have partially the same challenges as road vehicles. Energy storages don't provide enough energy density for fully electric operation and there are no big technological steps on the horizon. Additionally today's best battery technologies have limited availability and high prices. Working machines also set special requirements for energy storages. Full day operation requires extra durability in continuous rapid charging and deep discharge cycle. As mentioned, the work cycle during operation is different comparing to the on road cycles and varying from machine to machine. This might affect to the battery capacity, even the average power is the same. Careful analysis of different NRMM cycles would speed up the battery requirements instead of making battery loading tests for each machine [NREL].

4.9.2 Electric transmission components

The basic components: electric motors, motor controllers and DC/DC converters are ready from the technology point of view.

From the commercial point of view the situation is different. Most of these components are made for the industrial static use. It will take several years before there is a broad choice of suitable electric components for NRMM fulfilling the temperature, vibration and size requirements of mobile machinery. As integration type of industry the NRMM manufacturers are also interested to have - instead of single components - functional aggregates, which can easily been integrated into the machine. Such entities could be engine-generator-rectifier combination and different type of motor-gear-motor controller combinations for the traction. Contrary to the automotive industry the small production series makes it difficult to manufacture fully tailor-made components for a single machine model. High voltage auxiliary components, such as A/C, cooling fans, pumps, hydraulic pumps, etc., have also a very limited availability at the moment.

In NRMM there are several actuators, especially in booms, requiring so high power/torque/force density that hydraulics can't be fully replaced with electromechanical actuators. Therefore electro hydraulics is an important area, which needs both research and component development before the electrification of mobile machinery can be completed.

4.9.3 Conclusions

Electric transmission is not a new issue among NRMMs. Certain application areas are already running electrically. However, most of the machines are still based on traditional diesel-mechanical or diesel-hydraulic transmission. Energy efficiency of NRMMs could be dramatically improved with electric and hybrid electric solutions. Additionally electric transmission would generate side benefits such as lower maintenance costs and better controllability and drivability. Due to the huge amount and professional use of mobile machinery, the improved energy efficiency would generate a remarkable reduction in the GHG and other emissions.

The bottlenecks for rapid electrification are partly the same as in the automotive industry: lack of commercial electric components for mobile machinery and therefore higher price of the hybrid electric transmission. The 300 BUSD yearly market of NMRR will be attractive for component developers as soon as the market pull is high enough.

Already now there are application areas such as janitorial and underground applications where the customers are willing to pay more for the lower emissions than the saving of the better fuel efficiency. Increasing fuel price, tightening emission regulations and decreasing price of electric components will speed up the development and market of electric and hybrid electric machinery.

5 Conclusions and Recommendations

As concerns about environmental issues and energy security continue to grow, heavy-duty vehicle manufacturers have been challenged to reduce fuel consumption and emissions while also reducing vehicle costs. Operators of heavy-duty vehicles are finding their margins becoming tighter as their operating costs increase due to rising fuel costs. Advanced powertrain technologies such as hybrid electric or hybrid hydraulic drives can play a very important role in meeting these challenges if the business case is viable.

Drivers towards hybridization of heavy-duty vehicles are partly similar as in the car industry:

- reduction in the amount of fuel consumed per unit of distance or per unit of mass hauled
- reduction in emissions per unit distance or per unit mass hauled
- reduction of maintenance costs (e.g. less wear on brake pads and braking systems)
- integrated electrical power generation to run ancillary systems and auxiliary loads as well as the ability to provide off-vehicle power in some applications
- ability of hybrid electric systems to be tuned for performance (at the expense of the fuel economy benefit, however)
- ability to run on electricity only in some cases : local zero emission, low noise, …

But from the hybridization point of view, there are also important differences between passenger cars and heavy-duty vehicles (on and off-road). Most heavy-duty vehicles are mainly in professional use and thus the yearly operating hours are high and reliability is crucial. But the biggest difference is the huge variety in the duty or drive cycle. When passenger cars have more similar cycles (urban and highway), each heavy-duty vehicle has an own typical duty or drive cycle. The benefits of hybrid technology vary significantly according to a vehicle's duty cycle. The economic value of hybridization often depends on reduced in-use fuel consumption in order to justify the added purchase cost over that of a conventional vehicle. Thus, it is often critically important that hybrid vehicles be deployed over drive or duty cycles where they will show a clear benefit.

