AT 2029 NEW GENERATION AND HYBRID VEHICLES

UNIT - 1

ELECTRIC VEHICLES

An **electric vehicle** (**EV**), also referred to as an **electric drive vehicle**, uses one or more electric motors or traction motors for propulsion. Electric vehicles include electric cars, electric trains, electric lorries, electric aeroplanes, electric boats, electric motorcycles and scooters and electric spacecraft.

Electric vehicles first came into existence in the mid-19th century, when electricity was among the preferred methods for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. The internal combustion engine (ICE) is the dominant propulsion method for motor vehicles but electric power has remained commonplace in other vehicle types, such as trains and smaller vehicles of all types.

During the last few decades, environmental impact of the petroleum-based transportation infrastructure, along with the peak oil, has led to renewed interest in an electric transportation infrastructure.Electric vehicles differ from fossil fuel-powered vehicles in that the electricity they consume can be generated from a wide range of sources, including fossil fuels, nuclear power, and renewable sources such as tidal power, solar power, and wind power or any combination of those. Currently though there are more than 400 coal power plants in the U.S. alone. However it is generated, this energy is then transmitted to the vehicle through use of overhead lines, wireless energy transfer such as inductive charging, or a direct connection through an electrical cable. The electricity may then be stored on board the vehicle using a battery, flywheel, or supercapacitors. Vehicles making use of engines working on the principle of combustion can usually only derive their energy from a single or a few sources, usually non-renewable fossil fuels. A key advantage of electric or hybrid electric vehicles is regenerative braking and suspension; their ability to recover energy normally lost during braking as electricity to be restored to the on-board battery.

**Electricity sources**

There are many ways to generate electricity, some of them more ecological than others:

* on-board rechargeable electricity storage system (RESS), called Full Electric Vehicles (FEV). Power storage methods include:
	+ chemical energy stored on the vehicle in on-board batteries: [Battery electric vehicle](http://en.wikipedia.org/wiki/Battery_electric_vehicle) (BEV)
	+ static [energy](http://en.wikipedia.org/wiki/Energy) stored on the vehicle in on-board [electric double-layer capacitors](http://en.wikipedia.org/wiki/Electric_double-layer_capacitor)
	+ kinetic energy storage: [flywheels](http://en.wikipedia.org/wiki/Gyrobus)
* direct connection to generation plants as is common among [electric trains](http://en.wikipedia.org/wiki/Electric_train), [trolley buses](http://en.wikipedia.org/wiki/Trolleybus), and [trolley trucks](http://en.wikipedia.org/wiki/Trolleytruck) (See also : [overhead lines](http://en.wikipedia.org/wiki/Overhead_lines), [third rail](http://en.wikipedia.org/wiki/Third_rail) and [conduit current collection](http://en.wikipedia.org/wiki/Conduit_current_collection))
* renewable sources such as [solar power](http://en.wikipedia.org/wiki/Solar_power): [solar vehicle](http://en.wikipedia.org/wiki/Solar_vehicle)
* generated on-board using a diesel engine: [diesel-electric](http://en.wikipedia.org/wiki/Diesel-electric_transmission) locomotive
* generated on-board using a [fuel cell](http://en.wikipedia.org/wiki/Fuel_cell): [fuel cell vehicle](http://en.wikipedia.org/wiki/Fuel_cell_vehicle)
* generated on-board using [nuclear energy](http://en.wikipedia.org/wiki/Nuclear_energy): nuclear [submarines](http://en.wikipedia.org/wiki/Submarine) and [aircraft carriers](http://en.wikipedia.org/wiki/Aircraft_carrier)

It is also possible to have hybrid electric vehicles that derive electricity from multiple sources. Such as:

* on-board [rechargeable electricity storage system](http://en.wikipedia.org/wiki/Rechargeable_electricity_storage_system) (RESS) and a direct continuous connection to land-based generation plants for purposes of on-highway recharging with unrestricted highway range
* on-board rechargeable electricity storage system and a fueled propulsion power source ([internal combustion engine](http://en.wikipedia.org/wiki/Internal_combustion_engine)): [plug-in hybrid](http://en.wikipedia.org/wiki/Plug-in_hybrid)

[Batteries](http://en.wikipedia.org/wiki/Battery_%28electricity%29), [electric double-layer capacitors](http://en.wikipedia.org/wiki/Electric_double-layer_capacitor) and [flywheel energy storage](http://en.wikipedia.org/wiki/Flywheel_energy_storage) are forms of rechargeable on-board [electrical storage](http://en.wikipedia.org/wiki/Rechargeable_electricity_storage_system). By avoiding an intermediate mechanical step, the [energy conversion efficiency](http://en.wikipedia.org/wiki/Energy_conversion_efficiency) can be improved over the hybrids already discussed, by avoiding unnecessary energy conversions. Furthermore, electro-chemical batteries conversions are easy to reverse, allowing electrical energy to be stored in chemical form.

Another form of chemical to electrical conversion is [fuel cells](http://en.wikipedia.org/wiki/Fuel_cell), projected for future use.

For especially large electric vehicles, such as [submarines](http://en.wikipedia.org/wiki/Submarine), the chemical energy of the diesel-electric can be replaced by a [nuclear reactor](http://en.wikipedia.org/wiki/Nuclear_reactor). The nuclear reactor usually provides heat, which drives a [steam turbine](http://en.wikipedia.org/wiki/Steam_turbine), which drives a generator, which is then fed to the propulsion. *See* [*Nuclear Power*](http://en.wikipedia.org/wiki/Nuclear_Power)

A few experimental vehicles, such as some cars and a handful of aircraft use [solar panels](http://en.wikipedia.org/wiki/Solar_panel) for electricity.

 **Electric motor**

The power of a vehicle electric motor, as in other vehicles, is measured in [kilowatts](http://en.wikipedia.org/wiki/Kilowatt) (kW). 100 kW is roughly equivalent to 134 [horsepower](http://en.wikipedia.org/wiki/Horsepower), although most electric motors deliver full torque over a wide RPM range, so the performance is not equivalent, and far exceeds a 134 horsepower (100 kW) fuel-powered motor, which has a limited torque curve.

Usually, [direct current](http://en.wikipedia.org/wiki/Direct_current) (DC) electricity is fed into a DC/AC inverter where it is converted to [alternating current](http://en.wikipedia.org/wiki/Alternating_current) (AC) electricity and this AC electricity is connected to a 3-phase AC motor. For electric trains, DC motors are often used.

 **Vehicle types**

It is generally possible to equip any kind of vehicle with an electric powertrain.

 **Hybrid electric vehicle**

A hybrid electric vehicle combines a conventional (usually fossil fuel-powered) powertrain with some form of electric propulsion. Common examples include hybrid electric cars such as the [Toyota Prius](http://en.wikipedia.org/wiki/Toyota_Prius).

 **On- and off-road electric vehicles**

Electric vehicles are on the road in many functions, including [electric cars](http://en.wikipedia.org/wiki/Electric_car), [electric trolleybuses](http://en.wikipedia.org/wiki/Trolleybus), [electric bicycles](http://en.wikipedia.org/wiki/Motorized_bicycle#Electric), [electric motorcycles and scooters](http://en.wikipedia.org/wiki/Electric_motorcycles_and_scooters), [neighborhood electric vehicles](http://en.wikipedia.org/wiki/Neighborhood_electric_vehicle), [golf carts](http://en.wikipedia.org/wiki/Golf_carts), [milk floats](http://en.wikipedia.org/wiki/Milk_float), and [forklifts](http://en.wikipedia.org/wiki/Forklift_truck). Off-road vehicles include electrified [all-terrain vehicles](http://en.wikipedia.org/wiki/All-terrain_vehicles) and [tractors](http://en.wikipedia.org/wiki/Tractor).

 **Railborne electric vehicles**

The fixed nature of a rail line makes it relatively easy to power electric vehicles through permanent [overhead lines](http://en.wikipedia.org/wiki/Overhead_lines) or electrified [third rails](http://en.wikipedia.org/wiki/Third_rail), eliminating the need for heavy onboard batteries. [Electric locomotives](http://en.wikipedia.org/wiki/Electric_locomotive), electric [trams/streetcars/trolleys](http://en.wikipedia.org/wiki/Tram), electric [light rail systems](http://en.wikipedia.org/wiki/Light_rail_system), and electric [rapid transit](http://en.wikipedia.org/wiki/Rapid_transit) are all in common use today, especially in Europe and Asia.

Since electric trains do not need to carry a heavy internal combustion engine or large batteries, they can have very good [power-to-weight ratios](http://en.wikipedia.org/wiki/Power-to-weight_ratio). This allows [high speed trains](http://en.wikipedia.org/wiki/High_speed_train) such as France's double-deck [TGVs](http://en.wikipedia.org/wiki/TGV) to operate at speeds of 320 km/h (200 mph) or higher, and [electric locomotives](http://en.wikipedia.org/wiki/Electric_locomotive) to have a much higher power output than [diesel locomotives](http://en.wikipedia.org/wiki/Diesel_locomotive). In addition they have higher short-term [surge power](http://en.wikipedia.org/wiki/Overcurrent) for fast acceleration, and using [regenerative braking](http://en.wikipedia.org/wiki/Regenerative_braking) can put braking power back into the [electrical grid](http://en.wikipedia.org/wiki/Electrical_grid) rather than wasting it.

[Maglev](http://en.wikipedia.org/wiki/Maglev_%28transport%29) trains are also nearly always electric vehicles.

 **Airborne electric vehicles**

Since the beginning of the era of [aviation](http://en.wikipedia.org/wiki/Aviation), electric power for aircraft has received a great deal of experimentation. Currently flying [electric aircraft](http://en.wikipedia.org/wiki/Electric_aircraft) include manned and unmanned aerial vehicles.

 **Seaborne electric vehicles**

[Electric boats](http://en.wikipedia.org/wiki/Electric_boat) were popular around the turn of the 20th century. Interest in quiet and potentially renewable marine transportation has steadily increased since the late 20th century, as [solar cells](http://en.wikipedia.org/wiki/Solar_cells) have given [motorboats](http://en.wikipedia.org/wiki/Motorboat) the infinite range of [sailboats](http://en.wikipedia.org/wiki/Sailboats). [Submarines](http://en.wikipedia.org/wiki/Submarine) use batteries (charged by [diesel](http://en.wikipedia.org/wiki/Diesel-electric_transmission) or gasoline engines at the surface), [nuclear](http://en.wikipedia.org/wiki/Nuclear_submarine) power, or fuel cells to run electric motor driven propellers.

 **Spaceborne electric vehicles**

Main article: [Electrically powered spacecraft propulsion](http://en.wikipedia.org/wiki/Electrically_powered_spacecraft_propulsion)

Electric power has a long history of use in [spacecraft](http://en.wikipedia.org/wiki/Spacecraft). The power sources used for spacecraft are batteries, solar panels and nuclear power. Current methods of propelling a spacecraft with electricity include the [arcjet rocket](http://en.wikipedia.org/wiki/Arcjet_rocket), the [electrostatic ion thruster](http://en.wikipedia.org/wiki/Electrostatic_ion_thruster), the [Hall effect thruster](http://en.wikipedia.org/wiki/Hall_effect_thruster), and [Field Emission Electric Propulsion](http://en.wikipedia.org/wiki/Field_Emission_Electric_Propulsion). [A number of other methods have been proposed, with varying levels of feasibility](http://en.wikipedia.org/wiki/Spacecraft_propulsion#Table_of_methods).

 **Energy and motors**

Most large electric transport systems are powered by stationary sources of electricity that are directly connected to the vehicles through wires. Electric traction allows the use of [regenerative braking](http://en.wikipedia.org/wiki/Regenerative_braking), in which the motors are used as brakes and become generators that transform the motion of, usually, a train into electrical power that is then fed back into the lines. This system is particularly advantageous in mountainous operations, as descending vehicles can produce a large portion of the power required for those ascending. This regenerative system is only viable if the system is large enough to utilise the power generated by descending vehicles.

In the systems above motion is provided by a [rotary](http://en.wikipedia.org/wiki/Rotary_motor) [electric motor](http://en.wikipedia.org/wiki/Electric_motor). However, it is possible to "unroll" the motor to drive directly against a special matched track. These [linear motors](http://en.wikipedia.org/wiki/Linear_motor) are used in [maglev trains](http://en.wikipedia.org/wiki/Maglev_train) which float above the rails supported by [magnetic levitation](http://en.wikipedia.org/wiki/Magnetic_levitation). This allows for almost no rolling resistance of the vehicle and no mechanical wear and tear of the train or track. In addition to the high-performance control systems needed, [switching](http://en.wikipedia.org/wiki/Railroad_switch) and curving of the tracks becomes difficult with linear motors, which to date has restricted their operations to high-speed point to point services.

 **Properties of electric vehicles**

 **Energy sources**

Although electric vehicles have few direct emissions, all rely on energy created through [electricity generation](http://en.wikipedia.org/wiki/Electricity_generation), and will usually emit pollution and generate waste, unless it is generated by [renewable source](http://en.wikipedia.org/wiki/Renewable_source) power plants. Since electric vehicles use whatever electricity is delivered by their electrical utility/grid operator, electric vehicles can be made more or less efficient, polluting and expensive to run, by modifying the electrical generating stations. This would be done by an electrical utility under a government energy policy, in a timescale negotiated between utilities and government.

[Fossil fuel](http://en.wikipedia.org/wiki/Fossil_fuel) vehicle efficiency and pollution standards take years to filter through a nation's fleet of vehicles. New efficiency and pollution standards rely on the purchase of new vehicles, often as the current vehicles already on the road reach their end-of-life. Only a few nations set a retirement age for old vehicles, such as Japan or [Singapore](http://en.wikipedia.org/wiki/Driving_in_Singapore), forcing periodic upgrading of all vehicles already on the road.

Electric vehicles will take advantage of whatever environmental gains happen when a renewable energy generation station comes online, a [fossil-fuel power station](http://en.wikipedia.org/w/index.php?title=Fossil-fuel_power_station&action=edit&redlink=1) is decommissioned or upgraded. Conversely, if government policy or economic conditions shifts generators back to use more polluting fossil fuels and [internal combustion engine vehicles](http://en.wikipedia.org/wiki/Internal_combustion_engine_vehicle) (ICEVs), or more inefficient sources, the reverse can happen. Even in such a situation, electrical vehicles are still more efficient than a comparable amount of fossil fuel vehicles. In areas with a deregulated electrical energy market, an electrical vehicle owner can choose whether to run his electrical vehicle off conventional electrical energy sources, or strictly from renewable electrical energy sources (presumably at an additional cost), pushing other consumers onto conventional sources, and switch at any time between the two.

 **Issues with batteries**

 **Efficiency**

Because of the different methods of charging possible, the emissions produced have been quantified in different ways. Plug-in all-electric and hybrid vehicles also have different consumption characteristics.

 **Electromagnetic radiation**

Electromagnetic radiation from high performance electrical motors has been claimed to be associated with some human ailments, but such claims are largely unsubstantiated except for extremely high exposures.[[16]](http://en.wikipedia.org/wiki/Electric_vehicle#cite_note-15) Electric motors can be shielded within a metallic [Faraday cage](http://en.wikipedia.org/wiki/Faraday_cage), but this reduces efficiency by adding weight to the vehicle, while it is not conclusive that all electromagnetic radiation can be contained.

 **Charging**

 **Grid capacity**

If a large proportion of private vehicles were to convert to grid electricity it would increase the demand for generation and transmission, and consequent emissions. However, overall energy consumption and emissions would diminish because of the higher efficiency of electric vehicles over the entire cycle. In the USA it has been estimated there is already nearly sufficient existing power plant and transmission infrastructure, assuming that most charging would occur overnight, using the most efficient off-peak [base load](http://en.wikipedia.org/wiki/Base_load) sources.

 **Charging stations**

Electric vehicles typically charge from conventional power outlets or dedicated charging stations, a process that typically takes hours, but can be done overnight and often gives a charge that is sufficient for normal everyday usage.

However with the widespread implementation of [electric vehicle networks](http://en.wikipedia.org/wiki/Electric_vehicle_network) within large cities, such as those provided by POD Point in the UK and Europe, electric vehicle users can plug in their cars whilst at work and leave them to charge throughout the day, extending the possible range of commutes and eliminating range anxiety.

One proposed solution for daily recharging is a standardized [inductive charging](http://en.wikipedia.org/wiki/Inductive_charging) system such as Evatran's [Plugless Power](http://en.wikipedia.org/wiki/Plugless_Power). Benefits are the convenience of with parking over the charge station and minimized cabling and connection infrastructure.

Another proposed solution for the typically less frequent, long distance travel is "rapid charging", such as the [Aerovironment](http://en.wikipedia.org/wiki/Aerovironment) PosiCharge line (up to 250 kW) and the [Norvik](http://en.wikipedia.org/w/index.php?title=Norvik&action=edit&redlink=1) MinitCharge line (up to 300 kW). [Ecotality](http://en.wikipedia.org/w/index.php?title=Ecotality&action=edit&redlink=1) is a manufacturer of Charging Stations and has partnered with Nissan on several installations. Battery replacement is also proposed as an alternative, although no OEM's including Nissan/Renault have any production vehicle plans. Swapping requires standardization across platforms, models and manufacturers. Swapping also requires many times more battery packs to be in the system.

One type of battery "replacement" proposed is much simpler: while the latest generation of [vanadium redox battery](http://en.wikipedia.org/wiki/Vanadium_redox_battery) only has an energy density similar to lead-acid, the charge is stored solely in a vanadium-based electrolyte, which can be pumped out and replaced with charged fluid. The vanadium battery system is also a potential candidate for intermediate energy storage in quick charging stations because of its high power density and extremely good endurance in daily use. System cost however, is still prohibitive. As vanadium battery systems are estimated to range between $350–$600 per kWh, a battery that can service one hundred customers in a 24 hour period at 50 kWh per charge would cost $1.8-$3 million.

**Battery swapping**

There is another way to "refuel" electric vehicles. Instead of recharging them from electric socket, batteries could be mechanically replaced on special stations just in a couple of minutes ([battery swapping](http://en.wikipedia.org/wiki/Battery_swapping)).

Batteries with greatest [energy density](http://en.wikipedia.org/wiki/Energy_density) such as metal-air fuel cells usually cannot be recharged in purely electric way. Instead some kind of metallurgical process is needed, such as aluminum smelting and similar.

Silicon-air, aluminum-air and other metal-air fuel cells look promising candidates for swap batteries. Any source of energy, renewable or non-renewable, could be used to remake used metal-air fuel cells with relatively high efficiency. Investment in infrastructure will be needed. The cost of such batteries could be an issue, although they could be made with replaceable anodes and electrolyte.

 **Other in-development technologies**

Conventional [electric double-layer capacitors](http://en.wikipedia.org/wiki/Electric_double-layer_capacitor) are being worked to achieve the energy density of lithium ion batteries, offering almost unlimited lifespans and no environmental issues. High-K electric double-layer capacitors, such as [EEStor](http://en.wikipedia.org/wiki/EEStor)'s EESU, could improve lithium ion energy density several times over if they can be produced. Lithium-sulphur batteries offer 250Wh/kg. Sodium-ion batteries promise 400Wh/kg with only minimal expansion/contraction during charge/discharge and a very high surface area.[[27]](http://en.wikipedia.org/wiki/Electric_vehicle#cite_note-26) Researchers from one of the Ukrainian state universities claim that they have manufactured samples of supercapacitor based on intercalation process with 318 W-h/kg specific energy, which seem to be at least two times improvement in comparison to typical Li-ion batteries.[[28]](http://en.wikipedia.org/wiki/Electric_vehicle#cite_note-27)

 **Advantages and disadvantages of electric vehicles**

**Environmental**

Due to efficiency of electric engines as compared to combustion engines, even when the electricity used to charge electric vehicles comes from a [CO2](http://en.wikipedia.org/wiki/CO2) emitting source, such as a coal or gas fired powered plant, the net CO2 production from an electric car is typically one half to one third of that from a comparable combustion vehicle.

Electric vehicles release almost no air pollutants at the place where they are operated. In addition, it is generally easier to build pollution control systems into centralised power stations than retrofit enormous numbers of cars.

Electric vehicles typically have less [noise pollution](http://en.wikipedia.org/wiki/Noise_pollution) than an [internal combustion engine vehicle](http://en.wikipedia.org/wiki/Internal_combustion_engine_vehicle), whether it is at rest or in motion. Electric vehicles emit no tailpipe CO2 or pollutants such as [NOx](http://en.wikipedia.org/wiki/NOx), [NMHC](http://en.wikipedia.org/wiki/NMHC), CO and [PM](http://en.wikipedia.org/wiki/Particulate) at the point of use.

Electric motors don't require oxygen, unlike [internal combustion engines](http://en.wikipedia.org/wiki/Internal_combustion_engine); this is useful for [submarines](http://en.wikipedia.org/wiki/Submarine).

While electric and hybrid cars have reduced tailpipe carbon emissions, the energy they consume is sometimes produced by means that have environmental impacts. For example, the majority of [electricity produced in the United States](http://en.wikipedia.org/wiki/Electricity_generation) comes from [fossil fuels](http://en.wikipedia.org/wiki/Fossil_fuel) ([coal](http://en.wikipedia.org/wiki/Coal) and [natural gas](http://en.wikipedia.org/wiki/Natural_gas)) so use of an Electric Vehicle in the United States would not be completely [carbon neutral](http://en.wikipedia.org/wiki/Carbon_neutral). Electric and hybrid cars can help decrease energy use and pollution, with local no pollution at all being generated by electric vehicles, and may someday use only renewable resources, but the choice that would have the lowest negative environmental impact would be a lifestyle change in favor of walking, biking, use of public transit or [telecommuting](http://en.wikipedia.org/wiki/Telecommuting). Governments may invest in research and development of electric cars with the intention of reducing the impact on the environment where they could instead develop pedestrian-friendly communities or electric mass transit.

Electric motors are mechanically very simple.

Electric motors often achieve 90% [energy conversion efficiency](http://en.wikipedia.org/wiki/Energy_conversion_efficiency) over the full range of speeds and power output and can be precisely controlled. They can also be combined with [regenerative braking](http://en.wikipedia.org/wiki/Regenerative_braking) systems that have the ability to convert movement energy back into stored electricity. This can be used to reduce the wear on brake systems (and consequent brake pad dust) and reduce the total energy requirement of a trip. Regenerative braking is especially effective for start-and-stop city use.

They can be finely controlled and provide high torque from rest, unlike [internal combustion engines](http://en.wikipedia.org/wiki/Internal_combustion_engine), and do not need multiple gears to match power curves. This removes the need for [gearboxes](http://en.wikipedia.org/wiki/Transmission_%28mechanics%29) and [torque converters](http://en.wikipedia.org/wiki/Torque_converter).

Electric vehicles provide quiet and smooth operation and consequently have less noise and [vibration](http://en.wikipedia.org/wiki/Vibration) than internal combustion engines. While this is a desirable attribute, it has also evoked concern that the absence of the usual sounds of an approaching vehicle poses a danger to blind, elderly and very young pedestrians. To mitigate this situation, automakers and individual companies are developing systems that produce [warning sounds](http://en.wikipedia.org/wiki/Electric_vehicle_warning_sounds) when electric vehicles are moving slowly, up to a speed when normal motion and rotation (road, suspension, electric motor, etc.) noises become audible.

 **Energy resilience**

Electricity is a form of energy that remains within the country or region where it was produced and can be multi-sourced. As a result it gives the greatest degree of [energy resilience](http://en.wikipedia.org/wiki/Energy_resilience).

 **Energy efficiency**

Electric vehicle '[tank-to-wheels](http://en.wikipedia.org/wiki/Tank-to-wheel)' efficiency is about a factor of 3 higher than [internal combustion engine vehicles](http://en.wikipedia.org/wiki/Internal_combustion_engine_vehicle) It does not consume energy when it is not moving, unlike internal combustion engines where they continue running even during idling. However, looking at the [well-to-wheel](http://en.wikipedia.org/wiki/Well-to-wheel) efficiency of electric vehicles, their emissions are comparable to an efficient gasoline or diesel in most countries because electricity generation relies on fossil fuels.

 **Cost of recharge**

The GM Volt will cost "less than purchasing a cup of your favorite coffee" to recharge. The Volt should cost less than 2 cents per mile to drive on electricity, compared with 12 cents a mile on gasoline at a price of $3.60 a gallon. This means a trip from Los Angeles to New York would cost $56 on electricity, and $336 with gasoline. This would be the equivalent to paying 60 cents a gallon of gas.

 **Stabilization of the grid**

Since electric vehicles can be plugged into the [electric grid](http://en.wikipedia.org/wiki/Electric_grid) when not in use, there is a potential for battery powered vehicles to even out the demand for electricity by feeding electricity *into* the grid from their batteries during peak use periods (such as midafternoon air conditioning use) while doing most of their charging at night, when there is unused generating capacity. This [Vehicle to Grid](http://en.wikipedia.org/wiki/Vehicle_to_Grid) (V2G) connection has the potential to reduce the need for new power plants.

Furthermore, our current electricity infrastructure may need to cope with increasing shares of variable-output power sources such as windmills and PV solar panels. This variability could be addressed by adjusting the speed at which EV batteries are charged, or possibly even discharged.

Some concepts see battery exchanges and battery charging stations, much like gas/petrol stations today. Clearly these will require enormous storage and charging potentials, which could be manipulated to vary the rate of charging, and to output power during shortage periods, much as diesel generators are used for short periods to stabilize some national grids.

 **Range**

Many electric designs have limited range, due to the low energy density of batteries compared to the fuel of internal combustion engined vehicles. Electric vehicles also often have long recharge times compared to the relatively fast process of refueling a tank. This is further complicated by the current scarcity of public charging stations. "[Range anxiety](http://en.wikipedia.org/wiki/Range_anxiety)" is a label for consumer concern about EV range.

 **Heating of electric vehicles**

In cold climates considerable energy is needed to heat the interior of a vehicle and to defrost the windows. With internal combustion engines, this heat already exists from the combustion process from the waste heat from the engine cooling circuit and this offsets the [greenhouse gases](http://en.wikipedia.org/wiki/Greenhouse_gas)' external costs. If this is done with battery electric vehicles, this will require extra energy from the vehicles' batteries. Although some heat could be harvested from the motor(s) and battery, due to their greater efficiency there is not as much waste heat available as from a [combustion engine](http://en.wikipedia.org/wiki/Combustion_engine).

However, for vehicles which are connected to the grid, battery electric vehicles can be preheated, or cooled, and need little or no energy from the battery, especially for short trips.

Newer designs are focused on using super-[insulated](http://en.wikipedia.org/wiki/Thermal_insulation) [cabins](http://en.wikipedia.org/w/index.php?title=Vehicle_cabin&action=edit&redlink=1) which can heat the vehicle using the body heat of the passengers. This is not enough, however, in colder climates as a driver delivers only about 100 W of heating power. A reversible AC-system, cooling the cabin during summer and heating it during winter, seems to be the most practical and promising way of solving the thermal management of the EV. Ricardo Arboix introduced (2008) a new concept based on the principle of combining the thermal-management of the EV-battery with the thermal-management of the cabin using a reversible AC-system. This is done by adding a third heat-exchanger, thermally connected with the battery-core, to the traditional heat pump/air conditioning system used in previous EV-models like the GM EV1 and Toyota RAV4 EV. The concept has proven to bring several benefits, such as prolonging the life-span of the battery as well as improving the performance and overall energy-efficiency of the EV.

**Electric public transit efficiency**

Shifts from private to [public transport](http://en.wikipedia.org/wiki/Public_transport) (train, [trolleybus](http://en.wikipedia.org/wiki/Trolleybus) or [tram](http://en.wikipedia.org/wiki/Tram)) have the potential for large gains in efficiency in terms of [individual miles per kWh](http://en.wikipedia.org/w/index.php?title=Individual_mile_per_kWH&action=edit&redlink=1).

Research shows people do prefer trams,[[46]](http://en.wikipedia.org/wiki/Electric_vehicle#cite_note-45) because they are quieter and more comfortable and perceived as having higher status.[[47]](http://en.wikipedia.org/wiki/Electric_vehicle#cite_note-46)

Therefore, it may be possible to cut liquid fossil fuel consumption in cities through the use of electric trams.

Trams may be the most energy-efficient form of public transportation, with rubber wheeled vehicles using 2/3 more energy than the equivalent tram, and run on electricity rather than fossil fuels.

In terms of [net present value](http://en.wikipedia.org/wiki/Net_present_value), they are also the cheapest—[Blackpool trams](http://en.wikipedia.org/wiki/Blackpool_tram) are still running after 100-years, but combustion buses only last about 15-years.

 **Incentives and promotion**

 **Improved long term energy storage and nano batteries**

There have been several developments which could bring electric vehicles outside their current fields of application, as scooters, golf cars, neighborhood vehicles, in industrial operational yards and indoor operation. First, advances in [lithium-based battery technology](http://en.wikipedia.org/wiki/Lithium_ion_battery), in large part driven by the consumer electronics industry, allow full-sized, highway-capable electric vehicles to be propelled as far on a single charge as conventional cars go on a single tank of gasoline. Lithium batteries have been made safe, can be recharged in minutes instead of hours, and now last longer than the typical vehicle. The production cost of these lighter, higher-capacity lithium batteries is gradually decreasing as the technology matures and production volumes increase.

Rechargeable [Lithium-air batteries](http://en.wikipedia.org/wiki/Lithium_air_battery) potentially offer increased range over other types and are a current topic of research.

 **Introduction of battery management and intermediate storage**

Another improvement is to decouple the electric motor from the battery through electronic control, employing [ultra-capacitors](http://en.wikipedia.org/wiki/Ultra-capacitor) to buffer large but short power demands and [regenerative braking](http://en.wikipedia.org/wiki/Regenerative_braking) energy. The development of new cell types combined with intelligent cell management improved both weak points mentioned above. The cell management involves not only monitoring the health of the cells but also a redundant cell configuration (one more cell than needed). With sophisticated switched wiring it is possible to condition one cell while the rest are on duty.

 **Faster battery recharging**

By soaking the matter found in conventional lithium ion batteries in a special solution, lithium ion batteries were supposedly said to be recharged 100x faster. This test was however done with a specially-designed battery with little capacity. Batteries with higher capacity can be recharged 40x faster. The research was conducted by [Byoungwoo Kang](http://en.wikipedia.org/w/index.php?title=Byoungwoo_Kang&action=edit&redlink=1) and [Gerbrand Ceder](http://en.wikipedia.org/w/index.php?title=Gerbrand_Ceder&action=edit&redlink=1) of [MIT](http://en.wikipedia.org/wiki/MIT). The researchers believe the solution may appear on the market in 2011. Another method to speed up battery charging is by adding an additional oscillating electric field. This method was proposed by [Ibrahim Abou Hamad](http://en.wikipedia.org/w/index.php?title=Ibrahim_Abou_Hamad&action=edit&redlink=1) from [Mississippi State University](http://en.wikipedia.org/wiki/Mississippi_State_University). The company [Epyon](http://en.wikipedia.org/wiki/Epyon) specializes in faster charging of electric vehicles

HYBRID VEHICLES

A **hybrid electric vehicle** (HEV) is a type of [hybrid vehicle](http://en.wikipedia.org/wiki/Hybrid_vehicle) and [electric vehicle](http://en.wikipedia.org/wiki/Electric_vehicle) which combines a conventional [internal combustion engine](http://en.wikipedia.org/wiki/Internal_combustion_engine) (ICE) [propulsion](http://en.wikipedia.org/wiki/Ground_propulsion) system with an [electric](http://en.wikipedia.org/wiki/Electric_power) propulsion system. The presence of the electric powertrain is intended to achieve either better [fuel economy](http://en.wikipedia.org/wiki/Fuel_economy_in_automobiles) than a [conventional vehicle](http://en.wikipedia.org/wiki/Conventional_vehicle), or better performance. A variety of types of HEV exist, and the degree to which they function as EVs varies as well. The most common form of HEV is the hybrid electric car, although hybrid electric trucks (pickups and tractors) and buses also exist.

Modern HEVs make use of efficiency-improving technologies such as [regenerative braking](http://en.wikipedia.org/wiki/Regenerative_braking), which converts the vehicle's kinetic energy into battery-replenishing electric energy, rather than wasting it as heat energy as conventional brakes do. Some varieties of HEVs use their internal combustion engine to generate electricity by spinning an [electrical generator](http://en.wikipedia.org/wiki/Electrical_generator) (this combination is known as a [motor-generator](http://en.wikipedia.org/wiki/Motor-generator)), to either recharge their batteries or to directly power the electric drive motors. Many HEVs [reduce idle emissions](http://en.wikipedia.org/wiki/Idle_reduction) by [shutting down](http://en.wiktionary.org/wiki/shut_down) the ICE at [idle](http://en.wiktionary.org/wiki/idle) and restarting it when needed; this is known as a [start-stop system](http://en.wikipedia.org/wiki/Start-stop_system). A hybrid-electric produces less emissions from its ICE than a comparably-sized gasoline car, since an HEV's gasoline engine is usually smaller than a comparably-sized pure gasoline-burning vehicle (natural gas and propane fuels produce lower emissions) and if not used to directly drive the car, can be geared to run at maximum efficiency, further improving fuel economy.

A **flexible-fuel vehicle (FFV)** or **dual-fuel vehicle** ([colloquially](http://en.wikipedia.org/wiki/Colloquial) called a **flex-fuel vehicle**) is an [alternative fuel vehicle](http://en.wikipedia.org/wiki/Alternative_fuel_vehicle) with an [internal combustion engine](http://en.wikipedia.org/wiki/Internal_combustion_engine) designed to run on more than one [fuel](http://en.wikipedia.org/wiki/Fuel), usually [gasoline](http://en.wikipedia.org/wiki/Gasoline) blended with either [ethanol](http://en.wikipedia.org/wiki/Ethanol_fuel) or [methanol fuel](http://en.wikipedia.org/wiki/Methanol_fuel), and both fuels are stored in the same common tank. Flex-fuel engines are capable of burning any proportion of the resulting blend in the [combustion chamber](http://en.wikipedia.org/wiki/Combustion_chamber) as [fuel injection](http://en.wikipedia.org/wiki/Fuel_injection) and [spark timing](http://en.wikipedia.org/wiki/Ignition_timing) are adjusted automatically according to the actual blend detected by electronic sensors. Flex-fuel vehicles are distinguished from [bi-fuel vehicles](http://en.wikipedia.org/wiki/Bi-fuel_vehicle), where two fuels are stored in separate tanks and the engine runs on one fuel at a time, for example, [compressed natural gas](http://en.wikipedia.org/wiki/Compressed_natural_gas) (CNG), [liquefied petroleum gas](http://en.wikipedia.org/wiki/Autogas) (LPG), or [hydrogen](http://en.wikipedia.org/wiki/Hydrogen_vehicle).

The most common commercially available FFV in the world market is the ethanol flexible-fuel vehicle, with 22.6 million [automobiles](http://en.wikipedia.org/wiki/Automobile), [motorcycles](http://en.wikipedia.org/wiki/Motorcycle) and [light duty trucks](http://en.wikipedia.org/wiki/Light_duty_truck) sold worldwide by 2010, and concentrated in four markets, [Brazil](http://en.wikipedia.org/wiki/Brazil) (12.5 million), the [United States](http://en.wikipedia.org/wiki/United_States) (9.3 million), [Canada](http://en.wikipedia.org/wiki/Canada) (more than 600,000), and [Europe](http://en.wikipedia.org/wiki/Europe), led by [Sweden](http://en.wikipedia.org/wiki/Sweden) (216,975). The Brazilian flex fuel fleet includes 515,726 flexible-fuel motorcycles sold since 2009. In addition to flex-fuel vehicles running with ethanol, in Europe and the US, mainly in [California](http://en.wikipedia.org/wiki/California), there have been successful test programs with methanol flex-fuel vehicles, known as [M85](http://en.wikipedia.org/wiki/Methanol_fuel#Methanol_fuel_programs_in_the_U.S._and_other_nations) flex-fuel vehicles. There have been also successful tests using [P-series fuels](http://en.wikipedia.org/wiki/P-series_fuels) with E85 flex fuel vehicles, but as of June 2008, this fuel is not yet available to the general public. These successful tests with P-series fuels were conducted on [Ford Taurus](http://en.wikipedia.org/wiki/Ford_Taurus) and [Dodge Caravan](http://en.wikipedia.org/wiki/Dodge_Caravan) flexible-fuel vehicles.

Though technology exists to allow ethanol FFVs to run on any mixture of gasoline and ethanol, from pure gasoline up to 100% ethanol ([E100](http://en.wikipedia.org/wiki/Neat_ethanol_fuel)), North American and European flex-fuel vehicles are optimized to run on a maximum blend of 15% gasoline with 85% [anhydrous](http://en.wikipedia.org/wiki/Anhydrous) ethanol (called [E85](http://en.wikipedia.org/wiki/E85) fuel). This limit in the ethanol content is set to reduce ethanol emissions at low temperatures and to avoid cold starting problems during cold weather, at temperatures lower than 11 [°C](http://en.wikipedia.org/wiki/Degrees_Celsius) The alcohol content is reduced during the winter in regions where temperatures fall below 0 °C to a winter blend of [E70](http://en.wikipedia.org/wiki/Common_ethanol_fuel_mixtures#E70.2C_E75) in the U.S. or to [E75](http://en.wikipedia.org/wiki/Common_ethanol_fuel_mixtures#E70.2C_E75) in Sweden from November until March. Brazilian flex fuel vehicles are optimized to run on any mix of [E20-E25](http://en.wikipedia.org/wiki/Common_ethanol_fuel_mixtures#E20.2C_E25) gasoline and up to 100% [hydrous](http://en.wikipedia.org/wiki/Hydrous) ethanol fuel (E100). The Brazilian flex vehicles are built-in with a small gasoline reservoir for cold starting the engine when temperatures drop below 15 °C. An improved flex motor generation was launched in 2009 which eliminated the need for the secondary gas tank.

**Terminology**

As ethanol FFVs became commercially available during the late 1990s, the common use of the term "flexible-fuel vehicle" became synonymous with ethanol FFVs. In the United States flex-fuel vehicles are also known as "E85 vehicles". In Brazil, the FFVs are popularly known as "total flex" or simply "flex" cars. In Europe, FFVs are also known as "flexifuel" vehicles. Automakers, particularly in Brazil and the European market, use badging in their FFV models with the some variant of the word "flex", such as [Volvo](http://en.wikipedia.org/wiki/Volvo) *Flexifuel*, or [Volkswagen](http://en.wikipedia.org/wiki/Volkswagen) *Total Flex*, or [Chevrolet](http://en.wikipedia.org/wiki/Chevrolet) *FlexPower* or [Renault](http://en.wikipedia.org/wiki/Renault) *Hi-Flex*, and [Ford](http://en.wikipedia.org/wiki/Ford) sells its [Focus](http://en.wikipedia.org/wiki/Ford_Focus_%28international%29) model in Europe as *Flexifuel* and as *Flex* in Brazil. In the US, only since 2008 FFV models feature a yellow gas cap with the label "E85/Gasoline" written on the top of the cap to differentiate E85s from gasoline only models.

Flexible-fuel vehicles (FFVs) are based on dual-fuel systems that supply both fuels into the combustion chamber at the same time in various calibrated proportions. The most common fuels used by FFVs today are unleaded gasoline and ethanol fuel. Ethanol FFVs can run on pure gasoline, pure ethanol (E100) or any combination of both. Methanol has also been blended with gasoline in flex-fuel vehicles known as [M85](http://en.wikipedia.org/wiki/Methanol_fuel#Methanol_fuel_by_country) FFVs, but their use has been limited mainly to demonstration projects and small government fleets, particularly in California.

* [Bi-fuel vehicles](http://en.wikipedia.org/wiki/Bi-fuel_vehicle). The term flexible-fuel vehicles is sometimes used to include other alternative fuel vehicles that can run with [compressed natural gas](http://en.wikipedia.org/wiki/Compressed_natural_gas) (CNG), [liquefied petroleum gas](http://en.wikipedia.org/wiki/Liquefied_petroleum_gas) (LPG; also known as [autogas](http://en.wikipedia.org/wiki/Autogas)), or [hydrogen](http://en.wikipedia.org/wiki/Hydrogen_vehicle). However, all these vehicles actually are bi-fuel and not flexible-fuel vehicles, because they have engines that store the other fuel in a separate tank, and the engine runs on one fuel at a time. Bi-fuel vehicles have the capability to switch back and forth from gasoline to the other fuel, manually or automatically. The most common available fuel in the market for bi-fuel cars is natural gas (CNG), and by 2008 there were 9,6 million natural gas vehicles, led by [Pakistan](http://en.wikipedia.org/wiki/Pakistan) (2.0 million), [Argentina](http://en.wikipedia.org/wiki/Argentina) (1.7 million), and Brazil (1.6 million). Natural gas vehicles are a popular choice as [taxicabs](http://en.wikipedia.org/wiki/Taxicab) in the main cities of Argentina and Brazil. Normally, standard gasoline vehicles are retrofitted in specialized shops, which involve installing the gas cylinder in the trunk and the CNG injection system and electronics.
* Multifuel vehicles are capable of operating with more than two fuels. In 2004 [GM do Brasil](http://en.wikipedia.org/wiki/GM_do_Brasil) introduced the [Chevrolet Astra](http://en.wikipedia.org/wiki/Chevrolet_Astra) 2.0 with a "MultiPower" engine built on flex fuel technology developed by [Bosch](http://en.wikipedia.org/wiki/Robert_Bosch_GmbH) of Brazil, and capable of using CNG, ethanol and gasoline (E20-E25 blend) as fuel. This automobile was aimed at the taxicab market and the switch among fuels is done manually. In 2006 [Fiat](http://en.wikipedia.org/wiki/Fiat) introduced the [Fiat Siena Tetra fuel](http://en.wikipedia.org/wiki/Fiat_Siena), a four-fuel car developed under [Magneti Marelli](http://en.wikipedia.org/wiki/Magneti_Marelli) of Fiat Brazil. This automobile can run as a flex-fuel on 100% ethanol (E100); or on E-20 to E25, Brazil's normal ethanol gasoline blend; on pure gasoline (though no longer available in Brazil since 1993, it is still used in neighboring countries); or just on natural gas. The Siena Tetrafuel was engineered to switch from any gasoline-ethanol blend to CNG automatically, depending on the power required by road conditions. Another existing option is to [retrofit](http://en.wikipedia.org/wiki/Retrofit) an ethanol flexible-fuel vehicle to add a natural gas tank and the corresponding injection system. This option is popular among taxicab owners in [São Paulo](http://en.wikipedia.org/wiki/S%C3%A3o_Paulo) and [Rio de Janeiro](http://en.wikipedia.org/wiki/Rio_de_Janeiro), Brazil, allowing users to choose among three fuels (E25, E100 and CNG) according to current market prices at the pump. Vehicles with this adaptation are known in Brazil as "tri-fuel" cars.
* Flex-fuel [hybrid electric](http://en.wikipedia.org/wiki/Hybrid_electric_vehicle) and flex-fuel [plug-in hybrid](http://en.wikipedia.org/wiki/Plug-in_hybrid) are two types of [hybrid vehicles](http://en.wikipedia.org/wiki/Hybrid_vehicle) built with a combustion engine capable of running on gasoline, E-85, or E-100 to help drive the wheels in conjunction with the electric engine or to recharge the battery pack that powers the electric engine. In 2007 [Ford](http://en.wikipedia.org/wiki/Ford_Motor_Corporation) produced 20 demonstration [Escape Hybrid](http://en.wikipedia.org/wiki/Ford_Escape_Hybrid) E85s for real-world testing in fleets in the U.S. Also as a demonstration project, Ford delivered in 2008 the first flexible-fuel plug-in hybrid SUV to the [U.S. Department of Energy](http://en.wikipedia.org/wiki/U.S._Department_of_Energy) (DOE), a [Ford Escape Plug-in Hybrid](http://en.wikipedia.org/wiki/Ford_Escape_Hybrid), which runs on gasoline or E85. GM announced that the [Chevrolet Volt](http://en.wikipedia.org/wiki/Chevrolet_Volt) plug-in hybrid, launched in the U.S. in late 2010, would be the first commercially available flex-fuel plug-in capable of adapting the propulsion to several world markets such as the U.S., Brazil or Sweden, as the combustion engine can be adapted to run on E85, E100 or diesel respectively. The Volt is expected to be flex-fuel-capable in 2013. [Lotus Engineering](http://en.wikipedia.org/wiki/Lotus_Engineering) unveiled the [Lotus CityCar](http://en.wikipedia.org/wiki/Lotus_CityCar) at the [2010 Paris Motor Show](http://en.wikipedia.org/wiki/2010_Paris_Motor_Show). The CityCar is a [plug-in hybrid](http://en.wikipedia.org/wiki/Plug-in_hybrid) [concept car](http://en.wikipedia.org/wiki/Concept_car) designed for flex-fuel operation on [ethanol](http://en.wikipedia.org/wiki/Ethanol_fuel), or [methanol](http://en.wikipedia.org/wiki/Methanol_fuel) as well as regular [gasoline](http://en.wikipedia.org/wiki/Gasoline).

**History**

The first commercial flexible fuel vehicle was the [Ford Model T](http://en.wikipedia.org/wiki/Ford_Model_T), produced from 1908 through 1927. It was fitted with a [carburetor](http://en.wikipedia.org/wiki/Carburetor) with adjustable jetting, allowing use of gasoline or ethanol, or a combination of both. Other car manufactures also provided engines for ethanol fuel use. [Henry Ford](http://en.wikipedia.org/wiki/Henry_Ford) continued to advocate for ethanol as fuel even during the [prohibition](http://en.wikipedia.org/wiki/Prohibition_in_the_United_States). However, cheaper oil caused gasoline to prevail, until the [1973 oil crisis](http://en.wikipedia.org/wiki/1973_oil_crisis) resulted in gasoline shortages and awareness on the dangers of oil dependence. This crisis opened a new opportunity for ethanol and other [alternative fuels](http://en.wikipedia.org/wiki/Alternative_fuel), such as [methanol](http://en.wikipedia.org/wiki/Methanol_fuel), gaseous fuels such as [CNG](http://en.wikipedia.org/wiki/Compressed_natural_gas) and [LPG](http://en.wikipedia.org/wiki/Liquefied_petroleum_gas), and also [hydrogen](http://en.wikipedia.org/wiki/Hydrogen_vehicle).[[9]](http://en.wikipedia.org/wiki/Flexible-fuel_vehicle#cite_note-Methanolstory-8)[[14]](http://en.wikipedia.org/wiki/Flexible-fuel_vehicle#cite_note-SusEthanol-13) Ethanol, methanol and natural gas CNG were the three alternative fuels that received more attention for [research and development](http://en.wikipedia.org/wiki/Research_and_development), and government support.

SOLAR POWERED VEHICLES

A **solar vehicle** is an [electric vehicle](http://en.wikipedia.org/wiki/Electric_vehicle) powered by [solar panels](http://en.wikipedia.org/wiki/Solar_panel) on the vehicle. [Photovoltaic](http://en.wikipedia.org/wiki/Photovoltaic) (PV) cells convert the sun's energy directly into [electric energy](http://en.wikipedia.org/wiki/Electric_energy). Solar power may be used to provide all or part of a vehicle's propulsion, or may be used to provide power for communcations, or controls, or other auxiliary functions.

Solar vehicles are not sold as practical day-to-day transportation devices at present, but are primarily demonstration vehicles and engineering exercises, often sponsored by government agencies. However, indirectly [solar-charged vehicles](http://en.wikipedia.org/wiki/Solar-charged_vehicle) are widespread and [solar boats](http://en.wikipedia.org/wiki/Electric_boat) are available commercially.

**Limitations**

There are limitations to using photovoltaic (PV) cells for vehicles:

* Power density: Maximum power from a solar array is limited by the size of the vehicle and area that can be exposed to sunlight. While energy can be accumulated in batteries to lower peak demand on the array and provide operation in sunless conditions, the battery adds weight and cost to the vehicle. The power limit can be mitigated by use of conventional electric cars supplied by solar (or other) power, recharging from the electrical grid.
* Cost: While sunlight is free, the creation of PV cells to capture that sunlight is expensive. Costs for solar panels are steadily declining (22% cost reduction per doubling of production volume).
* Design considerations: Even though sunlight has no lifespan, PV cells do. The lifetime of a solar module is approximately 30 years. Standard photovoltaics often come with a warranty of 90 % (from nominal power) after 10 years and 80 % after 25 years. Mobile applications are unlikely to require lifetimes as long as building integrated PV and solar parks. Current PV panels are mostly designed for stationary installations. However, to be successful in mobile applications, PV panels need to be designed to withstand vibrations. Also, solar panels, especially those incorporating glass have significant weight. To be useful, the energy harvested by a panel must exceed the added fuel consumption caused by the added weight.

Solar cars depend on PV cells to convert sunlight into electricity to drive electric motors. Unlike solar thermal energy which converts solar energy to heat, PV cells directly convert sunlight into electricity.