Barriers towards hybridization of heavy-duty vehicles:

- hybridization increases the system complexity and leads to higher purchasing price
- lifecycle cost heavy-duty vehicles very important due to tight margins in sector
- economy of scale : production volumes much lower than in passenger car market, huge number of different applications and wide range of duty or drive cycles
- durability requirements even higher than in passenger car market : full day operation, temperatures, vibrations, … : impact on availability and cost of components
- risk aversion to adopting new technology, reliability crucial in daily operation
- most governmental initiatives and incentives are dedicated to passenger car market
- green image, which is important in consumer market, is also a plus in the heavy-duty vehicle market but only very few customers are willing to pay extra for the green image

This final report clearly shows that the market of heavy-duty hybrid vehicles is growing from a prototype phase to a more demonstration/commercial phase. Market activities indicate increasing developments in all categories of heavy-duty hybrid vehicles: trucks, buses and mobile work machines. However, further research & development is needed to improve the efficiency of the heavy-duty hybrid vehicles on economic and ecologic level. Also the importance of bringing objective information to the end users and governments can not be underestimated. Therefore initiatives like the Hybrid Truck User's Forum (USA), the Hybrid User Forum (EU) and IEA-IA-HEV (International) are important to bring the stakeholders together.

6 References

Citation	Full Reference
21CT 2006	U.S. Department of Energy. (2006). "21st Century Truck Partnership: Roadmap and Technical White Papers." Technical Report 21CTP-0003. Available online: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/21ctp_roadmap_2007.pdf
Achten 2008	P. Achten. (2008). "A Serial Hydraulic Hybrid Drive Train for Off-Road Vehicles." Proceedings of the (IFPE) International Exposition for Power Transmission. March 11-15, 2008. Las Vegas, Nevada, USA.
AFDC 2009	Web site of the U.S. Department of Energy's Alternative Fuels & Advanced Vehicles Data Center, http://www.afdc.energy.gov
Allison Transmission 2008	Allison Transmission (2008). "GM-Allison Hybrid EP40 System Transit Bus." Online Specification Sheet, http://www.allisontransmission.com/servlet/DownloadFile?Dir=publications/pubs&FileToGet=SA3576EN.pdf ; last accessed 2008-12-18.
Allison Transmission 2008b	Allison Transmission (2008b). "It's the right thing to do." Marketing brochure for the Allison Hybrid System. Available online: http://www.allisontransmission.com/servlet/DownloadFile?Dir=publications/pubs&FileToGet=SA3592EN.pdf; last accessed 2008-12-18.
ANL 2007	Web site of the Argonne National Laboratory PSAT Model (last accessed April 2009). http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html
ANL 2009	Web site of the Argonne National Laboratory GREET Model (last Accessed April 2009). http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
Ashitani et al. 2006	C. Ashitani, R. Wright, G. Hunt. (2006). "Ultracapacitors for Automotive Applications." *Journal of Power Sources.* Vol. 154. pp. 561–566.
ATA 2009	American Trucking Associations (last accessed 2009). Web site. See http://www.truckline.com/Pages/Home.aspx
ATVS 2005	National Renewable Energy Laboratory (NREL). (April 2005). "Advanced Technology Vehicles in Service: New York City Transit Drives Hybrid Electric Buses into the Future." DOE/GO-102005-2009.
Auer and Miller 2007	J. Auer and J. Miller. (2007). "Ultracapacitor-based energy management strategies for eCVT hybrid vehicles." IEEE 2007 3rd Institution of Engineering and Technology Conference on Automotive Electronics, 28-29 June 2007.
Auer et al. 2006	J. Auer, A. Schneuwly, and J. Miller. (2006). "Ultracapacitor—The Boost in Alternative Powertrains." The 22nd International Battery Hybrid and Fuel Cell Electric Vehicle Symposium, EVS-22, Yokohama, Japan, October 23-28, 2006.
AVL 2009	Web site of the AVL Advisor Vehicle Simulation Tool (last accessed April 2009). http://www.avl.com/advisor/
AVL-b 2009	Web site of AVL Cruise (last accessed April 2009). "AVL Cruise." http://www.avl.com/wo/webobsession.servlet.go/encoded/YXBwPWJjbXMmcGFnZT12aWV3Jm5vZGVpZD00MDAwNjEwNzk_3D.html