Solar cars combine technology typically used in the [aerospace](http://en.wikipedia.org/wiki/Aerospace), [bicycle](http://en.wikipedia.org/wiki/Bicycle), [alternative energy](http://en.wikipedia.org/wiki/Alternative_energy) and [automotive](http://en.wikipedia.org/wiki/Automotive) industries. The design of a solar car is severely limited by the amount of energy input into the car. Solar cars are built for [solar car races](http://en.wikipedia.org/wiki/Solar_car_racing). Even the best solar cells can only collect limited power and energy over the area of a car's surface. This limits solar cars to a single seat, with no cargo capacity, and ultralight composite bodies to save weight. Solar cars lack the safety and convenience features of conventional vehicles.

Solar cars are often fitted with gauges to warn the driver of possible problems. Cars without gauges almost always feature wireless telemetry, which allows the driver's team to monitor the car's energy consumption, solar energy capture and other parameters and free the driver to concentrate on driving.

As an alternative, a battery-powered electric vehicle may use a solar array to recharge; the array may be connected to the general electrical distribution grid.

 **Single-track vehicles**

A solar bicycle or tricycle has the advantage of very low weight and can use the riders foot power to supplement the power generated by the solar panel roof. In this way, a comparatively simple and inexpensive vehicle can be driven without the use of any fossil fuels.

Solar photovoltaics helped power India's first Quadricycle developed since 1996 in Gujarat state's SURAT city.

The first solar "cars" were actually tricycles or quadricycles built with bicycle technology. These were called solarmobiles at the first solar race, the [Tour de Sol](http://en.wikipedia.org/wiki/Tour_de_Sol) in Switzerland in 1985 with 72 participants, half using exclusively solar power and half solar-human-powered hybrids. A few true solar bicycles were built, either with a large solar roof, a small rear panel, or a trailer with a solar panel. Later more practical solar bicycles were built with foldable panels to be set up only during parking. Even later the panels were left at home, feeding into the electric mains, and the bicycles charged from the mains. Today highly developed [electric bicycles](http://en.wikipedia.org/wiki/Electric_bicycles) are available and these use so little power that it costs little to buy the equivalent amount of solar electricity. The "solar" has evolved from actual hardware to an indirect accounting system. The same system also works for electric motorcycles, which were also first developed for the [Tour de Sol](http://en.wikipedia.org/wiki/Tour_de_Sol). This is rapidly becoming an era of solar production. With today's high performance solar cells, a front and rear PV panel on [this solar bike](http://www.avdweb.nl/solar-bike/solar-bike-intro.html) can give sufficient assistance, where the range is not limited by batteries.

 **Applications**

One practical application for solar powered vehicles is possibly golf carts, some of which are used relatively little but spend most of their time parked in the sun.

 **Auxiliary power**

Photovoltaic modules are used commercially as [auxiliary power units](http://en.wikipedia.org/wiki/Auxiliary_power_unit) on passenger cars in order to ventilate the car, reducing the temperature of the passenger compartment while it is parked in the sun. Vehicles such as the 2010 [Prius](http://en.wikipedia.org/wiki/Toyota_Prius#2009.E2.80.93_.28model_ZVW30.29), [Aptera 2](http://en.wikipedia.org/wiki/Aptera_2_Series#Accessories_and_interior), [Audi A8](http://en.wikipedia.org/wiki/Audi_A8#D2), and [Mazda 929](http://en.wikipedia.org/wiki/Mazda_929#1990) have had solar [sunroof](http://en.wikipedia.org/wiki/Sunroof#Sunroof_Types) options for ventilation purposes.

The area of photovoltaic modules required to power a car with conventional design is too large to be carried onboard. A prototype car and trailer has been built [Solar Taxi](http://www.solartaxi.com/). According to the website, it is capable of 100 km/day using 6m2 of standard crystalline silicon cells. Electricity is stored using a [nickel/salt battery](http://en.wikipedia.org/wiki/Molten_salt_battery#Zebra_battery). A stationary system such as a rooftop solar panel, however, can be used to charge conventional electric vehicles.

It is also possible to use solar panels to extend the range of a hybrid or electric car, as incorporated in the [Fisker Karma](http://en.wikipedia.org/wiki/Fisker_Karma), available as an option on the [Chevy Volt](http://en.wikipedia.org/wiki/Chevy_Volt), on the hood and roof of "Destiny 2000" modifications of [Pontiac Fieros](http://en.wikipedia.org/wiki/Pontiac_Fiero), [Italdesign Quaranta](http://en.wikipedia.org/w/index.php?title=Italdesign_Quaranta&action=edit&redlink=1), Free Drive EV [Solar Bug](http://en.wikipedia.org/w/index.php?title=Solar_Bug&action=edit&redlink=1), and numerous other electric vehicles, both concept and production. In May 2007 a partnership of Canadian companies led by Hymotion added PV cells to a [Toyota Prius](http://en.wikipedia.org/wiki/Toyota_Prius) to extend the range. [SEV](http://www.solarelectricalvehicles.com/) claims 20 miles per day from their combined 215W module mounted on the car roof and an additional 3kWh battery.

On 9 June 2008, the German and French Presidents announced a plan to offer a cedit of 6-8g/km of CO2 emissions for cars fitted with technologies "not yet taken into consideration during the standard measuring cycle of the emissions of a car". This has given rise to speculation that photovoltaic panels might be widely adopted on autos in the near future.

It is also technically possible to use photovoltaic technology, (specifically [thermophotovoltaic](http://en.wikipedia.org/wiki/Thermophotovoltaic) (TPV) technology) to provide motive power for a car. Fuel is used to heat an emitter. The infrared radiation generated is converted to electricity by a low band gap PV cell (e.g. GaSb). A protoype TPV hybrid car was even built. The "Viking 29" was the World’s first thermophotovoltaic (TPV) powered automobile, designed and built by the Vehicle Research Institute (VRI) at Western Washington University. Efficiency would need to be increased and cost decreased to make TPV competitive with fuel cells or internal combustion engines.

MAGNETIC TRACK VEHICLES

**Maglev** (derived from [magnetic levitation](http://en.wikipedia.org/wiki/Magnetic_levitation)), is a system of transportation that suspends, guides and propels vehicles, predominantly trains, using magnetic levitation from a very large number of magnets for lift and propulsion. This method has the potential to be faster, quieter and smoother than wheeled [mass transit](http://en.wikipedia.org/wiki/Mass_transit) systems. The power needed for levitation is usually not a particularly large percentage of the overall consumption; most of the power used is needed to overcome air [drag](http://en.wikipedia.org/wiki/Drag_%28physics%29), as with any other high speed train.

The highest recorded speed of a Maglev train is 581 kilometres per hour, achieved in Japan in 2003, 6 kilometres per hour faster than the conventional [TGV](http://en.wikipedia.org/wiki/TGV) wheel-rail speed record.

The first commercial maglev [people mover](http://en.wikipedia.org/wiki/People_mover) was simply called "[MAGLEV](http://en.wikipedia.org/wiki/AirRail_Link#Maglev)" and officially opened in 1984 near [Birmingham](http://en.wikipedia.org/wiki/Birmingham), [England](http://en.wikipedia.org/wiki/England). It operated on an elevated 600-metre section of monorail track between [Birmingham International Airport](http://en.wikipedia.org/wiki/Birmingham_Airport%2C_West_Midlands) and [Birmingham International railway station](http://en.wikipedia.org/wiki/Birmingham_International_railway_station), running at speeds up to 42 km/h; the system was eventually closed in 1995 due to reliability problems.

Perhaps the most well known implementation of high-speed maglev technology currently operating commercially is the [Shanghai Maglev Train](http://en.wikipedia.org/wiki/Shanghai_Maglev_Train), an IOS (initial operating segment) demonstration line of the German-built [Transrapid](http://en.wikipedia.org/wiki/Transrapid) train in [Shanghai](http://en.wikipedia.org/wiki/Shanghai), China that transports people 30 km to the airport in just 7 minutes 20 seconds, achieving a top speed of 431 km/h, averaging 250 km/h.

Several favourable conditions existed when the link was built:

* The British Rail Research vehicle was 3 tonnes and extension to the 8 tonne vehicle was easy.
* Electrical power was easily available.
* The airport and rail buildings were suitable for terminal platforms.
* Only one crossing over a public road was required and no steep gradients were involved.
* Land was owned by the railway or airport.
* Local industries and councils were supportive.
* Some government finance was provided and because of sharing work, the cost per organization was not high.

**Technology**

The term "maglev" refers not only to the vehicles, but to the railway system as well, specifically designed for magnetic levitation and propulsion. All operational implementations of maglev technology have had minimal overlap with wheeled [train](http://en.wikipedia.org/wiki/Train) technology and have not been compatible with conventional [rail tracks](http://en.wikipedia.org/wiki/Rail_track). Because they cannot share existing infrastructure, these maglev systems must be designed as complete transportation systems. The [Applied Levitation](http://en.wikipedia.org/w/index.php?title=Applied_Levitation&action=edit&redlink=1) SPM Maglev system is inter-operable with steel rail tracks and would permit maglev vehicles and conventional trains to operate at the same time on the same right of way. [MAN](http://en.wikipedia.org/wiki/MAN_SE) in Germany also designed a maglev system that worked with conventional rails, but it was never fully developed.

There are two particularly notable types of maglev technology:

* For [electromagnetic suspension](http://en.wikipedia.org/wiki/Electromagnetic_suspension) (EMS), electromagnets in the train attract it to a magnetically conductive (usually steel) track.
* [Electrodynamic suspension](http://en.wikipedia.org/wiki/Electrodynamic_suspension) (EDS) uses electromagnets on both track and train to push the train away from the rail.

Another experimental technology, which was designed, proven mathematically, peer reviewed, and patented, but is yet to be built, is the [magnetodynamic suspension](http://en.wikipedia.org/wiki/Magnetodynamic_suspension) (MDS), which uses the attractive magnetic force of a permanent magnet array near a steel track to lift the train and hold it in place. Other technologies such as repulsive permanent magnets and superconducting magnets have seen some research.

 **Electromagnetic suspension**

In current electromagnetic suspension (EMS) systems, the train levitates above a steel rail while [electromagnets](http://en.wikipedia.org/wiki/Electromagnet), attached to the train, are oriented toward the rail from below. The system is typically arranged on a series of C-shaped arms, with the upper portion of the arm attached to the vehicle, and the lower inside edge containing the magnets. The rail is situated between the upper and lower edges.

Magnetic attraction varies inversely with the cube of distance, so minor changes in distance between the magnets and the rail produce greatly varying forces. These changes in force are dynamically unstable - if there is a slight divergence from the optimum position, the tendency will be to exacerbate this, and complex systems of feedback control are required to maintain a train at a constant distance from the track, (approximately 15 millimeters).

The major advantage to suspended maglev systems is that they work at all speeds, unlike electrodynamic systems which only work at a minimum speed of about 30 km/h. This eliminates the need for a separate low-speed suspension system, and can simplify the track layout as a result. On the downside, the dynamic instability of the system demands high tolerances of the track, which can offset, or eliminate this advantage. Laithwaite, highly skeptical of the concept, was concerned that in order to make a track with the required tolerances, the gap between the magnets and rail would have to be increased to the point where the magnets would be unreasonably large. In practice, this problem was addressed through increased performance of the feedback systems, which allow the system to run with close tolerances.

 **Electrodynamic suspension**





JR-Maglev EDS suspension is due to the magnetic fields induced either side of the vehicle by the passage of the vehicles superconducting magnets.





EDS Maglev Propulsion via propulsion coils

In electrodynamic suspension (EDS), both the rail and the train exert a magnetic field, and the train is levitated by the repulsive force between these magnetic fields. The magnetic field in the train is produced by either superconducting magnets (as in [JR-Maglev](http://en.wikipedia.org/wiki/JR-Maglev)) or by an array of permanent magnets (as in [Inductrack](http://en.wikipedia.org/wiki/Inductrack)). The repulsive force in the track is created by an [induced magnetic field](http://en.wikipedia.org/wiki/Electromagnetic_induction) in wires or other conducting strips in the track. A major advantage of the repulsive maglev systems is that they are naturally stable—minor *narrowing* in distance between the track and the magnets creates strong forces to repel the magnets back to their original position, while a slight increase in distance greatly reduces the force and again returns the vehicle to the right separation. No feedback control is needed.

Repulsive systems have a major downside as well. At slow speeds, the current induced in these coils and the resultant magnetic flux is not large enough to support the weight of the train. For this reason the train must have wheels or some other form of landing gear to support the train until it reaches a speed that can sustain levitation. Since a train may stop at any location, due to equipment problems for instance, the entire track must be able to support both low-speed and high-speed operation. Another downside is that the repulsive system naturally creates a field in the track in front and to the rear of the lift magnets, which act against the magnets and create a form of drag. This is generally only a concern at low speeds, at higher speeds the effect does not have time to build to its full potential and other forms of drag dominate.

The drag force can be used to the electrodynamic system's advantage, however, as it creates a varying force in the rails that can be used as a reactionary system to drive the train, without the need for a separate reaction plate, as in most linear motor systems. Laithwaite led development of such "traverse-flux" systems at his [Imperial College](http://en.wikipedia.org/wiki/Imperial_College) laboratory. Alternatively, propulsion coils on the guideway are used to exert a force on the magnets in the train and make the train move forward. The propulsion coils that exert a force on the train are effectively a [linear motor](http://en.wikipedia.org/wiki/Linear_motor): an alternating current flowing through the coils generates a continuously varying magnetic field that moves forward along the track. The frequency of the alternating current is synchronized to match the speed of the train. The offset between the field exerted by magnets on the train and the applied field creates a force moving the train forward.

 **Pros and cons of different technologies**

Each implementation of the magnetic levitation principle for train-type travel involves advantages and disadvantages.

|  |
| --- |
|  |
| ***Technology*** |    | ***Pros*** |    | ***Cons*** |
|  |
| **EMS** ([Electromagnetic suspension](http://en.wikipedia.org/wiki/Electromagnetic_suspension)) | Magnetic fields inside and outside the vehicle are less than EDS; proven, commercially available technology that can attain very high speeds (500 km/h); no wheels or secondary propulsion system needed. | The separation between the vehicle and the guideway must be constantly monitored and corrected by computer systems to avoid collision due to the unstable nature of electromagnetic attraction; due to the system's inherent instability and the required constant corrections by outside systems, vibration issues may occur. |
|  |
| **EDS**(Electrodynamic suspension) | [Onboard](http://en.wikipedia.org/wiki/Onboard) magnets and large margin between rail and train enable highest recorded train speeds (581 km/h) and heavy load capacity; has demonstrated (December 2005) successful operations using [high-temperature superconductors](http://en.wikipedia.org/wiki/High-temperature_superconductivity) in its onboard magnets, cooled with inexpensive liquid [nitrogen](http://en.wikipedia.org/wiki/Nitrogen). | Strong magnetic fields onboard the train would make the train inaccessible to passengers with [pacemakers](http://en.wikipedia.org/wiki/Artificial_pacemaker) or magnetic data storage media such as hard drives and credit cards, necessitating the use of [magnetic shielding](http://en.wikipedia.org/wiki/Magnetic_shielding); limitations on guideway inductivity limit the maximum speed of the vehicle; vehicle must be [wheeled](http://en.wikipedia.org/wiki/Wheeled) for travel at low speeds. |
|  |
| [**Inductrack**](http://en.wikipedia.org/wiki/Inductrack) **System**(Permanent Magnet EDS) | [Failsafe](http://en.wikipedia.org/wiki/Failsafe) [Suspension](http://en.wikipedia.org/wiki/Suspension_%28vehicle%29)—no power required to activate magnets; Magnetic field is localized below the car; can generate enough force at low speeds (around 5 km/h) to levitate maglev train; in case of power failure cars slow down on their own safely; [Halbach arrays](http://en.wikipedia.org/wiki/Halbach_array) of permanent magnets may prove more cost-effective than electromagnets. | Requires either wheels or track segments that move for when the vehicle is stopped. New technology that is still under development (as of 2008) and as yet has no commercial version or full scale system prototype. |

Neither [Inductrack](http://en.wikipedia.org/wiki/Inductrack) nor the Superconducting EDS are able to levitate vehicles at a standstill, although [Inductrack](http://en.wikipedia.org/wiki/Inductrack) provides levitation down to a much lower speed; wheels are required for these systems. EMS systems are [wheel-less](http://en.wikipedia.org/wiki/Wheel-less).

The German Transrapid, Japanese HSST (Linimo), and Korean [Rotem](http://en.wikipedia.org/wiki/Hyundai_Rotem) EMS maglevs levitate at a standstill, with electricity extracted from guideway using power rails for the latter two, and wirelessly for Transrapid. If guideway power is lost on the move, the Transrapid is still able to generate levitation down to 10 km/h speed, using the power from onboard batteries. This is not the case with the HSST and Rotem systems.

 **Propulsion**

An EDS system can provide both [levitation](http://en.wikipedia.org/wiki/Levitation) and [propulsion](http://en.wikipedia.org/wiki/Ground_propulsion) using an onboard linear motor. EMS systems can only levitate the train using the magnets onboard, not propel it forward. As such, vehicles need some other technology for [propulsion](http://en.wikipedia.org/wiki/Ground_propulsion). A linear motor (propulsion coils) mounted in the track is one solution. Over long distances where the cost of propulsion coils could be prohibitive, a [propeller](http://en.wikipedia.org/wiki/Propeller_%28aircraft%29) or [jet engine](http://en.wikipedia.org/wiki/Jet_engine) could be used.

 **Stability**

[Earnshaw's theorem](http://en.wikipedia.org/wiki/Earnshaw%27s_theorem) shows that any combination of static magnets cannot be in a stable equilibrium. However, the various levitation systems achieve stable levitation by violating the assumptions of Earnshaw's theorem. Earnshaw's theorem assumes that the magnets are static and unchanging in field strength and that the relative [permeability](http://en.wikipedia.org/wiki/Magnetic_permeability) is constant and greater than unity everywhere. EMS systems rely on active electronic [stabilization](http://en.wikipedia.org/wiki/Voltage_regulator). Such systems constantly measure the bearing distance and adjust the electromagnet current accordingly. All EDS systems are moving systems (no EDS system can levitate the train unless it is in motion).

Because Maglev vehicles essentially fly, stabilisation of pitch, roll and yaw is required by magnetic technology. In addition to rotation, surge (forward and backward motions), sway (sideways motion) or heave (up and down motions) can be problematic with some technologies.

If superconducting magnets are used on a train above a track made out of a permanent magnet, then the train would be locked in to its lateral position on the track. It can move linearly along the track, but not off the track. This is due to the [Meissner Effect](http://en.wikipedia.org/wiki/Meissner_Effect).

 **Guidance**

Some systems use Null Current systems (also sometimes called Null Flux systems); these use a coil which is wound so that it enters two opposing, alternating fields, so that the average flux in the loop is zero. When the vehicle is in the straight ahead position, no current flows, but if it moves off-line this creates a changing flux that generates a field that pushes it back into line. However, some systems use coils that try to remain as much as possible in the null flux point between repulsive magnets, as this reduces eddy current losses.

 **Evacuated tubes**

Some systems (notably the [swissmetro](http://en.wikipedia.org/wiki/Swissmetro) system) propose the use of vactrains—maglev train technology used in evacuated (airless) tubes, which removes [air drag](http://en.wikipedia.org/wiki/Air_drag). This has the potential to increase speed and efficiency greatly, as most of the energy for conventional Maglev trains is lost in air drag.

One potential risk for passengers of trains operating in evacuated tubes is that they could be exposed to the risk of cabin depressurization unless tunnel safety monitoring systems can repressurize the tube in the event of a train malfunction or accident. The [Rand Corporation](http://en.wikipedia.org/wiki/Rand_Corporation) has designed a vacuum tube train that could, in theory, cross the Atlantic or the USA in 20 minutes.

 **Power and energy usage**

Energy for maglev trains is used to accelerate the train, and may be regained when the train slows down ("[regenerative braking](http://en.wikipedia.org/wiki/Regenerative_braking)"). It is also used to make the train levitate and to stabilise the movement of the train. The main part of the energy is needed to force the train through the air ("[air drag](http://en.wikipedia.org/wiki/Air_drag)"). Also some energy is used for air conditioning, heating, lighting and other miscellaneous systems.The maglev trains are powered on electromagnetism.

At very low speeds the percentage of power (energy per time) used for levitation can be significant. Also for very short distances the energy used for acceleration might be considerable. But the power used to overcome air drag increases with the cube of the velocity, and hence dominates at high speed (note: the energy needed per mile increases by the square of the velocity and the time decreases linearly.).

 **Advantages and disadvantages**

 **Compared to conventional trains**

Major comparative differences exist between the two technologies. First of all, maglevs are not trains, they are non-contact electronic transport systems, not mechanical friction-reliant rail systems. Their differences lie in maintenance requirements and the reliability of electronic versus mechanically based systems, all-weather operations, backward-compatibility, rolling resistance, weight, noise, design constraints, and control systems.

* **Maintenance Requirements Of Electronic Versus Mechanical Systems**: Maglev trains currently in operation have demonstrated the need for nearly insignificant guideway maintenance. Their electronic vehicle maintenance is minimal and more closely aligned with aircraft maintenance schedules based on hours of operation, rather than on speed or distance traveled. Traditional rail is subject to the wear and tear of miles of friction on mechanical systems and increases exponentially with speed, unlike maglev systems. This basic difference is the huge cost difference between the two modes and also directly affects system reliability, availability and sustainability.
* **All-Weather Operations**: Maglev trains currently in operation are not stopped, slowed, or have their schedules affected by snow, ice, severe cold, rain or high winds. This cannot be said for traditional friction-based rail systems. Also, maglev vehicles accelerate and decelerate faster than mechanical systems regardless of the slickness of the guideway or the slope of the grade because they are non-contact systems.
* **Backwards Compatibility**: Maglev trains currently in operation are not compatible with conventional track, and therefore require all new infrastructure for their entire route, but this is not a negative if high levels of reliability and low operational costs are the goal. By contrast conventional high speed trains such as the TGV are able to run at reduced speeds on existing rail infrastructure, thus reducing expenditure where new infrastructure would be particularly expensive (such as the final approaches to city terminals), or on extensions where traffic does not justify new infrastructure. However, this "shared track approach" ignores mechanical rail's high maintenance requirements, costs and disruptions to travel from periodic maintenance on these existing lines. The use of a completely separate maglev infrastructure more than pays for itself with dramatically higher levels of all-weather operational reliability and almost insignificant maintenance costs. So, maglev advocates would argue against rail backward compatibility and its concomitant high maintenance needs and costs.
* **Efficiency**: Due to the lack of physical contact between the track and the vehicle, maglev trains experience no [rolling resistance](http://en.wikipedia.org/wiki/Rolling_resistance), leaving only [air resistance](http://en.wikipedia.org/wiki/Air_resistance) and [electromagnetic drag](http://en.wikipedia.org/wiki/Eddy_current), potentially improving power efficiency.
* **Weight**: The weight of the electromagnets in many EMS and EDS designs seems like a major design issue to the uninitiated. A strong magnetic field is required to levitate a maglev vehicle. For the Transrapid, this is about 56 watts per ton. Another path for levitation is the use of superconductor magnets to reduce the energy consumption of the electromagnets, and the cost of maintaining the field. However, a 50-ton Transrapid maglev vehicle can lift an additional 20 tons, for a total of 70 tones, which surprisingly does not consume an exorbitant amount of energy. Most energy use for the TRI is for propulsion and overcoming the friction of air resistance. At speeds over 100 mph, which is the point of a high-speed maglev, maglevs use less energy than traditional fast trains.
* **Noise**: Because the major source of noise of a maglev train comes from displaced air, maglev trains produce less noise than a conventional train at equivalent speeds. However, the [psychoacoustic](http://en.wikipedia.org/wiki/Psychoacoustic) profile of the maglev may reduce this benefit: a study concluded that maglev noise should be rated like road traffic while conventional trains have a 5-10 dB "bonus" as they are found less annoying at the same loudness level.
* **Design Comparisons**: Braking and overhead wire wear have caused problems for the [Fastech 360](http://en.wikipedia.org/wiki/Fastech_360) railed Shinkansen. Maglev would eliminate these issues. Magnet reliability at higher temperatures is a countervailing comparative disadvantage (see suspension types), but new alloys and manufacturing techniques have resulted in magnets that maintain their levitational force at higher temperatures.

As with many technologies, advances in linear motor design have addressed the limitations noted in early maglev systems. As linear motors must fit within or straddle their track over the full length of the train, track design for some EDS and EMS maglev systems is challenging for anything other than point-to-point services. Curves must be gentle, while [switches](http://en.wikipedia.org/wiki/Railroad_switch) are very long and need care to avoid breaks in current. An SPM maglev system, in which the vehicle is permanently levitated over the tracks, can instantaneously switch tracks using electronic controls, with no moving parts in the track. A prototype SPM maglev train has also navigated curves with radius equal to the length of the train itself, which indciates that a full-scale train should be able to navigate curves with the same or narrower radius as a conventional train.

* **Control Systems**: EMS Maglev needs very fast-responding control systems to maintain a stable height above the track; multiple redundancy is built into these systems in the event of component failure and the Transrapid system has still levitated and operated with fully 1/2 of its magnet control systems shut down. Other maglev systems not using EMS active control are still in the experimental stage, except for the Central Japan Railway's MLX-01 superconducting EDS repulsive maglev system that levitates 11 centimeters above its guideway.

guinea pigs

 **Compared to aircraft**

For many systems, it is possible to define a [lift-to-drag ratio](http://en.wikipedia.org/wiki/Lift-to-drag_ratio). For maglev systems these ratios can exceed that of aircraft (for example [Inductrack](http://en.wikipedia.org/wiki/Inductrack) can approach 200:1 at high speed, far higher than any aircraft). This can make maglev more efficient per kilometre. However, at high cruising speeds, aerodynamic drag is much larger than lift-induced drag. Jet transport aircraft take advantage of low air density at high altitudes to significantly reduce drag during cruise, hence despite their lift-to-drag ratio disadvantage, they can travel more efficiently at high speeds than maglev trains that operate at sea level (this has been proposed to be fixed by the [vactrain](http://en.wikipedia.org/wiki/Vactrain) concept). Aircraft are also more flexible and can service more destinations with provision of suitable airport facilities.

Unlike airplanes, maglev trains are powered by electricity and thus need not carry fuel. Aircraft fuel is a significant danger during takeoff and landing accidents. Also, electric trains emit little direct [carbon dioxide emissions](http://en.wikipedia.org/wiki/Carbon_dioxide_emission), especially when powered by [nuclear](http://en.wikipedia.org/wiki/Nuclear_power) or [renewable](http://en.wikipedia.org/wiki/Renewable_energy) sources, but more than aircraft if powered by [fossil fuels](http://en.wikipedia.org/wiki/Fossil_fuels).

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FUEL CELL VEHICLES

A **Fuel cell vehicle** or **Fuel Cell Electric Vehicle** (FCEV) is a type of [hydrogen vehicle](http://en.wikipedia.org/wiki/Hydrogen_vehicle) which uses a [fuel cell](http://en.wikipedia.org/wiki/Fuel_cell) to produce electricity, powering its on-board electric motor. Fuel cells in vehicles create electricity to power an [electric motor](http://en.wikipedia.org/wiki/Electric_motor) using [hydrogen](http://en.wikipedia.org/wiki/Hydrogen) and oxygen from the air.

**Efficiency**

Fuel cell efficiency is limited because "the energy required to isolate hydrogen from natural compounds (water, natural gas, biomass), package the light gas by compression or liquefaction, transfer the energy carrier to the user, plus the energy lost when it is converted to useful electricity with fuel cells, leaves around 25% for practical use... For comparison, the 'well-to-wheel' efficiency is at least three times greater for electric cars than for hydrogen fuel cell vehicles."

The efficiency of the vehicle's engine does not take into account the efficiency at which hydrogen is produced, stored, and transported today. Fuel cell vehicles running on compressed hydrogen may have a power-plant-to-wheel efficiency of 22% if the hydrogen is stored as high-pressure gas, and 17% if it is stored as [liquid hydrogen](http://en.wikipedia.org/wiki/Liquid_hydrogen). In addition to the production losses, some of the electricity used for hydrogen production, comes from [thermal power](http://en.wikipedia.org/wiki/Thermal_power), which only has an efficiency of 33% to 48% resulting in emission of carbon dioxide.

 **Codes and standards**

*Fuel cell vehicle* is a classification in FC [Hydrogen codes and standards](http://en.wikipedia.org/wiki/Hydrogen_codes_and_standards) and [fuel cell](http://en.wikipedia.org/wiki/Fuel_cell) codes and standards other main standards are [Stationary fuel cell applications](http://en.wikipedia.org/wiki/Stationary_fuel_cell_applications) and [Portable fuel cell applications](http://en.wikipedia.org/wiki/Portable_fuel_cell_applications).

 **Hybrid fuel combustion vehicle**

To promote the demand side for hydrogen (to promote the creation of more [hydrogen filling stations](http://en.wikipedia.org/wiki/Hydrogen_station)), hybrid fuel combustion vehicles like the [Mazda RX-8 Hydrogen RE](http://en.wikipedia.org/wiki/Mazda_RX-8_Hydrogen_RE) on [Hynor](http://en.wikipedia.org/wiki/Hynor) and the [Premacy Hydrogen RE Hybrid](http://en.wikipedia.org/wiki/Premacy_Hydrogen_RE_Hybrid) running on [hydrogen](http://en.wikipedia.org/wiki/Hydrogen) or another [fuel](http://en.wikipedia.org/wiki/Fuel) have been introduced.

 **Description and purpose of fuel cells in vehicles**

All fuel cells are made up of three parts: an electrolyte, an anode and a cathode. Fuel cells function similarly to a conventional battery, but instead of recharging, they are refilled with hydrogen. Different types of fuel cells include Polymer Electrolyte Membrane (PEM) Fuel Cells, Direct Methanol Fuel Cells, Phosphoric Acid Fuel Cells, Molten Carbonate Fuel Cells, Solid Oxide Fuel Cells, and Regenerative Fuel Cells.

As of 2009, motor vehicles used most of the petroleum used in the U.S. and produced over 60% of the carbon monoxide emissions and about 20% of greenhouse gas emissions in the United States. In contrast, a [vehicle fueled with pure hydrogen](http://en.wikipedia.org/wiki/Hydrogen_vehicle) emits few pollutants, producing mainly water and heat, although the production of the hydrogen would create pollutants unless the hydrogen used in the fuel cell were produced using only renewable energy.

Hybrid Vehicle engines

A **hybrid electric vehicle** (HEV) is a type of [hybrid vehicle](http://en.wikipedia.org/wiki/Hybrid_vehicle) and [electric vehicle](http://en.wikipedia.org/wiki/Electric_vehicle) which combines a conventional [internal combustion engine](http://en.wikipedia.org/wiki/Internal_combustion_engine) (ICE) [propulsion](http://en.wikipedia.org/wiki/Ground_propulsion) system with an [electric](http://en.wikipedia.org/wiki/Electric_power) propulsion system. The presence of the electric powertrain is intended to achieve either better [fuel economy](http://en.wikipedia.org/wiki/Fuel_economy_in_automobiles) than a [conventional vehicle](http://en.wikipedia.org/wiki/Conventional_vehicle), or better performance. A variety of types of HEV exist, and the degree to which they function as EVs varies as well. The most common form of HEV is the hybrid electric car, although hybrid electric trucks (pickups and tractors) and buses also exist.

Modern HEVs make use of efficiency-improving technologies such as [regenerative braking](http://en.wikipedia.org/wiki/Regenerative_braking), which converts the vehicle's kinetic energy into battery-replenishing electric energy, rather than wasting it as heat energy as conventional brakes do. Some varieties of HEVs use their internal combustion engine to generate electricity by spinning an [electrical generator](http://en.wikipedia.org/wiki/Electrical_generator) (this combination is known as a [motor-generator](http://en.wikipedia.org/wiki/Motor-generator)), to either recharge their batteries or to directly power the electric drive motors. Many HEVs [reduce idle emissions](http://en.wikipedia.org/wiki/Idle_reduction) by [shutting down](http://en.wiktionary.org/wiki/shut_down) the ICE at [idle](http://en.wiktionary.org/wiki/idle) and restarting it when needed; this is known as a [start-stop system](http://en.wikipedia.org/wiki/Start-stop_system). A hybrid-electric produces less emissions from its ICE than a comparably-sized gasoline car, since an HEV's gasoline engine is usually smaller than a comparably-sized pure gasoline-burning vehicle (natural gas and propane fuels produce lower emissions) and if not used to directly drive the car, can be geared to run at maximum efficiency, further improving fuel economy.

**Types of powertrain**

Hybrid electric vehicles can be classified according to the way in which power is supplied to the drivetrain:

* In [parallel hybrids](http://en.wikipedia.org/wiki/Parallel_hybrid), the ICE and the [electric motor](http://en.wikipedia.org/wiki/Electric_motor) are both connected to the mechanical [transmission](http://en.wikipedia.org/wiki/Transmission_%28mechanics%29) and can simultaneously transmit power to drive the wheels, usually through a conventional transmission. Honda's Integrated Motor Assist (IMA) system as found in the [Insight](http://en.wikipedia.org/wiki/Honda_Insight), [Civic](http://en.wikipedia.org/wiki/Honda_Civic_Hybrid), [Accord](http://en.wikipedia.org/wiki/Honda_Accord_Hybrid), as well as the GM Belted Alternator/Starter ([BAS Hybrid](http://en.wikipedia.org/wiki/BAS_Hybrid)) system found in the [Chevrolet Malibu](http://en.wikipedia.org/wiki/Chevrolet_Malibu) hybrids are examples of production parallel hybrids. Current, commercialized parallel hybrids use a single, small (<20 kW) electric motor and small battery pack as the electric motor is not designed to be the sole source of motive power from launch. Parallel hybrids are also capable of [regenerative braking](http://en.wikipedia.org/wiki/Regenerative_braking) and the internal combustion engine can also act a generator for supplemental recharging. Parallel hybrids are more efficient than comparable non-hybrid vehicles especially during urban stop-and-go conditions and at times during highway operation where the electric motor is permitted to contribute.
* In [series hybrids](http://en.wikipedia.org/wiki/Hybrid_vehicle_drivetrain#Series_hybrid), only the electric motor drives the drivetrain, and the ICE works as a [generator](http://en.wikipedia.org/wiki/Electrical_generator) to power the electric motor or to recharge the batteries. The battery pack can be recharged through regenerative braking or by the ICE. Series hybrids usually have a smaller combustion engine but a larger battery pack as compared to parallel hybrids, which makes them more expensive than parallels. This configuration makes series hybrids more efficient in city driving. The [Chevrolet Volt](http://en.wikipedia.org/wiki/Chevrolet_Volt) is a [series](http://en.wikipedia.org/wiki/Series_hybrid) [plug-in hybrid](http://en.wikipedia.org/wiki/Plug-in_hybrid), although GM prefers to describe the Volt as an [electric vehicle](http://en.wikipedia.org/wiki/Electric_vehicle) equipped with a "range extending" gasoline powered ICE as a generator and therefore dubbed an "Extended Range Electric Vehicle" or E-REV.
* [Power-split hybrids](http://en.wikipedia.org/wiki/Hybrid_vehicle_drivetrain#Power-split_or_series-parallel_hybrid) have the benefits of a combination of series and parallel characteristics. As a result, they are more efficient overall, because series hybrids tend to be more efficient at lower speeds and parallel tend to be more efficient at high speeds; however, the power-split hybrid is higher than a pure parallel. Examples of power-split (referred to by some as "series-parallel") hybrid powertrains include current models of [Ford](http://en.wikipedia.org/wiki/Ford_Motor_Company), [General Motors](http://en.wikipedia.org/wiki/General_Motors), [Lexus](http://en.wikipedia.org/wiki/Lexus), [Nissan](http://en.wikipedia.org/wiki/Nissan), and [Toyota](http://en.wikipedia.org/wiki/Toyota).

 **Types by degree of hybridization**

* [Full hybrid](http://en.wikipedia.org/wiki/Hybrid_vehicle_drivetrain#Full_Hybrids), sometimes also called a strong hybrid, is a vehicle that can run on just the engine, just the batteries, or a combination of both. [Ford](http://en.wikipedia.org/wiki/Ford_Motor_Company)'s hybrid system, Toyota's [Hybrid Synergy Drive](http://en.wikipedia.org/wiki/Hybrid_Synergy_Drive) and [General Motors](http://en.wikipedia.org/wiki/General_Motors)/[Chrysler](http://en.wikipedia.org/wiki/Chrysler)'s [Two-Mode Hybrid](http://en.wikipedia.org/wiki/Two-Mode_Hybrid) technologies are full hybrid systems.[[18]](http://en.wikipedia.org/wiki/Hybrid_electric_vehicle#cite_note-GreenMild-17) The [Toyota Prius](http://en.wikipedia.org/wiki/Toyota_Prius), [Ford Escape Hybrid](http://en.wikipedia.org/wiki/Ford_Escape_Hybrid), and [Ford Fusion Hybrid](http://en.wikipedia.org/wiki/Ford_Fusion_Hybrid) are examples of full hybrids, as these cars can be moved forward on battery power alone. A large, high-capacity battery pack is needed for battery-only operation. These vehicles have a split power path allowing greater flexibility in the drivetrain by interconverting mechanical and electrical power, at some cost in complexity.
* [Mild hybrid](http://en.wikipedia.org/wiki/Mild_hybrid), is a vehicle that can not be driven solely on its electric motor, because the electric motor does not have enough power to propel the vehicle on its own. Mild hybrids only include some of the features found in hybrid technology, and usually achieve limited [fuel consumption savings](http://en.wikipedia.org/wiki/Fuel_economy_in_automobiles), up to 15 percent in urban driving and 8 to 10 percent overall cycle. A mild hybrid is essentially a conventional vehicle with oversize starter motor, allowing the engine to be turned off whenever the car is coasting, braking, or stopped, yet restart quickly and cleanly. The motor is often mounted between the engine and transmission, taking the place of the torque converter, and is used to supply additional propulsion energy when accelerating. Accessories can continue to run on electrical power while the gasoline engine is off, and as in other hybrid designs, the motor is used for regenerative braking to recapture energy. As compared to full hybrids, mild hybrids have smaller batteries and a smaller, weaker motor/generator, which allows manufacturers to reduce cost and weight.

Stratified charge engines

In a **stratified charge engine**, the fuel is injected into the cylinder just before ignition. This allows for higher compression ratios without "knock," and leaner air/fuel mixtures than in conventional internal combustion engines.

Conventionally, a [four-stroke](http://en.wikipedia.org/wiki/Four-stroke_engine) (petrol or gasoline) [Otto cycle](http://en.wikipedia.org/wiki/Otto_cycle) engine is fuelled by drawing a mixture of air and fuel into the [combustion chamber](http://en.wikipedia.org/wiki/Combustion_chamber) during the intake stroke. This produces a **homogeneous charge**: a homogeneous mixture of air and fuel, which is ignited by a [spark plug](http://en.wikipedia.org/wiki/Spark_plug) at a predetermined moment near the top of the [compression stroke](http://en.wikipedia.org/wiki/Compression_stroke).

In a homogeneous charge system, the **air/fuel ratio** is kept very close to [stoichiometric](http://en.wikipedia.org/wiki/Stoichiometric). A stoichiometric mixture contains the exact amount of air necessary for a complete combustion of the fuel. This gives stable combustion, but places an upper limit on the engine's efficiency: any attempt to improve fuel economy by running a lean mixture with a homogeneous charge results in unstable combustion; this impacts on power and emissions, notably of nitrogen oxides or [NOx](http://en.wikipedia.org/wiki/NOx).

If the [Otto cycle](http://en.wikipedia.org/wiki/Otto_cycle) is abandoned, however, and [fuel is injected](http://en.wikipedia.org/wiki/Fuel_injection) directly into the combustion-chamber during the compression stroke, the petrol engine is liberated from a number of its limitations.

First, a higher mechanical [compression ratio](http://en.wikipedia.org/wiki/Compression_ratio) (or, with supercharged engines, maximum combustion pressure) may be used for better [thermodynamic efficiency](http://en.wikipedia.org/wiki/Thermodynamic_efficiency). Since fuel is not present in the combustion chamber until virtually the point at which combustion is required to begin, there is no risk of pre-ignition or [engine knock](http://en.wikipedia.org/wiki/Engine_knock).

The engine may also run on a much leaner overall air/fuel ratio, using **stratified charge**.

Combustion can be problematic if a lean mixture is present at the spark-plug. However, fueling a petrol engine directly allows more fuel to be directed towards the spark-plug than elsewhere in the combustion-chamber. This results in a stratified charge: one in which the air/fuel ratio is not homogeneous throughout the combustion-chamber, but varies in a controlled (and potentially quite complex) way across the volume of the cylinder.

A relatively rich air/fuel mixture is directed to the spark-plug using multi-hole injectors. This mixture is sparked, giving a strong, even and predictable flame-front. This in turn results in a high-quality combustion of the much weaker mixture elsewhere in the cylinder.

Direct fuelling of petrol engines is rapidly becoming the norm, as it offers considerable advantages over port-fuelling (in which the fuel injectors are placed in the intake ports, giving homogeneous charge), with no real drawbacks. Powerful electronic management systems mean that there is not even a significant cost penalty.

With the further impetus of tightening emissions legislation, the motor industry in Europe and north America has now switched completely to direct fuelling for the new petrol engines it is introducing.

It is worth comparing contemporary directly-fuelled petrol engines with **direct-injection diesels**. Petrol can burn faster than diesel fuel, allowing higher maximum engine speeds and thus greater maximum power for sporting engines. Diesel fuel, on the other hand, has a higher [energy density](http://en.wikipedia.org/wiki/Energy_density), and in combination with higher combustion pressures can deliver very strong torque and high thermodynamic efficiency for more 'normal' road vehicles.

Learn burn engines

## Principle

A lean burn mode is a way to reduce throttling losses. An engine in a typical vehicle is sized for providing the power desired for acceleration, but must operate well below that point in normal steady-speed operation. Ordinarily, the power is cut by partially closing a throttle. However, the extra work done in pumping air through the throttle reduces efficiency. If the fuel/air ratio is reduced, then lower power can be achieved with the throttle closer to fully open, and the efficiency during normal driving (below the maximum torque capability of the engine) can be higher.

The [engines](http://en.wikipedia.org/wiki/Internal_combustion_engine) designed for lean burning can employ higher [compression ratios](http://en.wikipedia.org/wiki/Compression_ratio) and thus provide better performance, [efficient fuel use](http://en.wikipedia.org/wiki/Fuel_efficiency) and low [exhaust](http://en.wikipedia.org/wiki/Exhaust_gas) hydrocarbon emissions than those found in conventional [petrol engines](http://en.wikipedia.org/wiki/Petrol_engine). Ultra lean mixtures with very high air-fuel ratios can only be achieved by [direct injection](http://en.wikipedia.org/wiki/Gasoline_Direct_Injection) engines.

The main drawback of lean burning is that a complex [catalytic converter](http://en.wikipedia.org/wiki/Catalytic_converter) system is required to reduce [NOx](http://en.wikipedia.org/wiki/NOx) emissions. Lean burn engines do not work well with modern 3-way [catalytic converter](http://en.wikipedia.org/wiki/Catalytic_converter)—which require a pollutant balance at the exhaust port so they can carry out oxidation and reduction reactions—so most modern engines run at or near the stoichiometric point. Alternatively, ultra-lean ratios can reduce NOx emissions.

##

##  Heavy-duty gas engines

Lean burn concepts are often used for the design of heavy-duty [natural gas](http://en.wikipedia.org/wiki/Natural_gas), [biogas](http://en.wikipedia.org/wiki/Biogas), and [liquefied petroleum gas](http://en.wikipedia.org/wiki/Liquefied_petroleum_gas) (LPG) fuelled engines. These engines can either be full-time lean burn, where the engine runs with a weak air-fuel mixture regardless of load and engine speed, or part-time lean burn (also known as "lean mix" or "mixed lean"), where the engine runs lean only during low load and at high engine speeds, reverting to a stoichiometric air-fuel mixture in other cases.

Heavy-duty lean burn gas engines admit as much as 75% more air than theoretically needed for complete combustion into the combustion chambers. The extremely weak air-fuel mixtures lead to lower combustion temperatures and therefore lower NOx formation. While lean-burn gas engines offer higher theoretical thermal efficiencies, transient response and performance may be compromised in certain situations. Lean burn gas engines are almost always turbocharged, resulting high power and torque figures not achieveable with stoichiometric engines due to high combustion temperatures.

Heavy duty gas engines may employ precombustion chambers in the cylinder head. A lean gas and air mixture is first highly compressed in the main chamber by the piston. A much richer, though much lesser volume gas/air mixture is introduced to the precombustion chamber and ignited by spark plug. The flame front spreads to the lean gas air mixture in the cylinder.

This two stage lean burn combustion produces low NOx and no particulate emissions. Thermal efficiency is better as higher compression ratios are achieved.

Manufacturers of heavy-duty lean burn gas engines include [GE Jenbacher](http://en.wikipedia.org/wiki/GE_Jenbacher), [MAN Diesel & Turbo](http://en.wikipedia.org/wiki/MAN_Diesel_%26_Turbo), [Wärtsilä](http://en.wikipedia.org/wiki/W%C3%A4rtsil%C3%A4), [Mitsubishi Heavy Industries](http://en.wikipedia.org/wiki/Mitsubishi_Heavy_Industries) and [Rolls-Royce plc](http://en.wikipedia.org/wiki/Rolls-Royce_plc).

##  Honda lean burn systems

One of the newest lean-burn technologies available in automobiles currently in production uses very precise control of fuel injection, a strong air-fuel swirl created in the combustion chamber, a new linear air-fuel sensor (LAF type [O2 sensor](http://en.wikipedia.org/wiki/O2_sensor)) and a lean-burn NOx catalyst to further reduce the resulting NOx emissions that increase under "lean-burn" conditions and meet NOx emissions requirements.

This stratified-charge approach to lean-burn combustion means that the air-fuel ratio isn't equal throughout the cylinder. Instead, precise control over [fuel injection](http://en.wikipedia.org/wiki/Fuel_injection) and intake flow dynamics allows a greater concentration of fuel closer to the [spark plug](http://en.wikipedia.org/wiki/Spark_plug) tip (richer), which is required for successful ignition and flame spread for complete combustion. The remainder of the cylinders' intake charge is progressively leaner with an overall average air:fuel ratio falling into the lean-burn category of up to 22:1.

The older [Honda](http://en.wikipedia.org/wiki/Honda) engines that used lean burn (not all did) accomplished this by having a parallel fuel and intake system that fed a pre-chamber the "ideal" ratio for initial combustion. This burning mixture was then opened to the main chamber where a much larger and leaner mix then ignited to provide sufficient power. During the time this design was in production this system ([CVCC, Compound Vortex Controlled Combustion](http://en.wikipedia.org/wiki/CVCC)) primarily allowed lower emissions without the need for a [catalytic converter](http://en.wikipedia.org/wiki/Catalytic_converter). These were [carbureted](http://en.wikipedia.org/wiki/Carburetor) engines and the relative "imprecise" nature of such limited the MPG abilities of the concept that now under MPI (Multi-Port fuel Injection) allows for higher MPG too.

The newer [Honda](http://en.wikipedia.org/wiki/Honda) stratified charge (lean burn engines) operate on air-fuel ratios as high as 22:1. The amount of fuel drawn into the engine is much lower than a typical gasoline engine, which operates at 14.7:1—the chemical stoichiometric ideal for complete combustion when averaging gasoline to the petrochemical industries' accepted standard of C6H8.

This lean-burn ability by the necessity of the limits of physics, and the chemistry of combustion as it applies to a current gasoline engine must be limited to light load and lower RPM conditions. A "top" speed cut-off point is required since leaner gasoline fuel mixtures burn slower and for power to be produced combustion must be "complete" by the time the exhaust valve open

Low heat rejection engines

Hydrogen engines

A **hydrogen internal combustion engine vehicle** (HICEV) is a type of [hydrogen vehicle](http://en.wikipedia.org/wiki/Hydrogen_vehicle) using an [internal combustion engine](http://en.wikipedia.org/wiki/Internal_combustion_engine). Hydrogen internal combustion engine vehicles are different from hydrogen [fuel cell vehicles](http://en.wikipedia.org/wiki/Fuel_cell_vehicle) (which use hydrogen + oxygen rather than hydrogen + air); the hydrogen internal combustion engine is simply a modified version of the traditional gasoline-powered internal combustion engine.[[](http://en.wikipedia.org/wiki/Hydrogen_internal_combustion_engine_vehicle#cite_note-1)

 **Low Emissions**

The combustion of hydrogen with oxygen produces water as its only product:

2H2 + O2 → 2H2O

The combustion of hydrogen with air can also produce oxides of nitrogen, though at negligibly small amounts. Tuning a hydrogen engine to create the most amount of emissions as possible results in emissions comparable with consumer operated gasoline engines from 1976.

H2 + O2 + N2 → H2O + N2 + NOx

 **Adaptation of Existing Engines**

Difference between a hydrogen ICE from a traditional gasoline engine could include hardened valves and valve seats, stronger connecting rods, non-platinum tipped spark plugs, higher voltage ignition coil, fuel injectors designed for a gas instead of a liquid, larger crankshaft damper, stronger head gasket material, modified (for supercharger) intake manifold, positive pressure supercharger, and a high temperature engine oil. All modifications would amount to about one point five times (1.5) the current cost of a gasoline engine. These hydrogen engines burn fuel in the same manner that gasoline engines do.