BAE New Flyer 2008	BAE Systems. http://www.baesystems.co.uk/BAEProd/groups/public/documents/bae_publication/bae_pdf_eis_hybridrivenewflyer.pdf
Bagatelle-Black 2007	F. Bagatelle-Black. (2007). "NiMH Batteries: Obsolete Technology or Suppressed EV Solution?" EV World. Published February 23, 2007.
Barnitt 2008	R. Barnitt. (2008). "In-Use Performance Comparison of Hybrid Electric, CNG, and Diesel Buses at New York City Transit." SAE Technical Paper 2008-01-1556. Available online: http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/42534.pdf.
Barnitt and Chandler 2006	R. Barnitt, K. Chandler. (2006). "New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses." National Renewable Energy Laboratory Technical Report NREL/TP-540-40125.
Blanco 2007	S. Blanco. (2007). "Odyne, Dueco will build PHEV aerial lift truck."
Bosch 2008	Bosch. Press releases for the 62nd IAA Commercial Vehicles 2008. http://www.bosch-presse.de/TBWebDB/en-US/PressText.cfm?CFID=547833&CFTOKEN=552637b5a93d8fe0-8F53B40F-BD5A-7430-EFAAF885C5783CF3&Search=0&id=3823
Brooker et al. 2007	A. Brooker, M. O'Keefe, D. Edwards, J. Green. (Oct. 2007). "Class 8 Hybrid Truck Fuel Economy Improvement Potential." A presentation to the 21st Century Truck Partnership.
BTS 2009	U.S. Bureau of Transportation Statistics (last accessed 2009). Web site. See http://www.bts.gov/publications/commodity_flow_survey/2002/united_states/html/table_01_b.html
Burress et al. 2008	T. Burress, C. Coomer, S. Campbell, L. Seiber, L. Marlino, R. Staunton, J. Cunningham. (January 2008). "Evaluation of the 2007 Toyota Camry Hybrid Synergy Drive System." Oak Ridge National Laboratory Technical Report ORNL/TM-2007/190. Available online: http://www.osti.gov/energycitations/servlets/purl/922327-5ktfCi/922327.PDF
Business Wire 2006	(November 2006). "Oshkosh Truck Unveils Fuel Saving Hybrid Drive Refuse Vehicle." *Business Wire.* Available online: http://www.allbusiness.com/services/business-services/3930045-1.html
CalCars 2007	CalCars-News Archive (August 23, 2007). "New PHEVs: Ford Escape/Eaton Utility Truck/Army/Mercedes by Siemens/Sprinter Expansion." Available online: http://www.calcars.org/calcars-news/831.html
Calstart 2009	Press release from the Calstart Hybrid Truck Users Forum. (July 10, 2009). "Hybrid Bus Group Selects StarTrans-Azure for National Hybrid Bus Deployment: Hybrid buses can cut fuel consumption by up to 40%." Available online: http://www.calstart.org/Projects/Hybrid-Truck-Users-Forum/Articles/Press-Release-HBUF-Selects-Supplier.aspx
Capps et al. 2008	G. Capps, O. Franzese, B. Knee, M. Lascurain, P. Otaduy. (December 2008). "Class-8 Heavy Truck Duty Cycle Project Final Report." Oak Ridge National Laboratory Technical Report. ORNL/TM-2008/122.
CARB 2008	California Air Resources Board. (2008). "Heavy-Duty Vehicle Idling Emission Reduction Program." Retrieved February 12, 2009, from http://www.arb.ca.gov/msprog/truck-idling/truck-idling.htm.
Chandler and Walkowicz 2006	K. Chandler and K. Walkowicz. (2006). "King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results." National Renewable Energy Laboratory. Technical Report NREL/TP-540-40585.

Cho 2004	P. Cho. (2004). "Advanced Electric Motor/ Generator/ Actuator Design and Analysis for Automotive Applications." Society of Automotive Engineers Seminar Series. Course notes from in-house seminar, 2004.
Connaught Engineering 2008	Connaught Engineering, "Press Release: Connaught Hybrid Technology Improves Fuel Consumption and Reduces CO_2 Emissions by up to 24.7%*." http://www.connaughtengineering.com/press_20081027.pdf
Connaught Engineering 2009	Connaught Engineering. (2009). "Connaught Engineering." Retrieved 12 February 2009, from http://www.connaughtengineering.com
Davis 2008	S. Davis. (2008). "U.S. Consortium to Tackle Lithium-Ion Battery Development for Transportation." *Power Electronics Technology.* Available online: http://powerelectronics.com/portable_power_management/news/us_consortium_transportation_li-ion_development-1223/
Davis et al. 2008	S. C. Davis, S.W. Diegel, R.G. Boundy, (2008). Transportation Energy Data Book, Oak Ridge National Laboratory. Edition 27. Oak Ridge National Laboratory report no. ORNL-6981.
Delphi 2001	Delphi Automotive Systems. (December 2001). "The Role of Batteries in Auxiliary Power for Heavy Trucks." http://www.osti.gov/bridge/servlets/purl/771215-HPNAue/native/771215.pdf
Denver 2010	Denver (2010). Greening Denver's Fleet. Public Works Fleet Division, Denver, Colorado, USA. Downloaded from http://www.denvergov.org/Fleet_Maintenance_Division/GreeningDenversFleet/tabid/433516/Default.aspx on 8 August 2010.
DOE-HVRG 2004	(2004). "Heavy Vehicle and Engine Resource Guide." U.S. Department of Energy, Energy Efficiency and Renewable Energy. DOE/GO-102004-1866.
DSNY 2009	DSNY (2009). Annual report 2009. New York City Department of Sanitation (DSNY).
Eaton 2008	Eaton Hybrid Power Web-Site. http://www.roadranger.com/Roadranger/productssolutions/HybridPower/index.htm; for specifications, see http://www.roadranger.com/Roadranger/productssolutions/SpecificationGuide/HybridPowerSystem/index.htm (last accessed 2008-12-18).
Eaton 2009	Eaton. (2009). "Hybrid Solutions for MD Commercial Vehicles". Presented at the ERC Symposium, University of Wisconsin, Madison. June 10, 2009. URL: http://www.erc.wisc.edu/documents/symp09-Cornils.pdf
Eaton Fact Sheet 2008	Eaton Corporation (accessed 2008). "FACT SHEET: Background on Eaton's Hydraulic Hybrid Technologies." site: http://www1.eaton.com/epa/facts.html and http://www1.eaton.com/epa/420f06043.pdf
Eaton Transmission 2009	Eaton Transmission. (2009). "Hybrid Power." Retrieved February 13, 2009, 2009, from http://www.eaton.com/EatonCom/ProductsServices/Hybrid/index.htm
Economist 2008	*The Economist.* (March 6, 2008). "In Search of the Perfect Battery."
EEA 2007	Energy and Environmental Analysis, Inc. (September 2007). "Technology and Cost of the MY2007 Toyota Camry HEV Final Report." Oak Ridge National Laboratory Subcontractor Report. ORNL/TM-2007/132.

EETT 2006	Electrical and Electronics Technical Team (DOE). (November 2006). "Electrical and Electronics Technical Team Roadmap." FreedomCar and Fuel Partnership Technical Roadmap. Available online: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap.pdf
Eisenstein 2005	P.A. Eisenstein. (2005). "Hybrids Hed2Hed: From the latest Prius to the new Highlander: tested & rated, Wired style". *Wired*. Issue 13.
EPA 2004	U.S. Environmental Protection Agency. "Hydraulic Hybrid Technology—A Proven Approach." EPA420-F-04-024. Available online: http://www.epa.gov/oms/technology/420f04024.pdf
EPA 2007	U.S. Environmental Protection Agency. (November 2007). "SmartWay Fuel Efficiency Test Protocol for Medium and Heavy Duty Vehicles: Working Draft." EPA Report Number EPA420-P-07-003. Available online: http://www.epa.gov/smartway/documents/420p07003.pdf
EPA 2008	U.S. Environmental Protection Agency. (September 2008). "Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2008: Executive Summary." EPA Report EPA420-S-08-003. Available online: http://www.epa.gov/oms/cert/mpg/fetrends/420s08003.pdf
EPA 2009	U.S. Environmental Protection Agency. MOVES software (last accessed April 2009). http://www.epa.gov/otaq/models/moves/index.htm
Eudy et al. 2008	L. Eudy, K. Chandler, C. Gikakis. (2008). "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2008." National Renewable Energy Laboratory Technical Report NREL/TP-560-44133.
***Fleets & Fuels* December 2008**	*Fleets and Fuels* (December 2008). Electronic newsletter. December 8, 2008.
***Fleets & Fuels* November 2008**	*Fleets and Fuels* (November 2008).Electronic newsletter. November10, 2008.
Fuel Cells Bulletin 2004	Fuel Cells Bulletin (June 2004). "Hydrogenics modules for SunLine truck APU." Volume 2004. Issue 6, p. 9.
Gonder 2008	J. Gonder. (2008). "Route-Based Control of Hybrid Electric Vehicles." Society of Automotive Engineers (SAE) Technical Paper 2008-01-1315.
Green Car Congress 2008	Green Car Congress. (September 23, 2008). "Bosch Highlighting Hydraulic and Electric Hybrid Systems at IAA." http://www.greencarcongress.com/2008/09/bosch-highlight.html
Greenbiz April 2009	Greenbiz (April 8, 2009). "FedEx Express Road Test of Iveco Hybrid Van Shows Fuel Savings of More than 25 Percent."
Hayes et al. 2006	R. Hayes, A. Williams, J. Ireland, K. Walkowicz. (September 2006). "King County Metro Transit: Allison Hybrid Electric Transit Bus Laboratory Testing." National Renewable Energy Laboratory Technical Report. TP-540-39996.
Hendricks and O'Keefe 2002	T. Hendricks, M. O'Keefe. (2002). "Heavy Vehicle Auxiliary Load Electrification for the Essential Power System Program: Benefits, Tradeoffs, and Remaining Challenges." SAE Technical Paper 2002-01-3135.