The power output of a direct injected hydrogen engine vehicle is 20% more than for a gasoline engine vehicle and 42% more than a hydrogen engine vehicle using a [carburetor](http://en.wikipedia.org/wiki/Carburetor).

HCCI engine

**Homogeneous charge compression ignition** (**HCCI**) is a form of [internal combustion](http://en.wikipedia.org/wiki/Internal_combustion_engine) in which well-mixed [fuel](http://en.wikipedia.org/wiki/Fuel) and [oxidizer](http://en.wikipedia.org/wiki/Oxidizer) (typically air) are compressed to the point of auto-ignition. As in other forms of [combustion](http://en.wikipedia.org/wiki/Combustion), this [exothermic reaction](http://en.wikipedia.org/wiki/Exothermic_reaction) releases chemical energy into a sensible form that can be transformed in an engine into [work](http://en.wikipedia.org/wiki/Work_%28thermodynamics%29) and heat.

**Introduction**

HCCI has characteristics of the two most popular forms of combustion used in SI engines: homogeneous charge spark ignition ([gasoline](http://en.wikipedia.org/wiki/Gasoline) engines) and CI engines: stratified charge compression ignition ([diesel engines](http://en.wikipedia.org/wiki/Diesel_engine)). As in homogeneous charge spark ignition, the fuel and oxidizer are mixed together. However, rather than using an electric discharge to ignite a portion of the mixture, the density and temperature of the mixture are raised by compression until the entire mixture reacts spontaneously. Stratified charge compression ignition also relies on temperature and density increase resulting from compression, but combustion occurs at the boundary of fuel-air mixing, caused by an injection event, to initiate combustion.

The defining characteristic of HCCI is that the ignition occurs at several places at a time which makes the fuel/air mixture burn nearly simultaneously. There is no direct initiator of combustion. This makes the process inherently challenging to [control](http://en.wikipedia.org/wiki/Control_theory). However, with advances in microprocessors and a physical understanding of the ignition process, HCCI can be controlled to achieve [gasoline engine](http://en.wikipedia.org/wiki/Gasoline_engine)-like emissions along with [diesel engine](http://en.wikipedia.org/wiki/Diesel_engine)-like efficiency. In fact, HCCI engines have been shown to achieve extremely low levels of Nitrogen oxide emissions (NOx) without an aftertreatment [catalytic converter](http://en.wikipedia.org/wiki/Catalytic_converter). The unburned hydrocarbon and carbon monoxide emissions are still high (due to lower peak temperatures), as in gasoline engines, and must still be treated to meet [automotive emission regulations](http://en.wikipedia.org/wiki/Automobile_emissions_control).

Recent research has shown that the use of two fuels with different reactivities (such as gasoline and diesel) can help solve some of the difficulties of controlling HCCI ignition and burn rates. RCCI or Reactivity Controlled Compression Ignition has been demonstrated to provide highly efficient, low emissions operation over wide load and speed ranges \*.

HCCI engines have a long history, even though HCCI has not been as widely implemented as spark ignition or diesel injection. It is essentially an [Otto combustion cycle](http://en.wikipedia.org/wiki/Otto_cycle). In fact, HCCI was popular before electronic [spark ignition](http://en.wikipedia.org/wiki/Ignition_system) was used. One example is the [hot-bulb engine](http://en.wikipedia.org/wiki/Hot_bulb_engine) which used a hot vaporization chamber to help mix fuel with air. The extra heat combined with compression induced the conditions for combustion to occur. Another example is the ["diesel" model aircraft engine](http://en.wikipedia.org/wiki/Carbureted_compression_ignition_model_engines).

 **Operation**

 **Methods**

A mixture of fuel and air will ignite when the concentration and temperature of reactants is sufficiently high. The concentration and/or temperature can be increased by several different ways:

* High [compression ratio](http://en.wikipedia.org/wiki/Compression_ratio)
* Pre-heating of induction gases
* Forced induction
* Retained or re-inducted exhaust gases

Once ignited, combustion occurs very quickly. When auto-ignition occurs too early or with too much chemical energy, combustion is too fast and high in-cylinder pressures can destroy an engine. For this reason, HCCI is typically operated at [lean](http://en.wikipedia.org/wiki/Lean_burn) overall fuel mixtures.

 **Advantages**

* HCCI provides up to a 30-percent fuel savings, while meeting current emissions standards.
* Since HCCI engines are fuel-lean, they can operate at a Diesel-like compression ratios (>15), thus achieving higher efficiencies than conventional spark-ignited gasoline engines.
* Homogeneous mixing of fuel and air leads to cleaner combustion and lower emissions. Actually, because peak temperatures are significantly lower than in typical spark ignited engines, [NOx](http://en.wikipedia.org/wiki/Nitrogen_oxide) levels are almost negligible. Additionally, the premixed lean mixture does not produce [soot](http://en.wikipedia.org/wiki/Soot).
* HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels.
* In regards to gasoline engines, the omission of throttle losses improves HCCI efficiency.

 **Disadvantages**

* High in-cylinder peak pressures may cause damage to the engine.
* High heat release and pressure rise rates contribute to engine wear.
* The autoignition event is difficult to control, unlike the ignition event in [spark ignition](http://en.wikipedia.org/wiki/Spark_ignition) (SI) and [diesel engines](http://en.wikipedia.org/wiki/Diesel_engine) which are controlled by spark plugs and in-cylinder fuel injectors, respectively.
* HCCI engines have a small power range, constrained at low loads by lean flammability limits and high loads by in-cylinder pressure restrictions.
* [Carbon monoxide](http://en.wikipedia.org/wiki/Carbon_monoxide) (CO) and [hydrocarbon](http://en.wikipedia.org/wiki/Hydrocarbon) (HC) pre-catalyst emissions are higher than a typical spark ignition engine, caused by incomplete oxidation (due to the rapid combustion event and low in-cylinder temperatures) and trapped crevice gases, respectively.

 **Control**

Controlling HCCI is a major hurdle to more widespread commercialization. HCCI is more difficult to control than other popular modern combustion engines, such as Spark Ignition (SI) and Diesel. In a typical [gasoline engine](http://en.wikipedia.org/wiki/Gasoline_engine), a spark is used to ignite the pre-mixed fuel and air. In [Diesel engines](http://en.wikipedia.org/wiki/Diesel_engines), combustion begins when the fuel is injected into compressed air. In both cases, the timing of combustion is explicitly controlled. In an HCCI engine, however, the homogeneous mixture of fuel and air is compressed and combustion begins whenever the appropriate conditions are reached. This means that there is no well-defined combustion initiator that can be directly controlled. Engines can be designed so that the ignition conditions occur at a desirable timing. To achieve dynamic operation in an HCCI engine, the [control system](http://en.wikipedia.org/wiki/Control_system) must change the conditions that induce combustion. Thus, the engine must control either the compression ratio, inducted gas temperature, inducted gas pressure, fuel-air ratio, or quantity of retained or re-inducted exhaust. Several control approaches are discussed below.

 **Variable compression ratio**

There are several methods for modulating both the geometric and effective compression ratio. The geometric compression ratio can be changed with a movable plunger at the top of the cylinder head. This is the system used in "diesel" [model aircraft engines](http://en.wikipedia.org/wiki/Model_engine). The effective compression ratio can be reduced from the geometric ratio by closing the intake valve either very late or very early with some form of variable valve actuation (i.e. [variable valve timing](http://en.wikipedia.org/wiki/Variable_valve_timing) permitting [Miller cycle](http://en.wikipedia.org/wiki/Miller_cycle)). Both of the approaches mentioned above require some amounts of energy to achieve fast responses. Additionally, implementation is expensive. Control of an HCCI engine using variable compression ratio strategies has been shown effective. The effect of compression ratio on HCCI combustion has also been studied extensively.

 **Variable induction temperature**

In HCCI engines, the autoignition event is highly sensitive to temperature. Various methods have been developed which use temperature to control combustion timing. The simplest method uses resistance heaters to vary the inlet temperature, but this approach is slow (cannot change on a cycle-to-cycle basis). Another technique is known as fast thermal management (FTM). It is accomplished by rapidly varying the cycle to cycle intake charge temperature by rapidly mixing hot and cold air streams. It is also expensive to implement and has limited bandwidth associated with actuator energy.

 **Variable exhaust gas percentage**

Exhaust gas can be very hot if retained or re-inducted from the previous combustion cycle or cool if recirculated through the intake as in conventional [EGR](http://en.wikipedia.org/wiki/Exhaust_gas_recirculation) systems. The exhaust has dual effects on HCCI combustion. It dilutes the fresh charge, delaying ignition and reducing the chemical energy and engine work. Hot combustion products conversely will increase the temperature of the gases in the cylinder and advance ignition. Control of combustion timing HCCI engines using EGR has been shown experimentally.

 **Variable valve actuation**

Variable valve actuation (VVA) has been proven to extend the HCCI operating region by giving finer control over the temperature-pressure-time history within the combustion chamber. VVA can achieve this via two distinct methods:

* Controlling the effective compression ratio: A variable duration VVA system on intake can control the point at which the intake valve closes. If this is retarded past bottom dead center (BDC), then the compression ratio will change, altering the in-cylinder pressure-time history prior to combustion.
* Controlling the amount of hot exhaust gas retained in the combustion chamber: A VVA system can be used to control the amount of hot internal exhaust gas recirculation (EGR) within the combustion chamber. This can be achieved with several methods, including valve re-opening and changes in valve overlap. By balancing the percentage of cooled external EGR with the hot internal EGR generated by a VVA system, it may be possible to control the in-cylinder temperature.

While electro-hydraulic and camless VVA systems can be used to give a great deal of control over the valve event, the componentry for such systems is currently complicated and expensive. Mechanical variable lift and duration systems, however, although still being more complex than a standard valvetrain, are far cheaper and less complicated. If the desired VVA characteristic is known, then it is relatively simple to configure such systems to achieve the necessary control over the valve lift curve. Also see [variable valve timing](http://en.wikipedia.org/wiki/Variable_valve_timing).

 **Variable fuel ignition quality**

Another means to extend the operating range is to control the onset of ignition and the heat release rate is by manipulating fuel itself. This is usually carried out by adopting multiple fuels and blending them "on the fly" for the same engine . Examples could be blending of commercial gasoline and diesel fuels , adopting natural gas or ethanol ". This can be achieved in a number of ways;

* Blending fuels upstream of the engine: Two fuels are mixed in the liquid phase, one with low resistance to ignition (such as diesel fuel) and a second with a greater resistance (gasoline), the timing of ignition is controlled by varying the compositional ratio of these fuels. Fuel is then delivered using either a port or direct injection event.
* Having two fuel circuits: Fuel A can be injected in the intake duct (port injection) and Fuel B using a direct injection (in-cylinder) event, the proportion of these fuels can be used to control ignition, heat release rate as well as exhaust gas emissions.

 **Direct Injection: PCCI or PPCI Combustion**

Compression Ignition Direct Injection (CIDI) combustion is a well established means of controlling ignition timing and heat release rate and is adopted in [Diesel engines](http://en.wikipedia.org/wiki/Diesel_engines) combustion. Partially Pre-mixed Charge Compression Ignition (PPCI) also known as Premixed Charge Compression Ignition (PCCI) is a compromise between achieving the control of CIDI combustion but with the exhaust gas emissions of HCCI, specifically soot . On a fundamental level, this means that the heat release rate is controlled preparing the combustible mixture in such a way that combustion occurs over a longer time duration and is less prone to knocking. This is done by timing the injection event such that the combustible mixture has a wider range of air/fuel ratios at the point of ignition, thus ignition occurs in different regions of the combustion chamber at different times - slowing the heat release rate. Furthermore this mixture is prepared such that when combustion occurs there are fewer rich pockets thus reducing the tendency for soot formation . The adoption of high EGR and adoption of diesel fuels with a greater resistance to ignition (more "gasoline like") enables longer mixing times prior to ignition and thus fewer rich pockets thus resulting in the possibility of both lower soot emissions and NOx.

 **High peak pressures and heat release rates**

In a typical gasoline or diesel engine, combustion occurs via a flame. Hence at any point in time, only a fraction of the total fuel is burning. This results in low peak pressures and low energy release rates. In HCCI, however, the entire fuel/air mixture ignites and burns nearly simultaneously resulting in high peak pressures and high energy release rates. To withstand the higher pressures, the engine has to be structurally stronger and therefore heavier. Several strategies have been proposed to lower the rate of combustion. Two different fuels, with different autoignition properties, can be used to lower the combustion speed. However, this requires significant infrastructure to implement. Another approach uses dilution (i.e. with exhaust gases) to reduce the pressure and combustion rates at the cost of work production.

**Power**

In both a [spark ignition engine](http://en.wikipedia.org/wiki/Spark_ignition_engine) and [diesel engine](http://en.wikipedia.org/wiki/Diesel_engine), power can be increased by introducing more fuel into the combustion chamber. These engines can withstand a boost in power because the heat release rate in these engines is slow. However, in HCCI engines the entire mixture burns nearly simultaneously. Increasing the fuel/air ratio will result in even higher peak pressures and [heat release rates](http://en.wikipedia.org/w/index.php?title=Heat_release_rate&action=edit&redlink=1). In addition, many of the viable control strategies for HCCI require thermal preheating of the charge which reduces the density and hence the mass of the air/fuel charge in the combustion chamber, reducing power. These factors make increasing the power in HCCI engines challenging.

One way to increase power is to use fuels with different [autoignition](http://en.wikipedia.org/wiki/Autoignition) properties. This will lower the heat release rate and peak pressures and will make it possible to increase the equivalence ratio. Another way is to thermally stratify the charge so that different points in the compressed charge will have different temperatures and will burn at different times lowering the heat release rate making it possible to increase power. A third way is to run the engine in HCCI mode only at part load conditions and run it as a diesel or spark ignition engine at full or near full load conditions. Since much more research is required to successfully implement thermal stratification in the compressed charge, the last approach is being studied more intensively.

 **Emissions**

Because HCCI operates on lean mixtures, the peak temperatures are lower in comparison to spark ignition (SI) and [Diesel engines](http://en.wikipedia.org/wiki/Diesel_engines). The low peak temperatures prevent the formation of NOx. This leads to NOx emissions at levels far less than those found in traditional engines. However, the low peak temperatures also lead to incomplete burning of fuel, especially near the walls of the combustion chamber. This leads to high carbon monoxide and hydrocarbon emissions. An oxidizing catalyst would be effective at removing the regulated species because the exhaust is still oxygen rich.

 **Difference from Knock**

Engine [knock or pinging](http://en.wikipedia.org/wiki/Engine_knocking) occurs when some of the unburnt gases ahead of the flame in a spark ignited engine spontaneously ignite. The unburnt gas ahead of the flame is compressed as the flame propagates and the pressure in the combustion chamber rises. The high pressure and corresponding high temperature of unburnt reactants can cause them to spontaneously ignite. This causes a shock wave to traverse from the end gas region and an expansion wave to traverse into the end gas region. The two waves reflect off the boundaries of the combustion chamber and interact to produce high amplitude [standing waves](http://en.wikipedia.org/wiki/Standing_waves).

A similar ignition process occurs in HCCI. However, rather than part of the reactant mixture being ignited by compression ahead of a flame front, ignition in HCCI engines occurs due to piston compression. In HCCI, the entire reactant mixture ignites (nearly) simultaneously. Since there are very little or no pressure differences between the different regions of the gas, there is no shock wave propagation and hence no knocking. However at high loads (i.e. high fuel/air ratios), knocking is a possibility even in HCCI.

 **Simulation of HCCI Engines**

The development of computational models for simulating combustion and heat release rates of HCCI engines has required the advancement of detailed chemistry models. This is largely because ignition is most sensitive to chemical kinetics rather than turbulence/spray or spark processes as are typical in direct injection compression ignition or spark ignition engines. Computational models have demonstrated the importance of accounting for the fact that the in-cylinder mixture is actually in-homogeneous, particularly in terms of temperature. This in-homogeneity is driven by turbulent mixing and heat transfer from the combustion chamber walls, the amount of temperature stratification dictates the rate of heat release and thus tendency to knock . This limits the applicability of considering the in-cylinder mixture as a single zone resulting in the uptake of 3D computational fluid dynamics and faster solving probability density function modelling codes.

 **Other Applications of HCCI Research**

To date there have only been few prototype engines running in HCCI mode however the research efforts invested into HCCI research have disseminated into/resulted in direct advancements in fuel and engine development. Examples are;

* PCCI/PPCI combustion - A hybrid of HCCI and conventional diesel combustion offing more control over ignition and heat release rates with lower soot and NOx emissions.
* Advancements in fuel modelling - HCCI combustion is driven mainly by chemical kinetics rather than turbulent mixing or injection, this reduces the complexity of simulating the chemistry which results in fuel oxidation and emissions formation. This has led to increasing interest and development of chemical kinetics which describe hydrocarbon oxidation.
* Fuel blending applications- Due to the advancements in fuel modelling, it is now possible to carry out detailed simulations of hydrocarbon fuel oxidation, enabling simulations of practical fuels such as gasoline/diesel and ethanol . Engineers can now blend fuels virtually and determine how they will perform in an engine context.

VCR engine

**Variable Compression Ratio (VCR) engines**

Because cylinder bore diameter, piston stroke length and combustion chamber volume are almost always constant, the compression ratio for a given engine is almost always constant, until engine wear takes its toll.

One exception is the [experimental](http://en.wikipedia.org/wiki/Experiment) [Saab Variable Compression engine](http://en.wikipedia.org/wiki/Saab_Variable_Compression_engine) (SVC). This engine, designed by [Saab Automobile](http://en.wikipedia.org/wiki/Saab_Automobile), uses a technique that dynamically alters the volume of the combustion chamber (Vc), which, via the above equation, changes the compression ratio (CR).

The [Atkinson cycle](http://en.wikipedia.org/wiki/Atkinson_cycle) engine was one of the first attempts at [variable compression](http://en.wikipedia.org/wiki/Variable_compression_ratio). Since the compression ratio is the ratio between dynamic and static volumes of the combustion chamber the Atkinson cycle's method of increasing the length of the power stroke compared to the intake stroke ultimately altered the compression ratio at different stages of the cycle.

 **Dynamic compression ratio**

The calculated compression ratio, as given above, presumes that the cylinder is sealed at the bottom of the stroke, and that the volume compressed is the actual volume.

However: intake valve closure (sealing the cylinder) always takes place after BDC, which may cause some of the intake charge to be compressed backwards out of the cylinder by the rising piston at very low speeds; only the percentage of the stroke after intake valve closure is compressed. Intake port tuning and scavenging may allow a greater mass of charge (at a higher than atmospheric pressure) to be trapped in the cylinder than the static volume would suggest ( This "corrected" compression ratio is commonly called the "*dynamic compression ratio*".

This ratio is higher with more conservative (i.e., earlier, soon after BDC) intake cam timing, and lower with more radical (i.e., later, long after BDC) intake cam timing, but always lower than the static or "nominal" compression ratio.

The actual position of the piston can be determined by trigonometry, using the stroke length and the [connecting rod](http://en.wikipedia.org/wiki/Connecting_rod) length (measured between centers). The absolute cylinder pressure is the result of an exponent of the dynamic compression ratio. This exponent is a polytropic value for the ratio of variable heats for air and similar gases at the temperatures present. This compensates for the temperature rise caused by compression, as well as heat lost to the cylinder. Under ideal (adiabatic) conditions, the exponent would be 1.4, but a lower value, generally between 1.2 and 1.3 is used, since the amount of heat lost will vary among engines based on design, size and materials used, but provides useful results for purposes of comparison. For example, if the static compression ratio is 10:1, and the dynamic compression ratio is 7.5:1, a useful value for cylinder pressure would be (7.5)^1.3 × atmospheric pressure, or 13.7 [bar](http://en.wikipedia.org/wiki/Bar_%28unit%29). The two corrections for dynamic compression ratio affect cylinder pressure in opposite directions, but not in equal strength. An engine with high static compression ratio and late intake valve closure will have a DCR similar to an engine with lower compression but earlier intake valve closure.

Additionally, the cylinder pressure developed when an engine is running will be higher than that shown in a compression test for several reasons.

* The much higher velocity of a piston when an engine is running versus cranking allows less time for pressure to bleed past the piston rings into the crankcase.
* a running engine is coating the cylinder walls with much more oil than an engine that is being cranked at low RPM, which helps the seal.
* the higher temperature of the cylinder will create higher pressures when running vs. a static test, even a test performed with the engine near [operating temperature](http://en.wikipedia.org/wiki/Operating_temperature).
* A running engine does not stop taking air & fuel into the cylinder when the piston reaches BDC; The mixture that is rushing into the cylinder during the downstroke develops momentum and continues briefly after the vacuum ceases (in the same respect that rapidly opening a door will create a draft that continues after movement of the door ceases). This is called scavenging. Intake tuning, cylinder head design, valve timing and exhaust tuning determine how effectively an engine scavenges.

 **Compression ratio versus overall pressure ratio**

Compression ratio and [overall pressure ratio](http://en.wikipedia.org/wiki/Overall_pressure_ratio) are interrelated as follows:

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Compression ratio** | 2:1 | 3:1 | 5:1 | 10:1 | 15:1 | 20:1 | 25:1 | 35:1 |
| **Pressure ratio** | 2.64:1 | 4.66:1 | 9.52:1 | 25.12:1 | 44.31:1 | 66.29:1 | 90.60:1 | 145.11:1 |

The reason for this difference is that compression ratio is defined via the volume reduction:

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while pressure ratio is defined as the [pressure](http://en.wikipedia.org/wiki/Pressure) increase:

.

In calculating the pressure ratio, we assume that an [adiabatic compression](http://en.wikipedia.org/wiki/Adiabatic_compression) is carried out (i.e. that no heat energy is supplied to the gas being compressed, and that any temperature rise is solely due to the compression). We also assume that air is a perfect gas. With those two assumptions we can define the relationship between change of volume and change of pressure as follows:



where γ is the [ratio of specific heats](http://en.wikipedia.org/wiki/Ratio_of_specific_heats) for air (approximately 1.4). The values in the table above are derived using this formula. Note that in reality the ratio of specific heats changes with temperature and that significant deviations from adiabatic behavior will occur.

Surface ignition engines

Relative surface ignition resistance of fuels in engines could be predicted from data obtained in the laboratory: heat of combustion of the fuel, heat capacities of the fuel and its products, radiant energy of flames, ignition energies at the temperature and pressure existing in an engine at the time surface ignition occurs, extent and nature of preflame reactions at these temperatures and pressures, effect of fuel-air ratio on energy required for ignition at the temperature and pressure existing in an engine, and the relative activity of the igniting surface under the conditions existing in an engine. General experience has been that there are no short cuts. It is simpler and more satisfactory to measure surfaceignition resistance in an engine operating under the conditions of interest.

VVTI engines

**VVT-i**, or **Variable Valve Timing with intelligence**, is an [automobile](http://en.wikipedia.org/wiki/Automobile) [variable valve timing](http://en.wikipedia.org/wiki/Variable_valve_timing) technology developed by [Toyota](http://en.wikipedia.org/wiki/Toyota), similar in performance to the BMW's [VANOS](http://en.wikipedia.org/wiki/VANOS). The Toyota VVT-i system replaces the Toyota **VVT** offered starting in 24 December 1991 on the 5-valve per cylinder [*4A-GE*](http://en.wikipedia.org/wiki/Toyota_A_engine#20_Valve_4A-GE) engine. The VVT system is a 2-stage hydraulically controlled cam phasing system. The Toyota motors CEO has been reported to have said, "VVT is the heart of every modern Toyota!

VVT-i, introduced in 1996, varies the timing of the [intake](http://en.wikipedia.org/wiki/Intake) [valves](http://en.wikipedia.org/wiki/Poppet_valve) by adjusting the relationship between the [camshaft](http://en.wikipedia.org/wiki/Camshaft) drive (belt, scissor-gear or chain) and intake camshaft. Engine oil pressure is applied to an actuator to adjust the camshaft position. Adjustments in the overlap time between the exhaust valve closing and intake valve opening result in improved engine efficiency.Variants of the system, including **VVTL-i**, **Dual VVT-i**, **Triple VVT-iE**, and **Valvematic**, have followed.