Hino 2008	Hino Global News Release. (June 2008). "Hino Motors, Ltd. to provide shuttle buses for the G8 Hokkaido Toyako Summit."
House and Johnson 2009	K.Z. House, A. Johnson (2009) "The limits of energy storage technology." Bulletin of the Atomic Scientists.
Howell 2009	D. Howell. (2009). "2008 Annual Progress Report of the Vehicle Technologies Program: Energy Storage Research and Development." U.S. Department of Energy. Available online: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2008_energy_storage.pdf
Howell, Barnes, et. al. 2009	D. Howell, J. Barnes, G. Henriksen, V. Srinivasan, J. Deppe, and B.J. Kumar. (2009). "Current Status of D.O.E.-funded R&D on Energy Storage for Automotive Applications." EVS-24. Available online: http://www.cars21.com/files/news/EVS-24-980321%20Howell.pdf
Husain 2003	I. Husain. (2003). *Electric and Hybrid Vehicles: Design Fundamentals*. CRC Press.
ISE Corporation 2008	ISE Corporation (last accessed 2008). http://www.isecorp.com/ise_hybrid-electric-technology-benefits/thundervolt_drive_system/thundervolt-energy-storage-systems.php
ISER 2008	ISER (2008). "ISE Thundervolt TB40-HG." Available online: http://www.isecorp.com/ise_products_services/gasoline_hybrid_drive_system/pdf/TB40-HG.pdf
Jackson 2005	M. Jackson. (2005). "Comparative Costs of 2010 Heavy-Duty Diesel and Natural Gas Technologies." TIAX presentation. Reference D0286. Available online: http://www.cleanvehicle.org/conference/2005/Presentations/07JacksonTIAXComparativeCostsof2010Technology.pdf
JD Power 2008	JD Power (last accessed December 5, 2008). "Engine-Cylinder Deactivation Saves Fuel.". http://www.jdpower.com/autos/articles/Engine-Cylinder-Deactivation-Saves-Fuel
Kargul 2007	J. Kargul. (2007). Hydraulic hybrids. Advanced Technology Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Presentation 11 December 2007.
Kelly et al. 2008	K. Kelly, T. Abraham, K. Bennion, D. Bharathan, S. Narumanchi, M. O'Keefe. (2008). "Assessment of Thermal Control Technologies for Cooling Electric Vehicle Power Electronics." National Renewable Energy Laboratory. Technical Report NREL/CP-540-42267.
Kenjo and Nagamori 2003	T. Kenjo and S. Nagamori. (2003). *Brushless Motors: Advanced Theory and Modern Applications.* Sogo Electronics Press. Tokyo, Japan.
Knorra 2008	U. Knorra. (2008). "Hydraulischer Hybridantrieb kann bei Nutzfahrzeugen den Verbrauch um 25 Prozent senken. (Hydraulic hybrid drive may reduce fuel consumption of heavy-duty vehicles by 25 percent. In German.)" GWV Fachverlage GmbH, 11 August 2008. http://www.atzonline.de/index.php;do=show/site=a4e/sid=bd9d32f1ebc131270fbaa6f25d14ef85/alloc=1/id=8263/pr=1 viewed 18 August 2008.
Lee 2010	J. Lee. (2010). "Another Step Towards Securing Our Future in Energy". The White House Blog. May 21, 2010. Available on-line at: http://www.whitehouse.gov/blog/2010/05/21/another-step-towards-securing-our-future-energy
Leech 2008	E. Leech. (2008) "Bringing Hydraulic Hybrid Retrofits to Developing Nations (Colorado State University)." Planet Green.

Logistics manager.com 04-2009	Logisticsmanager.com (April 6, 2009). "FedEx cuts fuel use in Iveco hybrid trial." Available online: http://www.logisticsmanager.com/Articles/11311/FedEx+cuts+fuel+use+in+Iveco+hybrid+trial.html
MAE 2005	*Military and Aerospace Electronics* (2005). "Army fuel-cell truck completes cross-country test trip." http://mae.pennnet.com/articles/article_display.cfm?article_id=229751
Markel et al. 2002	T. Markel, A. Brooker, T. Hendricks, V. Johnson, K. Kelly, B. Kramer, M. O'Keefe, S. Sprik, K. Wipke. (2002). ADVISOR: A Systems Analysis Tool for Advanced Vehicle Modeling. *Journal of Power Sources*. Vol. 110(2), 2002; pp. 255-266; NREL Report No. 31719.
MathWorks 2009	The MathWorks Web site(last accessed April 2009). "Automotive." http://www.mathworks.com/industries/auto/index.html
Miller et al. 2006	J. Miller, M. Everett, J. Auer. (2006). "Ultracapacitor Enabled Gatekeeper Energy Management Strategy for Single Mode eCVT Hybrid Vehicle Propulsion." Proceedings of the IEEE Vehicle Power and Propulsion Systems Conference. September 6-8, 2006.
MSC 2009	MSC Software Web site (last accessed April 2009). http://www.mscsoftware.com/
MSC 2009	Mechanical Simulation Corporation Web site (last accessed April 2009).
NAVC 2000	Northeast Advanced Vehicle Consortium, M.J. Bradley & Associates, West Virginia University. (2000). "Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project: Final Emissions Report." NAVC Technical Report. Available online: http://www.navc.org/Navc9837.pdf
Navistar 2009	Navistar Press Release. (2009). "Navistar First OEM to Reach 5 Million Hybrid Miles." Available online: http://ir.navistar.com/releasedetail.cfm?releaseid=403538
Nishikawa et al. 2003	S. Nishikawa, M. Sasaki, A. Okazaki, S. Araki, T. Miyata, M. Nishina. (July 2003). "Development of Capacitor Hybrid Truck." JSAE Review. Volume 24. Number 3. pp. 249-254 (6).
O'Dell 2010	J. O'Dell. (2010). "Mitsubishi Heavy Industries to Experiment with Switchable Battery Electric Buses." Edmunds.com. Available online: http://blogs.edmunds.com/greencaradvisor/2010/04/mitsubishi-heavy-industries-to-experiment-with-switchable-battery-electric-buses.html
O'Keefe and Vertin 2002	M. O'Keefe and K. Vertin. (2002). "An Analysis of Hybrid Electric Propulsion Systems for Transit Buses." National Renewable Energy Laboratory Technical Report. NREL/MP-540-32858.
O'Keefe et al. 2007	M. O'Keefe, A. Simpson, K. Kelly, and D. Pedersen. (2007). "Duty Cycle Characterization and Evaluation Towards Heavy Hybrid Vehicle Applications." SAE Technical Paper 2007-01-0302.
Ogando 2008	J. Ogando. (April 2008). "Hydraulic Hybrid Cars: No Batteries Required.." *Design News*. http://www.designnews.com/article/7232-Hydraulic_Hybrid_Cars_No_Batteries_Required.php
Oshkosh Truck 2008	Oshkosh Truck ProPulse Web site: http://www.oshkoshcorporation.com/about/tech_innovations~propulse.cfm; see also http://www.oshkoshcorporation.com/pdfs/Oshkosh_ProPulse_drive_brochure.pdf
Oshkosh Truck 2009	Oshkosh Truck Corporation. (2009). "ProPulse (TM) Hybrid Electric Drive." Retrieved February 13, 2009, from http://www.oshkoshdefense.com/defense/technology~propulse.cfm.