**VVTL-i**

**VVTL-i** (Variable Valve Timing and Lift intelligent system) is a version that can alter valve *lift* (and *duration*) as well as valve timing. In the case of the 16 valve [*2ZZ-GE*](http://en.wikipedia.org/wiki/Toyota_ZZ_engine#2ZZ-GE), the engine has 2 camshafts, one operating intake valves and one operating exhaust valves. Each camshaft has two lobes per cylinder, one low rpm lobe and one high rpm, high lift, long duration lobe. Each cylinder has two intake valves and two exhaust valves. Each set of two valves are controlled by one rocker arm, which is operated by the camshaft. Each rocker arm has a slipper follower mounted to the rocker arm with a spring, allowing the slipper follower to move up and down with the high lobe without affecting the rocker arm. When the engine is operating below 6000-7000 rpm (dependent on year, car, and ECU installed), the low lobe is operating the rocker arm and thus the valves. When the engine is operating above the lift engagement point, the [ECU](http://en.wikipedia.org/wiki/Engine_Control_Unit) activates an oil pressure switch which pushes a sliding pin under the slipper follower on each rocker arm. This in effect, switches to the high lobe causing high lift and longer duration.

In 1998, **Dual VVT-i** which adjusts timing on both intake and exhaust camshafts was first introduced on the RS200 Altezza's [*3S-GE*](http://en.wikipedia.org/wiki/Toyota_3S-GE) engine.

Dual VVT-i is also found in Toyota's new generation V6 engine, the 3.5-liter [*2GR-FE*](http://en.wikipedia.org/wiki/Toyota_GR_engine#2GR-FE) first appearing on the [2005 Avalon](http://en.wikipedia.org/wiki/Toyota_Avalon). This engine can now be found on numerous Toyota and Lexus models. By adjusting the valve timing, engine start and stop occurs almost unnoticeably at minimum compression. In addition fast heating of the catalytic converter to its light-off temperature is possible thereby reducing hydrocarbon emissions considerably.

Toyota's [UR engine](http://en.wikipedia.org/wiki/Toyota_UR_engine) V8 also uses this technology. Dual VVT-i was later introduced to Toyota's latest small 4-cylinder [ZR engines](http://en.wikipedia.org/wiki/Toyota_ZR_engine) found in compact vehicles such as the new Toyota Corolla and Scion xD and in larger 4-cylinder [AR engines](http://en.wikipedia.org/wiki/Toyota_AR_engine) found in the Camry and RAV4.

 **VVT-iE**

**VVT-iE** (Variable Valve Timing - intelligent by Electric motor) is a version of Dual VVT-i that uses an electrically operated actuator to adjust and maintain intake [camshaft](http://en.wikipedia.org/wiki/Camshaft) timing. The exhaust camshaft timing is still controlled using a hydraulic actuator. This form of variable valve timing technology was developed initially for [Lexus](http://en.wikipedia.org/wiki/Lexus) vehicles. This system was first introduced on the 2007MY [Lexus LS 460](http://en.wikipedia.org/wiki/Lexus_LS) as [1UR](http://en.wikipedia.org/wiki/Toyota_UR_engine) engine.

The electric motor in the actuator spins together with the intake camshaft as the engine runs. To maintain camshaft timing, the actuator motor will operate at the same speed as the camshaft. To advance the camshaft timing, the actuator motor will rotate slightly faster than the camshaft speed. To retard camshaft timing, the actuator motor will rotate slightly slower than camshaft speed. The speed difference between the actuator motor and camshaft timing is used to operate a mechanism that varies the camshaft timing. The benefit of the electric actuation is enhanced response and accuracy at low engine speeds and at lower temperatures. Furthermore, it ensures precise positioning of the camshaft for and immediately after engine starting, as well as a greater total range of adjustment. The combination of these factors allows more precise control, resulting in an improvement of both fuel economy, engine output and emissions performance.

 **Valvematic**

It offers continuous adjustment to lift volume and timing. **Valvematic** made its first appearance in 2007 in the [Noah](http://en.wikipedia.org/wiki/Toyota_Noah) and later in early-2009 in the [ZR](http://en.wikipedia.org/wiki/Toyota_ZR_engine)

High energy and power density batteries

A **lithium-ion battery** (sometimes **Li-ion battery** or **LIB**) is a family of [rechargeable battery](http://en.wikipedia.org/wiki/Rechargeable_battery) types in which [lithium](http://en.wikipedia.org/wiki/Lithium) ions move from the negative [electrode](http://en.wikipedia.org/wiki/Electrode) to the positive electrode during discharge, and back when charging. Chemistry, performance, cost, and safety characteristics vary across LIB types. Unlike lithium [primary batteries](http://en.wikipedia.org/wiki/Primary_battery) (which are disposable), lithium-ion [electrochemical cells](http://en.wikipedia.org/wiki/Electrochemical_cell) use an [intercalated](http://en.wikipedia.org/wiki/Intercalation_%28chemistry%29) lithium compound as the electrode material instead of metallic lithium.

Lithium-ion batteries are common in [consumer electronics](http://en.wikipedia.org/wiki/Consumer_electronics). They are one of the most popular types of rechargeable battery for [portable electronics](http://en.wikipedia.org/wiki/Portable_electronics), with one of the best [energy densities](http://en.wikipedia.org/wiki/Energy_density), no [memory effect](http://en.wikipedia.org/wiki/Memory_effect), and a slow [loss of charge](http://en.wikipedia.org/wiki/Loss_of_charge) when not in use. Beyond consumer electronics, LIBs are also growing in popularity for military, [electric vehicle](http://en.wikipedia.org/wiki/Electric_vehicle), and [aerospace](http://en.wikipedia.org/wiki/Aerospace) applications. Research is yielding a stream of improvements to traditional LIB technology, focusing on energy density, durability, cost, and [intrinsic safety](http://en.wikipedia.org/wiki/Intrinsic_safety).

**Charge and discharge**

During discharge, lithium ions Li+ carry the [current](http://en.wikipedia.org/wiki/Electrical_current) from the negative to the positive electrode, through the non-[aqueous](http://en.wikipedia.org/wiki/Aqueous_solution) [electrolyte](http://en.wikipedia.org/wiki/Electrolyte) and separator diaphrage.

During charging, an external electrical power source (the charging circuit) applies a higher voltage (but of the same polarity) than that produced by the battery, forcing the current to pass in the reverse direction. The lithium ions then migrate from the positive to the negative electrode, where they become embedded in the porous electrode material in a process known as intercalation.

 **Construction**



Cylindrical 18650 cell before closing

The three primary functional components of a lithium-ion battery are the [anode](http://en.wikipedia.org/wiki/Anode), [cathode](http://en.wikipedia.org/wiki/Cathode), and [electrolyte](http://en.wikipedia.org/wiki/Electrolyte). The anode of a conventional lithium-ion cell is made from [carbon](http://en.wikipedia.org/wiki/Carbon), the cathode is a metal [oxide](http://en.wikipedia.org/wiki/Oxide), and the [electrolyte](http://en.wikipedia.org/wiki/Electrolyte) is a [lithium](http://en.wikipedia.org/wiki/Lithium) [salt](http://en.wikipedia.org/wiki/Salt_%28chemistry%29) in an [organic](http://en.wikipedia.org/wiki/Organic_compound) [solvent](http://en.wikipedia.org/wiki/Solvent).

The most commercially popular anode material is [graphite](http://en.wikipedia.org/wiki/Graphite). The cathode is generally one of three materials: a layered [oxide](http://en.wikipedia.org/wiki/Oxide) (such as [lithium cobalt oxide](http://en.wikipedia.org/wiki/Lithium_cobalt_oxide)), a [polyanion](http://en.wikipedia.org/wiki/Polyelectrolyte) (such as [lithium iron phosphate](http://en.wikipedia.org/wiki/Lithium_iron_phosphate)), or a [spinel](http://en.wikipedia.org/wiki/Spinel) (such as lithium [manganese](http://en.wikipedia.org/wiki/Manganese) [oxide](http://en.wikipedia.org/wiki/Oxide)).

The electrolyte is typically a mixture of organic carbonates such as [ethylene carbonate](http://en.wikipedia.org/wiki/Ethylene_carbonate) or [diethyl carbonate](http://en.wikipedia.org/wiki/Diethyl_carbonate) containing [complexes](http://en.wikipedia.org/wiki/Coordination_complex) of lithium ions. These non-[aqueous](http://en.wikipedia.org/wiki/Aqueous) electrolytes generally use non-coordinating anion salts such as lithium hexafluorophosphate (LiPF6), lithium hexafluoroarsenate monohydrate (LiAsF6), lithium perchlorate (LiClO4), lithium tetrafluoroborate (LiBF4), and lithium triflate (LiCF3SO3).

Depending on materials choices, the [voltage](http://en.wikipedia.org/wiki/Voltage), capacity, life, and safety of a lithium-ion battery can change dramatically. Recently, [novel architectures](http://en.wikipedia.org/wiki/Nanoarchitectures_for_lithium-ion_batteries) using [nanotechnology](http://en.wikipedia.org/wiki/Nanotechnology) have been employed to improve performance.

Pure lithium is very [reactive](http://en.wikipedia.org/wiki/Reactivity_%28chemistry%29). It reacts vigorously with water to form [lithium hydroxide](http://en.wikipedia.org/wiki/Lithium_hydroxide) and [hydrogen](http://en.wikipedia.org/wiki/Hydrogen) gas is liberated. Thus a non-aqueous electrolyte is typically used, and a sealed container rigidly excludes water from the battery pack.

Lithium ion batteries are more expensive than [NiCd](http://en.wikipedia.org/wiki/NiCd) batteries but operate over a wider temperature range with higher energy densities, while being smaller and lighter. They are fragile and so need a protective circuit to limit peak voltages.

 **Electrochemistry**

The three participants in the electrochemical reactions in a lithium-ion battery are the anode, cathode, and electrolyte.

Both the anode and cathode are materials into which, and from which, lithium can migrate. During *insertion* (or [*intercalation*](http://en.wikipedia.org/wiki/Graphite_intercalation_compound)) lithium moves into the electrode. During the reverse process, *extraction* (or *deintercalation*), lithium moves back out. When a lithium-based cell is [discharging](http://en.wikipedia.org/wiki/Battery_%28electricity%29#Battery_capacity_and_discharging), the lithium is extracted from the anode and inserted into the cathode. When the cell is [charging](http://en.wikipedia.org/wiki/Battery_%28electricity%29#Battery_capacity_and_discharging), the reverse occurs.

Useful [work](http://en.wikipedia.org/wiki/Work_%28physics%29) can only be extracted if [electrons](http://en.wikipedia.org/wiki/Electron) flow through a closed external circuit. The following equations are in units of [moles](http://en.wikipedia.org/wiki/Mole_%28chemistry%29), making it possible to use the coefficient *x*.

The positive electrode [half-reaction](http://en.wikipedia.org/wiki/Half-reaction) (with charging being forwards) is:



The negative electrode half-reaction is:



The overall reaction has its limits. Overdischarge supersaturates [lithium cobalt oxide](http://en.wikipedia.org/wiki/Lithium_cobalt_oxide), leading to the production of [lithium oxide](http://en.wikipedia.org/wiki/Lithium_oxide), possibly by the following irreversible reaction:



Overcharge up to 5.2 [Volts](http://en.wikipedia.org/wiki/Volts) leads to the synthesis of cobalt(IV) oxide, as evidenced by [x-ray diffraction](http://en.wikipedia.org/wiki/X-ray_diffraction)



In a lithium-ion battery the lithium ions are transported to and from the cathode or anode, with the transition metal, cobalt ([Co](http://en.wikipedia.org/wiki/Cobalt)), in Li*x*CoO2 being oxidized from Co3+ to Co4+ during charging, and reduced from Co4+ to Co3+ during discharge.

 **Positive electrodes**

|  |  |  |  |
| --- | --- | --- | --- |
| **Electrode material** | **Average potential difference** | **Specific capacity** | **Specific energy** |
| LiCoO2 | 3.7 V | 140 mA·h/g | 0.518 k[W·h](http://en.wikipedia.org/wiki/Watt-hour)/kg |
| LiMn2O4 | 4.0 V | 100 mA·h/g | 0.400 kW·h/kg |
| LiNiO2 | 3.5 V | 180 mA·h/g | 0.630 kW·h/kg |
| LiFePO4 | 3.3 V | 150 mA·h/g | 0.495 kW·h/kg |
| Li2FePO4F | 3.6 V | 115 mA·h/g | 0.414 kW·h/kg |
| LiCo1/3Ni1/3Mn1/3O2 | 3.6 V | 160 mA·h/g | 0.576 kW·h/kg |
| Li(Li*a*Ni*x*Mn*y*Co*z*)O2 | 4.2 V | 220 mA·h/g | 0.920 kW·h/kg |

 **Negative electrodes**

|  |  |  |  |
| --- | --- | --- | --- |
| **Electrode material** | **Average potential difference** | **Specific capacity** | **Specific energy** |
| Graphite (LiC6) | 0.1-0.2 V | 372 mA·h/g | 0.0372-0.0744 [kW·h](http://en.wikipedia.org/wiki/Watt-hour)/kg |
| Hard Carbon (LiC6) | ? V | ? mA·h/g | ? kW·h/kg |
| Titanate (Li4Ti5O12) | 1-2 V | 160 mA·h/g | 0.16-0.32 kW·h/kg |
| Si (Li4.4Si) | 0.5-1 V | 4212 mA·h/g | 2.106-4.212 kW·h/kg |
| Ge (Li4.4Ge) | 0.7-1.2 V | 1624 mA·h/g | 1.137-1.949 kW·h/kg |

 **Electrolytes**

The cell voltages given in the Electrochemistry section are larger than the potential at which [aqueous solutions](http://en.wikipedia.org/wiki/Aqueous_solution) can [electrolyze](http://en.wikipedia.org/wiki/Electrolysis), in addition lithium is highly reactive to water, therefore, nonaqueous or aprotic solutions are used.

[Liquid](http://en.wikipedia.org/wiki/Liquid) electrolytes in lithium-ion batteries consist of lithium [salts](http://en.wikipedia.org/wiki/Salt_%28chemistry%29), such as [LiPF6](http://en.wikipedia.org/wiki/Lithium_hexafluorophosphate), [LiBF4](http://en.wikipedia.org/wiki/Lithium_tetrafluoroborate) or [LiClO4](http://en.wikipedia.org/wiki/Lithium_perchlorate) in an [organic](http://en.wikipedia.org/wiki/Organic_compound) [solvent](http://en.wikipedia.org/wiki/Solvent), such as [ethylene carbonate](http://en.wikipedia.org/wiki/Ethylene_carbonate), [dimethyl carbonate](http://en.wikipedia.org/wiki/Dimethyl_carbonate), and [diethyl carbonate](http://en.wikipedia.org/wiki/Diethyl_carbonate). A liquid electrolyte conducts lithium ions, acting as a carrier between the cathode and the anode when a battery passes an electric current through an external circuit. Typical conductivities of liquid electrolyte at room temperature (20 °C ) are in the range of 10 [mS](http://en.wikipedia.org/wiki/Millisiemens)/cm (1 S/m), increasing by approximately 30–40% at 40 °C and decreasing by a slightly smaller amount at 0 °C.

Unfortunately, organic solvents easily decompose on anodes during charging. However, when appropriate [organic solvents](http://en.wikipedia.org/wiki/Organic_solvent) are used as the electrolyte, the solvent decomposes on initial charging and forms a solid layer called the solid electrolyte interphase (SEI)., which is electrically insulating yet provides sufficient ionic conductivity. The interphase prevents decomposition of the electrolyte after the second charge. For example, [ethylene carbonate](http://en.wikipedia.org/wiki/Ethylene_carbonate) is decomposed at a relatively high voltage, 0.7 V vs. lithium, and forms a dense and stable interface.

A good solution for the interface instability is the application of a new class of composite electrolytes based on POE (poly(oxyethylene)) developed by Syzdek et al. It can be either solid (high molecular weight) and be applied in dry Li-polymer cells, or liquid (low molecular weight) and be applied in regular Li-ion cells.

Another issue that Li-ion technology is facing is safety. Large scale application of Li cells in Electric Vehicles needs a dramatic decrease in the failure rate. One of the solutions is the novel technology based on reversed-phase composite electrolytes, employing porous ceramic material filled with electrolyte.

 **Advantages and disadvantages**

Note that both advantages and disadvantages depend on the materials and design that make up the battery. This summary reflects older designs that use [carbon](http://en.wikipedia.org/wiki/Carbon) anode, metal [oxide](http://en.wikipedia.org/wiki/Oxide) cathodes, and [lithium](http://en.wikipedia.org/wiki/Lithium) [salt](http://en.wikipedia.org/wiki/Salt_%28chemistry%29) in an [organic](http://en.wikipedia.org/wiki/Organic_compound) [solvent](http://en.wikipedia.org/wiki/Solvent) for the [electrolyte](http://en.wikipedia.org/wiki/Electrolyte).

 **Advantages**

* Wide variety of shapes and sizes efficiently fitting the devices they power.
* Much lighter than other energy-equivalent [secondary batteries](http://en.wikipedia.org/wiki/Secondary_battery).
* High [open circuit voltage](http://en.wikipedia.org/wiki/Open_circuit_voltage) in comparison to [aqueous batteries](http://en.wikipedia.org/wiki/Aqueous_battery) (such as [lead acid](http://en.wikipedia.org/wiki/Lead-acid_battery), [nickel-metal hydride](http://en.wikipedia.org/wiki/Nickel-metal_hydride_battery) and [nickel-cadmium](http://en.wikipedia.org/wiki/Nickel-cadmium_battery)). This is beneficial because it increases the amount of power that can be transferred at a lower current.
* No [memory effect](http://en.wikipedia.org/wiki/Memory_effect).
* [Self-discharge](http://en.wikipedia.org/wiki/Self-discharge) rate of approximately 5-10% per month, compared to over 30% per month in common [nickel metal hydride batteries](http://en.wikipedia.org/wiki/Nickel_metal_hydride_battery), approximately 1.25% per month for [Low Self-Discharge NiMH batteries](http://en.wikipedia.org/wiki/Low_self-discharge_NiMH_battery) and 10% per month in [nickel-cadmium batteries](http://en.wikipedia.org/wiki/Nickel-cadmium_battery). According to one manufacturer, lithium-ion cells (and, accordingly, "dumb" lithium-ion batteries) do not have any [self-discharge](http://en.wikipedia.org/wiki/Self-discharge) in the usual meaning of this word. What looks like a self-discharge in these batteries is a permanent loss of capacity. On the other hand, "smart" lithium-ion batteries do self-discharge, due to the drain of the built-in voltage monitoring circuit.
* Components are environmentally safe as there is no free lithium metal.

 **Disadvantages**

 **Cell life**

* Charging forms deposits inside the electrolyte that inhibit ion transport. Over time, the cell's capacity diminishes. The increase in internal resistance reduces the cell's ability to deliver current. This problem is more pronounced in high-current applications. The decrease means that older batteries do not charge as much as new ones (charging time required decreases proportionally).
* High charge levels and elevated temperatures (whether from charging or ambient air) hasten capacity loss. Charging heat is caused by the carbon anode (typically replaced with [lithium titanate](http://en.wikipedia.org/wiki/Lithium_titanate) which drastically reduces damage from charging, including expansion and other factors).
* A Standard (Cobalt) Li-ion cell that is full most of the time at 25 °C irreversibly loses approximately 20% capacity per year. Poor ventilation may increase temperatures, further shortening battery life. Loss rates vary by temperature: 6% loss at 0 °C, 20% at 25 °C, and 35% at 40 °C. When stored at 40%–60% charge level, the capacity loss is reduced to 2%, 4%, and 15%, respectively. In contrast, the calendar life of [LiFePO4](http://en.wikipedia.org/wiki/Lithium_iron_phosphate_battery) cells is not affected by being kept at a high state of charge.

 **Internal resistance**

* The [internal resistance](http://en.wikipedia.org/wiki/Internal_resistance) of standard (Cobalt) lithium-ion batteries is high compared to both other rechargeable chemistries such as nickel-metal hydride and nickel-cadmium, and LiFePO4 and lithium-polymer cells. [Internal resistance](http://en.wikipedia.org/wiki/Internal_resistance) increases with both cycling and age. Rising internal resistance causes the voltage at the terminals to drop under load, which reduces the maximum current draw. Eventually increasing resistance means that the battery can no longer operate for an adequate period.
* To power larger devices, such as electric cars, connecting many small batteries in a parallel circuit is more effective and efficient than connecting a single large battery.

 **Safety requirements**

If overheated or overcharged, Li-ion batteries may suffer [thermal runaway](http://en.wikipedia.org/wiki/Thermal_runaway) and cell rupture. In extreme cases this can lead to combustion. Deep discharge may short-circuit the cell, in which case recharging would be unsafe. To reduce these risks, Lithium-ion battery packs contain fail-safe circuity that shuts down the battery when its voltage is outside the safe range of 3–4.2 V per cell. When stored for long periods the small current draw of the protection circuitry itself may drain the battery below its shut down voltage; normal chargers are then ineffective. Many types of lithium-ion cell cannot be charged safely below 0°C.

Other safety features are required in each cell:

* shut-down separator (for overtemperature)
* tear-away tab (for internal pressure)
* vent (pressure relief)
* thermal interrupt (overcurrent/overcharging)

These devices occupy useful space inside the cells, add additional points of failure and irreversibly disable the cell when activated. They are required because the anode produces heat during use, while the cathode may produce oxygen. These devices and improved electrode designs reduce/eliminate the risk of fire or explosion.

These safety features increase costs compared to nickel metal hydride batteries, which require only a hydrogen/oxygen recombination device (preventing damage due to mild overcharging) and a back-up pressure valve.

**Specifications and design**

* Specific energy density: 150 to 250 [W·h](http://en.wikipedia.org/wiki/Watt-hour)/kg (540 to 900 [kJ](http://en.wikipedia.org/wiki/Kilojoule)/kg)
* Volumetric energy density: 250 to 620 W·h/l (900 to 1900 J/cm³)
* Specific power density: 300 to 1500 W/kg (@ 20 seconds and 285 W·h/l)

Because lithium-ion batteries can have a variety of cathode and anode materials, the energy density and voltage vary accordingly.

Lithium-ion batteries with a lithium iron phosphate cathode and graphite anode have a nominal [open-circuit voltage](http://en.wikipedia.org/wiki/Open-circuit_voltage) of 3.2 [V](http://en.wikipedia.org/wiki/Volt) and a typical charging voltage of 3.6 V. Lithium nickel manganese cobalt (NMC) oxide cathode with graphite anodes have a 3.7 V nominal voltage with a 4.2 V max charge. The charging procedure is performed at constant voltage with current-limiting circuitry (i.e., charging with constant current until a voltage of 4.2 V is reached in the cell and continuing with a constant voltage applied until the current drops close to zero). Typically, the charge is terminated at 3% of the initial charge current. In the past, lithium-ion batteries could not be fast-charged and needed at least two hours to fully charge. Current-generation cells can be fully charged in 45 minutes or less. Some lithium-ion varieties can reach 90% in as little as 10 minutes.

**Charging procedure**

**Stage 1**: Apply charging current until the voltage limit per cell is reached.

**Stage 2**: Apply maximum voltage per cell limit until the current declines below 3% of rated charge current.

**Stage 3**: Periodically apply a top-off charge about once per 500 hours.The charge time is about three to five hours, depending on the charger used. Generally, cell phone batteries can be charged at 1*C* and laptop-types at 0.8*C*, where *C* is the current that would discharge the battery in one hour. Charging is usually stopped when the current goes below 0.03*C* but it can be left indefinitely depending on desired charging time. Some fast chargers skip stage 2 and claim the battery is ready at 70% charge.

Top-off charging is recommended when voltage goes below 4.05 V/cell.

Typically, lithium-ion cells are charged with 4.2 ± 0.05 V/cell, except for military long-life cells where 3.92 V is used for extending battery life. Most protection circuits cut off if either 4.3 V or 90 °C is reached. If the voltage drops below 2.50 V per cell, the battery protection circuit may also render it unchargeable with regular charging equipment. Most battery protection circuits stop at 2.7–3.0 V per cell.

For safety reasons it is recommended the battery be kept at the manufacturer's stated voltage and current ratings during both charge and discharge cycles.