Parker 2009	Parker (2009). Parker Hannifin RunWise® *hydraulic hybrid technology dramatically improves fuel efficiency while reducing carbon emissions on Class 8 trucks.* Parker Hannifin, Hydraulics Group, press release 11 December 2009.
Pesaran et al. 2006	A. Pesaran, A. Vlahinos, D. Bharathan, and T. Duong. (2006). "Electrothermal Analysis of Lithium Ion Batteries." The 23rd International Battery Seminar & Exhibit. March 13-16, 2006, Fort Lauderdale, Florida.
PNNL 2008	Pacific Northwest National Laboratory (2008). Hydrogen Analysis and Resource Center: Lower and Higher Heating Values of Hydrogen and Fuels. Microsoft Excel Document. Available from http://hydrogen.pnl.gov/cocoon/morf/projects/hydrogen/datasheets/lower_and_higher_heating_values.xls
Power Management Design Line 2008	Power Management Design Line (2008). "AFS Trinity's battery/ultracapacitor plug in hybrid offers greater durability." Power Management Design Line. Available from http://www.powermanagementdesignline.com
Rexroth 2010	Rexroth (2010). World's first hydraulic hybrid CNG refuse truck to hit New York city streets. Product news: Mobile hydraulics, at the Rexroth internet website http://www.boschrexroth.com/various/utilities/print_view.jsp;jsessionid=bca6UucLisHOb4cb5VqPs?printoid=631454
Ricardo 2009	Ricardo Press Release. (2009). "Flybus Project Aims to Cut Fuel Costs and Emissions for New and Existing Buses: Torotrak-led Team Targets Twenty Percent Fuel Savings using Mechanical Hybrid System". Available on-line at: http://www.ricardo.com/Documents/PRs%20pdf/PRs%202009/Flybus%20project%20press%20release.pdf
Romero 2009	S. Romero. (2009). "In Bolivia, Untapped Bounty Meets Nationalism." *The New York Times*. Published February 2, 2009. Available online: http://www.nytimes.com/2009/02/03/world/americas/03lithium.html?_r=3&pagewanted=1
Runningen and Hughes 2010	R. Runningen, J. Hughes. (2010). "Obama Orders Work on New Vehicle Efficiency Standards (Update 2)". Bloomburg Businessweek. May 21, 2010. Available on-line: http://www.businessweek.com/news/2010-05-21/obama-orders-work-on-new-vehicle-efficiency-standards-update2-.html
Rydberg 2009	K. Rydberg. (2009). "Energy efficient hydraulic hybrid drives". The 11th Scandinavian International Conference on Fluid Power, SICFP'09, June 2-4, 2009, Linköping, Sweden.
Schueneman 2008	T. Schueneman. (2008). "Alliance Between U.S. Government Lab and Battery Makers for Development and Production of Lithium-Ion Batteries in New 'Green' Cars." *Triplepundit.* Available online: http://www.triplepundit.com/2008/12/alliance-between-u-s-government-lab-and-battery-makers-for-development-and-production-of-lithium-ion-batteries-in-new-green-cars/
Shachtman 2006	N. Shachtman. (2006). "Hybrid Truck's Katrina Duty." Available online: http://www.noahshachtman.com/archives/002277.html
Show Times 2005	*Show Times: Clean Cities*. (May 2, 2005). "Electricity Boosts Truck Efficiency as 'Parasitic' Losses are Reduced." http://www.ctnpublishing.com/pubs/CCC/CCC_05/media/ShowTimes_CC05_5-2-05.pdf

Singh 2007	J. Singh. (October 4, 2007). "Testimony of Jagjit 'JJ' Singh, Chairman, President, and CEO of the Transportation Alliance Bank before the Senate Committee on Banking, Housing, and Urban Affairs." Available online: http://banking.senate.gov/public/_files/singh.pdf
Smith Electric 2008	Smith Electric Vehicles (2008). "Why Choose Electric?" Brochure. Available online: http://www.smithelectricvehicles.com/ChooseElectric.pdf
Smith Electric Vehicles News 2009	*Smith Electric Vehicles News.* (February 9, 2009). "Smith Electric Vehicles Collaboration with Ford Motor Company." Available online: http://www.smithelectricvehicles.com/newsevents_news.asp?p=n&itemid=260
Southwest Research Institute 2005	Southwest Research Institute. (May 26, 2005). "Fuel cell-assisted truck completes cross-country trek." Press release. Available online: http://www.swri.org/9what/releases/2005/FuelCell.htm
Staunton et al. 2006	R. Staunton, C. Ayers, L. Marlino, J. Chiasson, T. Burress. (2006). "Evaluation of 2004 Toyota Prius Hybrid Electric Drive System." Oak Ridge National Laboratory Technical Report ORNL/TM-2006/423. Available online: http://www.osti.gov/energycitations/servlets/purl/930735-hcON1m/
Sunline 2005	Sunline Transit Agency (May 26, 2005). "Fuel Cell-Assisted Truck Completes Cross-Country Trek." Press release. Available online: http://www.sunline.org/home/index.asp?page=126
SwRI 2009	Southwest Research Institute (last accessed April 2009). Web site for the RAPTOR software.. http://www.swri.org/4org/d03/vehsys/advveh/raptor/default.htm
TCRP-59 2000	Transit Cooperative Research Program (2000). "Hybrid-Electric Transit Buses: Status, Issues, and Benefits." TCRP Report 59. Northeast Advanced Vehicle Consortium (NAVC) and M.J. Bradley & Associates.
UNECE 2009	United National Economic Commission on Europe Working Party 29 on Pollution and Energy. Web site: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grpe/grpeage.html
UPS 2008	UPS (2008). UPS first in industry to purchase hydraulic hybrid vehicles. UPS press release, Atlanta, USA, October 27, 2008.
Vehicle Technology 2007	Vehicle Technology.org (Spring 2007). "Advanced GM Allison Two-Mode Parallel Hybrid Technology Ready for Europe". pp 36-39.
Voelcker 2007	J. Voelcker. (2007). "Lithium Batteries Take the Road." *IEEE Spectrum* September 2007. Available on-line: http://www.spectrum.ieee.org/green-tech/advanced-cars/lithium-batteries-take-to-the-road
Walkowicz 2010	K. Walkowicz. (2010). "Incorporation of Renewable Energy Technologies at Anheuser-Busch". NREL Technical Report TP-7A1-48409. Available online: http://www.nrel.gov/docs/fy10osti/48409.pdf
Ward and Davis 2009	J. Ward, and S. Davis. (2009). "2008 Vehicle Technologies Market Report." U.S. Department of Energy Technical Report. Available online: http://www.nrel.gov/docs/fy09osti/46018.pdf
[Construction market 1]	http://www.prlog.org/10043171-world-construction-machinery-forecasts-for-2011-2016.html
[Freedonia]	Freedonia Group, Introduction – world heavy construction equipment to 2009, market study, http://www.freedoniagroup.com/World-Heavy-Construction-Equipment.html

[Agricultural market]	http://www.freedoniagroup.com/World-Agricultural-Equipment.html
[Kunze, G.]	Kunze G., Mobile construction machinery – trends and new developments, ATZ Online, special edition, April 2010, http://www.atzonline.de/Artikel/3/11237/Mobile-Baumaschinen-Trends-und-neue-Entwicklungen.html
[EC-directive]	Directive 2004/26/EC of the European Parliament and of the Council of 21 April 2004 amending Directive 97/68/EC on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery. Official Journal of the European Union L 146 of 30 April 2004, page 1 et seq., and also available on the European Commission website at http://ec.europa.eu/enterprise/sectors/mechanical/non-road-mobile-machinery/index_en.htm
[Hahn, 2008]	Klaus Hahn, High voltage electric tractor – implement interface, SAE International Journal of Commercial Vehicles, Issue 1, Vol 1, 2008
[Deere]	http://www.farmersguardian.com/home/machinery/machinery-news/tractor-test-john-deere-7530e-premium/28393.article
Woof M.	Technology for Underground Loading and Hauling Systems Offers Exciting Prospects, Engineering and Mining Journal, April 2005.
The Warren Centre	http://www.warren.usyd.edu.au/bulletin/NO39/ed39art1.htm, e-bulletin, ISSUE 39, September 2004.
[Elforest 1]	http://www.el-forest.se/
[Elforest 2]	Oristo U., Sähkökäyttöinen EL-Forest ajokone (Electric EL-forest forwarder), Koneviesti, Vol. 10, 15.7.2005 (in Finnish)
[Komatsu]	http://www.komatsu.com/CompanyInfo/csr/2008/pdf/04.pdf
[Cat1]	http://www.cat.com/D7E
[Cat2]	http://www.caranddriver.com/reviews/car/10q2/caterpillar_d7e-feature_test
[Volvo1]	http://www.volvo.com/nr/rdonlyres/volvo_hybrid_hjullastare_entreprenadmaskiner.pdf
[Volvo2]	http://moderncontractorsolutions.com/articlesdetail.php?id_articles=224&id_artcatg=3
[Military 1]	Ogorkiewicz R. M., Electric drives for vehicles gain ground, Jane's International Defense Review, May 2004
[Ehsani 1]	M.Ehsani et. al. Hybrid Electric Vehicles: Architecture and Motor Drives, Proceedings of the IEEE, Vol. 95, No. 4, April 2007
[Ehsani 2]	Mehrdad Ehsani, Yimin Gao, Ali Emadi, Modern electric, hybrid electric, and fuel cell vehicles: fundamentals, theory, and design, CRC Press, 2009, ISBN 1420053981
[EGCI]	European Green Cars Initiative PPP : Multi-annual roadmap and long-term strategy