**Variations in materials and construction**

|  |  |
| --- | --- |
| Mergefrom.svg | It has been suggested that [*Nanoball batteries*](http://en.wikipedia.org/wiki/Nanoball_batteries) be [merged](http://en.wikipedia.org/wiki/Wikipedia%3AMerging) into this article or section. ([Discuss](http://en.wikipedia.org/wiki/Talk%3ALithium-ion_battery)) *Proposed since September 2010.* |

The increasing demand for batteries has led vendors and academics to focus on improving the power density, operating temperature, safety, durability, charging time, output power, and cost of LIB solutions.

|  |
| --- |
| LIB types |
| **Area** | **Technology** | **Researchers** | **Target application** | **Date** | **Benefit** |
| Cathode | Manganese spinel (LMO) | [Lucky Goldstar Chemical](http://en.wikipedia.org/wiki/LG_Chem),[[57]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-56) [NEC](http://en.wikipedia.org/wiki/NEC), [Samsung](http://en.wikipedia.org/wiki/Samsung),[[58]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-IEEELiRoad-57) [Hitachi](http://en.wikipedia.org/wiki/Hitachi),[[59]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-58) Nissan/AESC[[60]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-59) | [Hybrid electric vehicle](http://en.wikipedia.org/wiki/Hybrid_electric_vehicle), [cell phone](http://en.wikipedia.org/wiki/Cell_phone), [laptop](http://en.wikipedia.org/wiki/Laptop) | 1996 | durability, cost |
|  | Lithium iron phosphate | [University of Texas](http://en.wikipedia.org/wiki/University_of_Texas)/[Hydro-Québec](http://en.wikipedia.org/wiki/Hydro-Qu%C3%A9bec),[[61]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-60)/Phostech Lithium Inc., [Valence Technology](http://en.wikipedia.org/wiki/Valence_Technology), [A123Systems](http://en.wikipedia.org/wiki/A123Systems)/[MIT](http://en.wikipedia.org/wiki/MIT)[[62]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-61)[[63]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-62) | [Segway Personal Transporter](http://en.wikipedia.org/wiki/Segway_Personal_Transporter), power tools, aviation products, automotive hybrid systems, [PHEV](http://en.wikipedia.org/wiki/PHEV) conversions | 1996 | moderate density (2 A·h outputs 70 amperes) operating temperature >60 °C (140 °F) |
|  | [Lithium nickel manganese cobalt](http://en.wikipedia.org/w/index.php?title=Lithium_nickel_manganese_cobalt&action=edit&redlink=1) (NMC) | Imara Corporation, [Nissan Motor](http://en.wikipedia.org/wiki/Nissan_Motor)[[64]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-63)[[65]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-64) |  | 2008 | density, output, safety |
|  | LMO/NMC | Sony, Sanyo |  |  | power, safety (although limited durability) |
|  | Lithium iron fluorophosphate | [University of Waterloo](http://en.wikipedia.org/wiki/University_of_Waterloo)[[66]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-65) |  | 2007 | durability, cost (replace Li with Na or Na/Li) |
|  | [Lithium air](http://en.wikipedia.org/wiki/Lithium_air_battery) | [University of Dayton Research Institute](http://en.wikipedia.org/wiki/University_of_Dayton_Research_Institute)[[67]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-dayton-66) | automotive | 2009 | density, safety[[67]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-dayton-66) |
|  | 5% Vanadium-doped Lithium iron phosphate olivine | [Binghamton University](http://en.wikipedia.org/wiki/Binghamton_University)[[68]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-67) |  | 2008 | output |
| Anode | [Lithium-titanate battery](http://en.wikipedia.org/wiki/Lithium-titanate_battery) (LT) | [Altairnano](http://en.wikipedia.org/wiki/Altairnano) | automotive ([Phoenix Motorcars](http://en.wikipedia.org/wiki/Phoenix_Motorcars)), electrical grid (PJM Interconnection Regional Transmission Organization control area,[[69]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-68) [United States Department of Defense](http://en.wikipedia.org/wiki/United_States_Department_of_Defense)[[70]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-69)), bus (Proterra[[71]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-70)) | 2008 | output, charging time, durability (20 years, 9,000 cycles), safety, operating temperature (-50–70 °C (-58–158 °F)[[72]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-71)[[*dead link*](http://en.wikipedia.org/wiki/Wikipedia%3ALink_rot)] |
|  | [Lithium vanadium oxide](http://en.wikipedia.org/w/index.php?title=Lithium_vanadium_oxide&action=edit&redlink=1) | Samsung/Subaru.[[73]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-72) | automotive | 2007 | density (745Wh/l)[[74]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-73) |
|  | Cobalt-oxide nano wires from [genetically modified virus](http://en.wikipedia.org/wiki/Genetically_modified_virus) | MIT |  | 2006 | density, thickness[[75]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-74) |
|  | Three-Dimensional (3D) Porous Particles Composed of Curved Two-Dimensional (2D) Nano-Sized Layers | Georgia Institute of Technology [[76]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-75) | high energy batteries for electronics and electrical vehicles | 2011 | specific capacity > 2000 mA·h/g, high efficiency, rapid low-cost synthesis [[77]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-76) |
|  | Iron-phosphate nano wires from genetically modified virus | MIT |  | 2009 | density, thickness[[78]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-77)[[79]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-78)[[80]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-79) |
|  | Silicon/titanium dioxide composite nano wires from genetically modified tobacco virus | University of Maryland | explosive detection sensors, biomimetic structures, water-repellent surfaces, micro/nano scale heat pipes | 2010 | density, low charge time[[81]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-80) |
|  | Porous silicon/carbon nanocomposite spheres | Georgia Institute of Technology | portable electronics, electrical vehicles, electrical grid | 2010 | high stability, high capacity, low charge time[[82]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-81) |
|  | nano-sized wires on stainless steel | [Stanford University](http://en.wikipedia.org/wiki/Stanford_University) | wireless sensors networks, | 2007 | density[[83]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-82)[[84]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-83) (shift from anode- to cathode-limited), durability issue remains (wire cracking) |
|  | Metal [hydrides](http://en.wikipedia.org/wiki/Hydride) | Laboratoire de Réactivité et de Chimie des Solides, General Motors |  | 2008 | density (1480 mA·h/g)[[85]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-84) |
|  | Silicon Nanotubes (or Silicon Nanospheres) Confined within Rigid Carbon Outer Shells | Georgia Institute of Technology, MSE, NanoTech Yushin's group [[86]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-85) | stable high energy batteries for cell phones, laptops, netbooks, radios, sensors and electrical vehicles | 2010 | specific capacity 2400 mA·h/g, ultra-high Coulombic Efficiency and outstanding SEI stability [[87]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-86) |
| Electrode | LT/LMO | [Ener1](http://en.wikipedia.org/wiki/Ener1)/[Delphi](http://en.wikipedia.org/wiki/Delphi_Corporation),[[88]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-87)[[89]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-88) |  | 2006 | durability, safety (limited density) |
|  | [Nanostructure](http://en.wikipedia.org/wiki/Nanoarchitectures_for_lithium-ion_batteries) | [Université Paul Sabatier](http://en.wikipedia.org/w/index.php?title=Universit%C3%A9_Paul_Sabatier&action=edit&redlink=1)/[Université Picardie Jules Verne](http://en.wikipedia.org/w/index.php?title=Universit%C3%A9_Picardie_Jules_Verne&action=edit&redlink=1)[[90]](http://en.wikipedia.org/wiki/Lithium-ion_battery#cite_note-89) |  | 2006 | density |

Fuel cells

A **fuel cell** is an [electrochemical cell](http://en.wikipedia.org/wiki/Electrochemical_cell) that [converts](http://en.wikipedia.org/wiki/Energy_transformation) [chemical energy](http://en.wikipedia.org/wiki/Chemical_energy) from a fuel into [electric energy](http://en.wikipedia.org/wiki/Electric_energy). Electricity is generated from the reaction between a fuel supply and an oxidizing agent. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained.

Fuel cells are different from conventional electrochemical cell [batteries](http://en.wikipedia.org/wiki/Battery_%28electricity%29) in that they consume reactant from an external source, which must be replenished[[1]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-0) – a [thermodynamically open system](http://en.wikipedia.org/wiki/Thermodynamic_system). By contrast, batteries store [electric energy](http://en.wikipedia.org/wiki/Electric_energy) chemically and hence represent a thermodynamically closed system.

Many combinations of fuels and oxidants are possible. A hydrogen fuel cell uses [hydrogen](http://en.wikipedia.org/wiki/Hydrogen) as its fuel and [oxygen](http://en.wikipedia.org/wiki/Oxygen) (usually from air) as its oxidant. Other fuels include [hydrocarbons](http://en.wikipedia.org/wiki/Hydrocarbon) and [alcohols](http://en.wikipedia.org/wiki/Alcohol). Other oxidants include [chlorine](http://en.wikipedia.org/wiki/Chlorine) and [chlorine dioxide](http://en.wikipedia.org/wiki/Chlorine_dioxide).[[2](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-1)

**Design**

Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three segments which are sandwiched together: the [anode](http://en.wikipedia.org/wiki/Anode), the [electrolyte](http://en.wikipedia.org/wiki/Electrolyte), and the [cathode](http://en.wikipedia.org/wiki/Cathode). Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electric current is created, which can be used to power electrical devices, normally referred to as the load.

At the anode a [catalyst](http://en.wikipedia.org/wiki/Catalyst) oxidizes the fuel, usually hydrogen, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electric current. The ions travel through the electrolyte to the cathode. Once reaching the cathode, the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.





A block diagram of a fuel cell

The most important design features in a fuel cell are:

* The electrolyte substance. The electrolyte substance usually defines the *type* of fuel cell.
* The fuel that is used. The most common fuel is hydrogen.
* The anode catalyst, which breaks down the fuel into electrons and ions. The anode catalyst is usually made up of very fine platinum powder.
* The cathode catalyst, which turns the ions into the waste chemicals like water or carbon dioxide. The cathode catalyst is often made up of [nickel](http://en.wikipedia.org/wiki/Nickel).

A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. Voltage decreases as current increases, due to several factors:

* [Activation loss](http://en.wikipedia.org/wiki/Overpotential)
* Ohmic loss ([voltage drop](http://en.wikipedia.org/wiki/Voltage_drop) due to resistance of the cell components and interconnects)
* Mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage).

To deliver the desired amount of energy, the fuel cells can be combined in [series and parallel circuits](http://en.wikipedia.org/wiki/Series_and_parallel_circuits), where series yields higher [voltage](http://en.wikipedia.org/wiki/Voltage), and parallel allows a higher [current](http://en.wikipedia.org/wiki/Electric_current) to be supplied. Such a design is called a *fuel cell stack*. The cell surface area can be increased, to allow stronger [current](http://en.wikipedia.org/wiki/Electric_current) from each cell.

**Proton exchange membrane fuel cells**

In the archetypical hydrogen–oxygen [proton exchange membrane fuel cell](http://en.wikipedia.org/wiki/Proton_exchange_membrane_fuel_cell)[[4]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-3) (PEMFC) design, a proton-conducting polymer membrane, (the [electrolyte](http://en.wikipedia.org/wiki/Electrolyte)), separates the [anode](http://en.wikipedia.org/wiki/Anode) and [cathode](http://en.wikipedia.org/wiki/Cathode) sides. This was called a "solid polymer electrolyte fuel cell" (SPEFC) in the early 1970s, before the proton exchange mechanism was well-understood. (Notice that "polymer electrolyte membrane" and "proton exchange mechanism" result in the same [acronym](http://en.wikipedia.org/wiki/Acronym).)

On the anode side, hydrogen diffuses to the anode catalyst where it later dissociates into protons and electrons. These protons often react with oxidants causing them to become what is commonly referred to as multi-facilitated proton membranes. The protons are conducted through the membrane to the cathode, but the electrons are forced to travel in an external circuit (supplying power) because the membrane is electrically insulating. On the cathode catalyst, oxygen [molecules](http://en.wikipedia.org/wiki/Molecule) react with the electrons (which have traveled through the external circuit) and protons to form water — in this example, the only waste product, either [liquid](http://en.wikipedia.org/wiki/Water) or [vapor](http://en.wikipedia.org/wiki/Water_vapor).

In addition to this pure hydrogen type, there are [hydrocarbon](http://en.wikipedia.org/wiki/Hydrocarbon) fuels for fuel cells, including [diesel](http://en.wikipedia.org/wiki/Diesel_fuel), [methanol](http://en.wikipedia.org/wiki/Methanol) (*see:* [direct-methanol fuel cells](http://en.wikipedia.org/wiki/Direct-methanol_fuel_cell) and [indirect methanol fuel cells](http://en.wikipedia.org/wiki/Indirect_methanol_fuel_cell)) and chemical hydrides. The waste products with these types of fuel are [carbon dioxide](http://en.wikipedia.org/wiki/Carbon_dioxide) and water.





Construction of a high temperature [PEMFC](http://en.wikipedia.org/wiki/Proton_exchange_membrane_fuel_cell): Bipolar plate as [electrode](http://en.wikipedia.org/wiki/Electrode) with in-milled gas channel structure, fabricated from conductive [composites](http://en.wikipedia.org/wiki/Composite) (enhanced with [graphite](http://en.wikipedia.org/wiki/Graphite), [carbon black](http://en.wikipedia.org/wiki/Carbon_black), [carbon fiber](http://en.wikipedia.org/wiki/Carbon_fiber), and/or [carbon nanotubes](http://en.wikipedia.org/wiki/Carbon_nanotube) for more conductivity);[[5]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-4) [Porous](http://en.wikipedia.org/wiki/Porous) carbon papers; reactive layer, usually on the [polymer](http://en.wikipedia.org/wiki/Polymer) membrane applied; polymer membrane.





Condensation of water produced by a PEMFC on the air channel wall. The gold wire around the cell ensures the collection of electric current.[[6]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-5)

The different components of a PEMFC are (i) [bipolar plates](http://en.wikipedia.org/w/index.php?title=Bipolar_plate&action=edit&redlink=1), (ii) [electrodes](http://en.wikipedia.org/wiki/Electrode), (iii) [catalyst](http://en.wikipedia.org/wiki/Catalyst), (iv) [membrane](http://en.wikipedia.org/wiki/Membrane), and (v) the necessary hardwares.[[7]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-6) The materials used for different parts of the fuel cells differ by type. The bipolar plates may be made of different types of materials, such as, metal, coated metal, [graphite](http://en.wikipedia.org/wiki/Graphite), flexible graphite, C–C [composite](http://en.wikipedia.org/wiki/Composite), [carbon](http://en.wikipedia.org/wiki/Carbon)–[polymer](http://en.wikipedia.org/wiki/Polymer) composites etc.[[8]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-7) The [membrane electrode assembly](http://en.wikipedia.org/wiki/Membrane_electrode_assembly) (MEA), is referred as the heart of the PEMFC and usually made of a proton exchange membrane sandwiched between two [catalyst](http://en.wikipedia.org/wiki/Catalyst) coated [carbon papers](http://en.wikipedia.org/wiki/Carbon_paper). [Platinum](http://en.wikipedia.org/wiki/Platinum) and/or similar type of noble metals are usually used as the catalyst for PEMFC. The electrolyte could be a polymer [membrane](http://en.wikipedia.org/wiki/Artificial_membrane).

**[**[**edit**](http://en.wikipedia.org/w/index.php?title=Fuel_cell&action=edit&section=3)**] Proton exchange membrane fuel cell design issues**

* Costs. In 2002, typical fuel cell systems cost US$1000 per kilowatt of electric power output. In 2009, the Department of Energy reported that 80-kW automotive fuel cell system costs in volume production (projected to 500,000 units per year) are $61 per kilowatt.[[9]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-8) The goal is $35 per kilowatt. In 2008 UTC Power has 400 kW stationary fuel cells for $1,000,000 per 400 kW installed costs. The goal is to reduce the cost in order to compete with current market technologies including gasoline internal combustion engines. Many companies are working on techniques to reduce cost in a variety of ways including reducing the amount of platinum needed in each individual cell. [Ballard Power Systems](http://en.wikipedia.org/wiki/Ballard_Power_Systems) have experiments with a catalyst enhanced with [carbon silk](http://en.wikipedia.org/w/index.php?title=Carbon_silk&action=edit&redlink=1) which allows a 30% reduction (1 mg/cm² to 0.7 mg/cm²) in platinum usage without reduction in performance.[[10]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-9) [Monash University](http://en.wikipedia.org/wiki/Monash_University), [Melbourne](http://en.wikipedia.org/wiki/Melbourne) uses [PEDOT](http://en.wikipedia.org/wiki/Poly%283%2C4-ethylenedioxythiophene%29) as a [cathode](http://en.wikipedia.org/wiki/Cathode).[[11]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-Online-10) A 2011 published study[[12]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-11) documented the first ever metal free electrocatalyst using relatively inexpensive doped carbon nanotubes that are less than 1% the cost of platinum and are of equal or superior performance.
* The production costs of the PEM ([proton exchange membrane](http://en.wikipedia.org/wiki/Proton_exchange_membrane)). The [Nafion](http://en.wikipedia.org/wiki/Nafion) membrane currently costs $566/m². In 2005 Ballard Power Systems announced that its fuel cells will use Solupor, a porous [polyethylene](http://en.wikipedia.org/wiki/Polyethylene) film patented by [DSM](http://en.wikipedia.org/wiki/DSM_%28company%29).[[13]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-patent-solupor-12)[[14]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-13)
* Water and air management[[15]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-14) (in PEMFCs). In this type of fuel cell, the membrane must be hydrated, requiring water to be evaporated at precisely the same rate that it is produced. If water is evaporated too quickly, the membrane dries, resistance across it increases, and eventually it will crack, creating a gas "short circuit" where hydrogen and oxygen combine directly, generating heat that will damage the fuel cell. If the water is evaporated too slowly, the electrodes will flood, preventing the reactants from reaching the catalyst and stopping the reaction. Methods to manage water in cells are being developed like [electroosmotic pumps](http://en.wikipedia.org/wiki/Electroosmotic_pump) focusing on flow control. Just as in a combustion engine, a steady ratio between the reactant and oxygen is necessary to keep the fuel cell operating efficiently.
* Temperature management. The same temperature must be maintained throughout the cell in order to prevent destruction of the cell through [thermal loading](http://en.wikipedia.org/wiki/Thermal_loading). This is particularly challenging as the 2H2 + O2 -> 2H2O reaction is highly exothermic, so a large quantity of heat is generated within the fuel cell.
* Durability, [service life](http://en.wikipedia.org/wiki/Service_life), and special requirements for some type of cells. [Stationary fuel cell applications](http://en.wikipedia.org/wiki/Stationary_fuel_cell_applications) typically require more than 40,000 hours of reliable operation at a temperature of -35 °C to 40 °C, while automotive fuel cells require a 5,000 hour lifespan (the equivalent of 150,000 miles) under extreme temperatures. Current [service life](http://en.wikipedia.org/wiki/Service_life) is 7,300 hours under cycling conditions. Automotive engines must also be able to start reliably at -30 °C and have a high power to volume ratio (typically 2.5 kW per liter).
* Limited [carbon monoxide](http://en.wikipedia.org/wiki/Carbon_monoxide) tolerance of some (non-PEDOT) cathodes.

 **High temperature fuel cells**

 **SOFC**

A [solid oxide fuel cell](http://en.wikipedia.org/wiki/Solid_oxide_fuel_cell) (SOFC) is extremely advantageous “because of a possibility of using a wide variety of fuel”. Unlike most other fuel cells which only use hydrogen, SOFCs can run on hydrogen, butane, methanol, other petroleum products and producer gases from biomass gasification [[18]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-e-collection.ethbib.ethz.ch-17). The different fuels each have their own chemistry.

For SOFC methanol fuel cells, on the anode side, a catalyst breaks methanol and water down to form carbon dioxide, hydrogen ions, and free electrons. The hydrogen ions meet oxide ions that have been created on the cathode side and passed across the electrolyte to the anode side, where they react to create water. A load connected externally between the anode and cathode completes the electrical circuit. Below are the chemical equations for the reaction:

*Anode Reaction*: CH3OH + H2O + 3O= → CO2 + 3H2O + 6e-

*Cathode Reaction*: 3/2 O2 + 6e- → 3O=

*Overall Reaction*: CH3OH + 3/2 O2 → CO2 + 2H2O + electrical energy

At the anode SOFCs can use nickel or other catalysts to break apart the methanol and create hydrogen ions and [carbon monoxide](http://en.wikipedia.org/wiki/Carbon_monoxide). A solid called yttria stabilized zirconia (YSZ) is used as the electrolyte. Like all fuel cell electrolytes YSZ is conductive to certain ions, in this case the oxide ion (O=) allowing passage from the cathode to anode, but is non-conductive to electrons. It is a durable solid, advantageous in large industrial systems, and a good ion conductor. However, YSZ only works at very high temperatures, typically about 950oC. Running the fuel cell at such a high temperature easily breaks down the methane and oxygen into ions. A major disadvantage of the SOFC, as a result of the high heat, is that it “places considerable constraints on the materials which can be used for interconnections”.[[19]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-sahibzada-18) Another disadvantage of running the cell at such a high temperature is that other unwanted reactions may occur inside the fuel cell. It is common for carbon dust (graphite) to build up on the anode, preventing the fuel from reaching the catalyst. Much research is currently being done to find alternatives to YSZ that will carry ions at a lower temperature.

 **MCFC**

[Molten carbonate fuel cells](http://en.wikipedia.org/wiki/Molten_carbonate_fuel_cell) (MCFCs) operate in a similar manner, except the electrolyte consists of liquid (molten) carbonate, which is a negative ion and an oxidizing agent. Because the electrolyte loses carbonate in the oxidation reaction, the carbonate must be replenished through some means. This is often performed by recirculating the carbon dioxide from the oxidation products into the cathode where it reacts with the incoming air and reforms carbonate.

Unlike proton exchange fuel cells, the catalysts in SOFCs and MCFCs are not poisoned by carbon monoxide, due to much higher [operating temperatures](http://en.wikipedia.org/wiki/Operating_temperature). Because the oxidation reaction occurs in the anode, direct utilization of the carbon monoxide is possible. Also, steam produced by the oxidation reaction can [shift](http://en.wikipedia.org/wiki/Water_gas_shift) carbon monoxide and [steam reform](http://en.wikipedia.org/wiki/Fossil_fuel_reforming) hydrocarbon fuels inside the anode. These reactions can use the same catalysts used for the electrochemical reaction, eliminating the need for an external fuel reformer.

MCFC can be used for reducing the CO2 emission from coal fired power plants[[20]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-19) as well as gas turbine power plants.[[21]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-20)

 **Efficiency**

**[**[**edit**](http://en.wikipedia.org/w/index.php?title=Fuel_cell&action=edit&section=10)**] Fuel cell efficiency**

The efficiency of a fuel cell is dependent on the amount of power drawn from it. Drawing more power means drawing more current, which increases the losses in the fuel cell. As a general rule, the more power (current) drawn, the lower the efficiency. Most losses manifest themselves as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage. For this reason, it is common to show graphs of voltage versus current (so-called polarization curves) for fuel cells. A typical cell running at 0.7 V has an efficiency of about 50%, meaning that 50% of the energy content of the hydrogen is converted into electrical energy; the remaining 50% will be converted into heat. (Depending on the fuel cell system design, some fuel might leave the system unreacted, constituting an additional loss.)

For a hydrogen cell operating at standard conditions with no reactant leaks, the efficiency is equal to the cell voltage divided by 1.48 V, based on the [enthalpy](http://en.wikipedia.org/wiki/Enthalpy), or heating value, of the reaction. For the same cell, the [second law efficiency](http://en.wikipedia.org/wiki/Second_law_efficiency) is equal to cell voltage divided by 1.23 V. (This voltage varies with fuel used, and quality and temperature of the cell.) The difference between these numbers represents the difference between the reaction's [enthalpy](http://en.wikipedia.org/wiki/Enthalpy) and [Gibbs free energy](http://en.wikipedia.org/wiki/Gibbs_free_energy). This difference always appears as heat, along with any losses in electrical conversion efficiency.

Fuel cells are not heat engines and so the [Carnot cycle](http://en.wikipedia.org/wiki/Carnot_cycle) efficiency is not relevant to the thermodynamic efficiency of fuel cells.[[28]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-27) At times this is misrepresented by saying that fuel cells are exempt from the laws of thermodynamics, because most people think of thermodynamics in terms of combustion processes ([enthalpy of formation](http://en.wikipedia.org/wiki/Enthalpy_of_formation)). The laws of thermodynamics also hold for chemical processes ([Gibbs free energy](http://en.wikipedia.org/wiki/Gibbs_free_energy)) like fuel cells, but the maximum theoretical efficiency is higher (83% efficient at 298K [[29]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-28) in the case of hydrogen/oxygen reaction) than the [Otto cycle](http://en.wikipedia.org/wiki/Otto_cycle) thermal efficiency (60% for compression ratio of 10 and specific heat ratio of 1.4). Comparing limits imposed by thermodynamics is not a good predictor of practically achievable efficiencies. Also, if propulsion is the goal, electrical output of the fuel cell has to still be converted into mechanical power with another efficiency drop. In reference to the exemption claim, the correct claim is that "limitations imposed by the second law of thermodynamics on the operation of fuel cells are much less severe than the limitations imposed on conventional energy conversion systems". Consequently, they can have very high efficiencies in converting [chemical energy](http://en.wikipedia.org/wiki/Chemical_energy) to [electrical energy](http://en.wikipedia.org/wiki/Electrical_energy), especially when they are operated at low power density, and using pure hydrogen and oxygen as reactants.

It should be underlined that fuel cell (especially high temperature) can be used as a heat source in conventional heat engine (gas turbine system). In this case the ultra high efficiency is predicted (above 70%).

**In practice**

For a fuel cell operating on air, losses due to the air supply system must also be taken into account. This refers to the pressurization of the air and dehumidifying it. This reduces the efficiency significantly and brings it near to that of a compression ignition engine. Furthermore, fuel cell efficiency decreases as load increases.

The tank-to-wheel efficiency of a [fuel cell vehicle](http://en.wikipedia.org/wiki/Fuel_cell_vehicle) is greater than 45% at low loads and shows average values of about 36% when a driving cycle like the NEDC ([New European Driving Cycle](http://en.wikipedia.org/wiki/New_European_Driving_Cycle)) is used as test procedure. The comparable NEDC value for a Diesel vehicle is 22%. In 2008 Honda released a fuel cell electric vehicle (the [Honda FCX Clarity](http://en.wikipedia.org/wiki/Honda_FCX_Clarity)) with fuel stack claiming a 60% tank-to-wheel efficiency.

It is also important to take losses due to fuel production, transportation, and storage into account. Fuel cell vehicles running on compressed hydrogen may have a power-plant-to-wheel efficiency of 22% if the hydrogen is stored as high-pressure gas, and 17% if it is stored as [liquid hydrogen](http://en.wikipedia.org/wiki/Liquid_hydrogen).[[36]](http://en.wikipedia.org/wiki/Fuel_cell#cite_note-35) In addition to the production losses, over 70% of US' electricity used for hydrogen production comes from [thermal power](http://en.wikipedia.org/wiki/Thermal_power), which only has an efficiency of 33% to 48%, resulting in a net increase in carbon dioxide production by using hydrogen in vehicles. However, more than 90% of all hydrogen is produced by [steam methane reforming](http://en.wikipedia.org/wiki/Steam_methane_reforming).

Fuel cells cannot store energy like a battery, but in some applications, such as stand-alone power plants based on discontinuous sources such as [solar](http://en.wikipedia.org/wiki/Solar_energy) or [wind power](http://en.wikipedia.org/wiki/Wind_power), they are combined with [electrolyzers](http://en.wikipedia.org/wiki/Electrolysis) and storage systems to form an energy storage system. The overall efficiency (electricity to hydrogen and back to electricity) of such plants (known as *round-trip efficiency*) is between 30 and 50%, depending on conditions. While a much cheaper [lead-acid battery](http://en.wikipedia.org/wiki/Lead-acid_battery) might return about 90%, the electrolyzer/fuel cell system can store indefinite quantities of hydrogen, and is therefore better suited for long-term storage.

Solid-oxide fuel cells produce exothermic heat from the recombination of the oxygen and hydrogen. The ceramic can run as hot as 800 degrees Celsius. This heat can be captured and used to heat water in a [micro combined heat and power](http://en.wikipedia.org/wiki/Micro_combined_heat_and_power) (m-CHP) application. When the heat is captured, total efficiency can reach 80-90% at the unit, but does not consider production and distribution losses. CHP units are being developed today for the European home market.

**Fuel cell applications**

**Power**

Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, rural locations, and in certain military applications. A fuel cell system running on hydrogen can be compact and lightweight, and have no major moving parts. Because fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability. This equates to around one minute of down time in a two year period.

Since electrolyzer systems do not store fuel in themselves, but rather rely on external storage units, they can be successfully applied in large-scale energy storage, rural areas being one example. In this application, batteries would have to be largely oversized to meet the storage demand, but fuel cells only need a larger storage unit (typically cheaper than an electrochemical device).

One such pilot program is operating on Stuart Island in Washington State. There the Stuart Island Energy Initiative has built a complete, closed-loop system: Solar panels power an electrolyzer which makes hydrogen. The hydrogen is stored in a 1,900 L at 1,400 kPa, and runs a ReliOn fuel cell to provide full electric back-up to the off-the-grid residence.

 **Cogeneration**





Configuration of components in a fuel cell car.

[Micro combined heat and power](http://en.wikipedia.org/wiki/Micro_combined_heat_and_power) (MicroCHP) systems such as [home fuel cells](http://en.wikipedia.org/wiki/Home_fuel_cell) and [cogeneration](http://en.wikipedia.org/wiki/Cogeneration) for office buildings and factories are in the mass production phase. The system generates constant electric power (selling excess power back to the grid when it is not consumed), and at the same time produces hot air and water from the [waste heat](http://en.wikipedia.org/wiki/Waste_heat). MicroCHP is usually less than 5 kWe for a [home fuel cell](http://en.wikipedia.org/wiki/Home_fuel_cell) or small business. A lower fuel-to-electricity conversion efficiency is tolerated (typically 15-20%), because most of the energy not converted into electricity is utilized as heat. Some heat is lost with the exhaust gas just as in a normal [furnace](http://en.wikipedia.org/wiki/Furnace), so the combined heat and power efficiency is still lower than 100%, typically around 80%. In terms of [exergy](http://en.wikipedia.org/wiki/Exergy) however, the process is inefficient, and one could do better by maximizing the electricity generated and then using the electricity to drive a [heat pump](http://en.wikipedia.org/wiki/Heat_pump). [Phosphoric-acid fuel cells](http://en.wikipedia.org/wiki/Phosphoric-acid_fuel_cell) (PAFC) comprise the largest segment of existing CHP products worldwide and can provide combined efficiencies close to 90% (35-50% electric + remainder as thermal) [Molten-carbonate fuel cells](http://en.wikipedia.org/wiki/Molten-carbonate_fuel_cell) have also been installed in these applications, and [solid-oxide fuel cell](http://en.wikipedia.org/wiki/Solid-oxide_fuel_cell) prototypes exist.

**Hydrogen transportation and refueling**

Main articles: [Fuel cell vehicle](http://en.wikipedia.org/wiki/Fuel_cell_vehicle), [Hydrogen vehicle](http://en.wikipedia.org/wiki/Hydrogen_vehicle), [Hydrogen station](http://en.wikipedia.org/wiki/Hydrogen_station), and [Hydrogen highway](http://en.wikipedia.org/wiki/Hydrogen_highway)



**UNIT III VEHICLE OPERATION AND CONTROL**

Computer Control for pollution and noise control.

**Noise mitigation** is a set of strategies to reduce [noise pollution](http://en.wikipedia.org/wiki/Noise_pollution). The main areas of noise mitigation or abatement are: [transportation](http://en.wikipedia.org/wiki/Transportation) noise control, [architectural](http://en.wikipedia.org/wiki/Architecture) design, and [occupational noise](http://en.wikipedia.org/wiki/Industrial_noise) control. [Roadway noise](http://en.wikipedia.org/wiki/Roadway_noise) and [aircraft noise](http://en.wikipedia.org/wiki/Aircraft_noise) are the most pervasive sources of environmental noise worldwide, and little change has been effected in source control in these areas since the start of the problem,[[*citation needed*](http://en.wikipedia.org/wiki/Wikipedia%3ACitation_needed)] a possible exception being the development of [hybrid](http://en.wikipedia.org/wiki/Hybrid_vehicle) and [electric vehicles](http://en.wikipedia.org/wiki/Electric_vehicle).

Multiple techniques have been developed to address interior sound levels, many of which are encouraged by local [building codes](http://en.wikipedia.org/wiki/Building_code); in the best case of project designs, planners are encouraged to work with [design engineers](http://en.wikipedia.org/wiki/Design_engineer) to examine trade-offs of roadway design and architectural design. These techniques include design of exterior walls, party walls and floor and ceiling assemblies; moreover, there are a host of specialized means for dampening reverberation from special-purpose rooms such as [auditoria](http://en.wikipedia.org/wiki/Auditorium), [concert halls](http://en.wikipedia.org/wiki/Concert_hall), dining areas, audio recording rooms, and meeting rooms. Many of these techniques rely upon materials science applications of constructing [sound baffles](http://en.wikipedia.org/wiki/Sound_baffle) or using sound-absorbing liners for interior spaces. Industrial noise control is really a subset of interior architectural control of noise, with emphasis upon specific methods of sound isolation from industrial machinery and for protection of workers at their task stations.

[Sound masking](http://en.wikipedia.org/wiki/Sound_masking) is the active addition of noise to reduce the annoyance of certain sounds; the opposite of [soundproofing](http://en.wikipedia.org/wiki/Soundproofing).

Computer Control for fuel economy

Each year, cars seem to get more and more complicated. Cars today might have as many as 50 microprocessors on them. Although these microprocessors make it more difficult for you to work on your own car, some of them actually make your car easier to service.

Some of the reasons for this increase in the number of microprocessors are:

* The need for sophisticated engine controls to meet emissions and fuel-economy standards
* Advanced diagnostics
* Simplification of the manufacture and design of cars
* Reduction of the amount of wiring in cars
* New safety features
* New comfort and convenience features

Transducers and actuators

Information technology for receiving proper information and operation of the vehicle like optimum speed and direction

**UNIT IV VEHICLE AUTOMATED TRACKS**

Preparation and maintenance of proper road network

*Following the re-organisation of the roads sector and the formation of TANROADS and the Road Funds Board in 2000, there has been a greater need for a Road Management System to cover the whole of the national trunk and regional roads network. Performance targets are a feature of the new road maintenance arrangements. Since the beginning of 2001 TANROADS has been working with TRL Limited of the UK under a project managed by TANROADS and jointly funded by DFID and the Roads Fund Board, to provide an improved version of a project level system, Road Mentor 3. The improved system, Road Mentor 4, as well as being more suited to network use, has been rewritten in Visual Basic and uses Microsoft Access tables to store data, both in order to be compatible with current operating systems. It can be run on PCs equipped with either Windows 98 or 2000. The main modules of the new Road Mentor 4 programme were completed early in 2002. It was realised that considerable effort would be needed to populate the system with reliable and compatible data. Consequently a 2nd phase of the project is being carried out in which, with TRL assistance, the Road Mentor System would be implemented just within a single Zone. Experience gained in this exercise would be used to plan the subsequent implementation across the rest of Tanzania. This paper describes the progress made up to the end of September 2002 in implementing The Road Mentor system within the Central Zone and describes the general features of the system*

**Road Networks of the Future: can Data Networks Help?**

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# Introduction

Most people in Australasia would answer a 'What is traffic?' question with a description of vehicles moving in a network of roads. Upon further prompting, other transport-related definitions concerning sea- and air-based traffic would surface as would references to telecommunications, economic trading (share and stock markets), drug peddling and activity on the internet. In terms of the numbers of people who have an understanding of a particular definition of 'traffic' it is this last, data networks,that has increased most since the advent of computing to the mainstream and, of greater significance, the emergence of the internet since its beginnings in the 1960s. The term 'traffic' in the psyche of the interconnected masses has firmly come to be understood as data rocketing through optical fibres, wires and satellites to service the needs and desires of people for email communication and to browse favourite websites.

Users of both data and road transport networks are aware of distinct similarities between the two. Indeed the terminology is often very similar. In this paper we use the term ‘node’ to refer to a host in a computer network or a junction in a road network and the term ‘link’ is used to refer to a connection in a computer network and a road in a road network.

There have been numerous references in data or vehicular traffic network literature that use the other as an analogy to help explain specific behaviour patterns (eg Benameur and Roberts, 2002; Reed Business Information Limited and Gale Group, 2002). This paper looks specifically at two types of networks: road vehicle networks and data traffic networks. Pertinent descriptions of both are presented with the purpose of highlighting their features, making comparisons and suggesting ways that methods used in data networks can be used in road networks of the future. This paper looks at data network methods that can be combined with Intelligent Transport Systems (ITS) technologies to improve the functionality of road networks (supply) as they come under increasing pressure from users (demand) ultimately resulting in the road network and its vehicles becoming more automated.

# Origins of the Networks

Land-based transport networks have evolved over thousands of years to become what we refer to as ‘road networks’. The data networks with which we have become familiar have evolved in a lifetime. In both cases the networks have developed to meet needs from the military and commerce.

As an example of the military aspect, in Europe, the Roman Empire undertook a great deal of road building for the primary reason to speedily move legions of soldiers to and from the outer reaches of the empire. In the US, the government push to build interstate highways in the 1950s was, in part, motivated by a desire to enable fast troop movement.

The internet itself was conceived and designed in the 1960s in response to the Cold War, so that allies of the US could communicate during time of physical warfare. Furthermore, it was developed as a communications tool that was impervious to nuclear attack (Zakon, 2003; Smithsonian Institute, 2003) through the simple expedient of being resilient to the failure of individual nodes. This ensured that in the aftermath of a nuclear holocaust, communications-dominance would rest with the US and its allies. The idea was that this would allow for the expedition of re-instating a functional government to manage affairs of state should the US and allies survive such a conflagration. In the last decade or so, the network has become more centralised and the internet backbone now comprises a significant number of highly-connected nodes thereby reducing the ability of the original ARPANET to be resistant to node drop-out.

On the other hand, the development of both road networks and the internet have been stimulated greatly by the needs of commerce. In the case of road networks, the need to move goods from place to place overland was obviously a large reason for travel. In the case of the internet, through the growth of various forms of online shopping. One could argue though that in the last ten years the improvements to the internet have been catalysed by users’ interests in music, sex and digital photography.

Ultimately, the point of both roads and the internet is to move units/elements from an origin to a destination as quickly and efficiently as possible with no (or at least very minimal) negative impact on the units travelling.

# Road traffic networks

Though the road traffic network evident in Australia and in other so-called 'developed' countries is very familiar to us all, details of the data traffic network may not be quite so familiar. Hence it is beneficial to view the road network in terms that make a compare and contrast exercise with the data network as understandable as possible.

The action of a user of the road network embarking on and proceeding on a journey can be viewed as being conducted under the influences of itinerary and mode decisions and motion and right-of-way systems. The itinerary decision encompasses the time the journey is to be undertaken (often a broad estimate) and the outline of the route to be taken. It is important to recognise that a mode decision for users of the road network is necessary and though briefly mentioned here will be revisited in the discussion on data traffic networks. The motion system is that used to propel the user through the road network. The right-of-way system is that which controls when users can travel on various elements of the road network. These journey influences are discussed more fully later in this section after a short discussion on a purpose of signalised intersections.

One of the major design goals of all at-grade intersection control treatments, be they stop or give way signs, roundabouts or traffic signals, is to create an environment where all road users can safely proceed on their chosen itinerary. An added bonus is if the users feel comfortable with the manner in which they have to use the intersection itself. That is, comfortable with what they have to do to proceed in safety and comfortable with the infrastructure in terms of familiarity with its elements with regard to their appearance, position and purpose. This applies to the traffic lights themselves, the signage on the approaches to the intersection, the road markings, lane widths and kerb treatments.

There are two control systems for vehicle users at signalised intersections. The first is the motion system and the second is the right-of-way system. The motion system (concerned with propulsion and deceleration) is currently the responsibility of the user. For example the vehicle driver decides how the motive force is to be applied to the vehicle – when to accelerate, cruise, decelerate, stop – and decides in what direction that vehicle should travel. The same is true for pedestrians and cyclists though in this paper we do not delve into their particular requirements since we are concerned with applying methods and techniques to motorised vehicles with a view to road network automation. The right-of-way system determines when a user or a group of users can proceed through the intersection. Traffic lights are the right-of-way system at signalised intersections and can be optimised for particular types of users (eg motorists, pedestrians, bus passengers, cyclists) and for one or more objectives. Usually motorised vehicles are the subject of signal optimisation and the major goal is to minimise delay while maximising throughput though other measures such as minimising the number of vehicle stops and the lengths of queues are often given some consideration (Clement and Taylor, 1994; Clement, 1997).

When it comes to users making decisions on route-choice for their itinerary – assuming that the mode choice involves non-public transport conveyances – they are usually guided by a heuristic method of minimising a cost. This cost is not necessarily directly fiscal; it could be any combination of personal preferences. These include the need to be continually on the move, a fear of performing right-hand turns at unprotected signalised intersections/ unsignalised intersections, preference for specific road traffic conditions, the duties for the day etc. One view of the decisions users make before and during a journey that will take them through at least several signalised intersections is that the users embrace macroscopic, mesoscopic and microscopic viewpoints depending on where they are in relation to different elements of road network infrastructure. Vogiatzis (2005) refers to this as Simultaneous and Dynamic Network Scalability (SDNS), as applied within the context of Locality-Scope (LS) which is a new theory for network objectification and specifically for road network management. Within the LS context, all objects use the notion of SDNS to optimise their movement within the network based on the specific cost criteria or interest. Therefore decisions on the intended route can be viewed in the macroscopic sense of visualising movement along specific links and through specific nodes. In some cases the itinerary in this macroscopic viewpoint may not be completely connected in every detail but be connected enough to allow the journey to begin. Once on the journey, the user generally embraces a mesoscopic view of the itinerary where on-the-spot changes to the intended route are processed and effected. For example, when on the journey a driver realises that they will be passing near, but not right by, an 'attraction' such as a delightful lakeside scene, the itinerary may be altered to suit. A similar mesoscopic view is employed if a driver is confronted by a detour that requires a change of road. Microscopic decisions concern the positioning of the vehicle within the infrastructure used for the journey. For example, a microscopic decision is to place the vehicle in the correct lane to effect the desired passage through the intersection eg a right turn.

In some circumstances traffic signals can be used to control the amount of vehicular traffic using a given section of roadway. Such gating techniques are well known in some parts of Europe. They work on the principle that if on a regular basis a specific route appears to become congested, some users will alter their route to avoid the congested region. While the method outlined relies on experiential observation and decision-making on the part of the road users, other infrastructure such as Variable Message Signs (VMSs) can be used in conjunction with the signals to help users reach the desired conclusion with regard to route choice. An example of this was the EU-funded COSMOS project (Kruse, 1998). The principal objective of the COSMOS project was to build and verify traffic signal control demonstrators for congestion and incident management (CIM) in urban networks. The project addressed the problem of urban traffic congestion caused by incidents and/or over-saturation in areas controlled by Urban Traffic Control (UTC) systems. In such systems traffic data is analysed by the Path Flow Estimator (PFE) which was applied in cities such as Leicester, Toulouse, Lyon and Piraeus (Grosso, Bell, Clement and Kruse, 1998). In the Piraeus demonstrator, the results of the PFE analysis are passed to the MOTION traffic control system which (besides controlling the signals) then decides the displays for each of four VMSs. The objective of the Piraeus system is to balance the vehicle traffic load through the ancient town of Piraeus and out onto the two major arterial roads linking the port of Piraeus with Athens (Kruse, 1998; Grosso et al, 1998).

The road network can be viewed as a cooperative enterprise. That is, individual users cooperate with the express aim of safely proceeding from their starting point to their destination. A breakdown in cooperation can lead to undesirable behaviour, increase the possibility of road crashes and in extreme cases cause tragedy. The terminal loss of a traveller is an example of a complete breakdown in the road network system. This human consequence aspect is not generally included in studies of network reliability. This may be due to the difficulty in finding a 'straightforward and unambiguous definition' (Cassir, Bell and Iida, 2000) of the function and corresponding level of performance measures for networks as a whole. It may also be due to the difficulty in quantifying rare events in terms of the reliability of the underlying infrastructure. Network reliability is discussed more – but not solely – in terms of connectivity in Cassir, Bell and Iida (2000) and Taylor (2000). The focus here is on the transport of people (and goods) from one location to another.

Another concept related to but not the same as network reliability is that of vulnerability. This is defined by D'Este and Taylor (2003) as 'A node is vulnerable if loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node, as measured by a standard index of accessibility'. Nicholson, Schmöcker and Bell (2003) explore the 'worst-case scenario, where a network is under attack from a malevolent agency'. Clearly different road networks (ie dense and sparse) and in particular nodes possess different vulnerabilities. D'Este and Taylor (2003) state that one purpose of analysing network vulnerability is to identify points where network failure is critical and suggest that in a sparse network vulnerability is perhaps more important than reliability. The failure of a key link in a network such as the national strategic road network may well cause significantly more disruption than the failure of a link in an urban network where alternative links may cover the loss of connectivity. The D'Este-Taylor method of 'network analysis and diagnosis' in terms of vulnerability may well find the most critical links and nodes in a road network but the provision of redundant or 'latent alternative' links in a sparse network may be prohibitively expensive.

The ability to better manage roads also encompasses notions of Travel Demand Management (TDM). These measures are concerned with managing the needs and desires of people wishing to travel rather than managing the road traffic itself (Holyoak, 2002). From the Australian Greenhouse Office (2004), TDM is: '…a broad range of strategies aimed at reducing the impacts of travel through: 1) reducing single occupant vehicle use; 2) shifting to more sustainable transport modes (cycling, walking, public transport); and 3) reducing or removing the need to travel.' Examples of TDM include car pooling, telecommuting, improved pedestrian and cycling corridors, 'Park and Ride' initiatives, ride sharing and traffic calming (Holyoak, 2002; North Central Texas Council of Governments, 2004; Australian Greenhouse Office, 2004). TDM measures and traffic management in many senses are asymbiotic since improved travel times arising out of the improved management of traffic tend to induce traffic demand. That is, if it becomes easier to travel then people will.

# Data traffic networks

In the days before mass physical inter-connectivity of computers began, data traffic networks consisted of people physically carrying storage media between devices; the 'sneakernet' predated the 'internet'. From its humble beginnings the internet has grown ferociously in terms of the number of inter-connected devices and in the amount of data traffic conveyed through its uncountable wires, switches, routers, bridges and hubs.

For all its growth over the last twenty years, the basic means of transporting information through the internet has remained as sending 'packets' of data through the connection media. This media consists of copper and fibre-optic cables with hubs, switches and routers providing the 'glue' between all the origins and destinations within the internet. The internet operates on what is known as a 'best guess path determination' or 'best effort delivery' system. The majority of the internet routes packets on a ‘by hop’ basis, that is to say, no node knows how to reach every other node in the network. How then does a packet move through the network? When a packet arrives at a router, route determination algorithms decide which adjacent node the packet should be forwarded to. It is this on-the-fly decision-making process that is the crux of the internet and is essentially brought about by a raft of cooperating software algorithms called protocols. Each class of protocol has a specific, defined task and each algorithm within that class will accomplish that task. But no two algorithms (eg two of the same protocol built by different companies) may actually accomplish the task in exactly the same manner. Hence the selection of a set of protocols can be critical to the operation of a localised network eg within an organisation, university etc.

The mechanisms ensuring the internet can be grouped into four separate layers:

1. Application layer: this is the software running on a computer that wishes to communicate with some other computer. For example, a web browser or an email program would all work at the application layer.
2. Transport layer: this layer ensures the end-to-end connectivity of data. If necessary it detects when data has been lost and retransmits it.
3. Internet layer: this layer ensures that a packet can get between a source and a destination. It is in charge of working out which direction packets need to go at each node in order to get to their destination.
4. Host-to-network layer: this layer is the physical hardware which connects two adjacent machines, for example, a satellite link, an optical cable or simply some wires. It provides a basic level of connection between two machines which are logically adjacent to each other.

The route decision-making protocols running in the routers use the information gathered about the network topology by the second group of protocols to make appropriate decisions on which next hop to send a packet to. The algorithms in these first two protocol groups are becoming more and more sophisticated as the internet grows since one of the main requirements for network installation is to provide the greatest bandwidth (thus allowing the highest packet throughput) at the least cost. The carrier protocols set up the different means of information transfer. Protocols in this group differ due to different physical media or the reliability requirements of the data transfer. One protocol may operate by setting up a complete, known path from origin to destination before the first data packet in the transmission starts its journey. An alternative to ‘by hop’ routing which is used in the majority of the internet is to set up a 'virtual' path that is created temporarily and its constituent links may be removed as soon as the last of the set of data packets has completed its journey across that link.

One level of congestion control on the internet is provided by Transmission Control Protocol (TCP). The mechanism is as follows. When the network is congested then packets are lost or ‘dropped’. Packet loss is part of normal internet operation and should not be thought of as a failure of the network. A receipt mechanism (known as acknowledgements or ACKs) ensures that lost packets are retransmitted. However, this mechanism also allows a crude level of congestion control. If an ACK is not received for a packet then this packet is assumed lost and must be retransmitted. However, in addition, the sender reduces the rate at which data is sent under the assumption that this packet loss was caused by network congestion. In this way, a network, to a certain extent, is resilient against overloading.

To achieve this, network designers use systems like Data Stream Management Systems (DSMS) and Simple Network Management Protocol (SNMP) to monitor the movement of data packets within the network (Vogiatzis, Ikeda, Woolley and He, 2003; Babcock, Babu, Datar, Motwani and Widom, 2002; Arasu, Babcock, Babu, McAlister and Widom, 2002; Babu, Subramanian and Widom, 2001; Ikeda and Vogiatzis, 2003). Such systems allow network designers and network administrators the ability to manage the data traffic within the network and to formulate new techniques to improve the movement of data within those networks.

The network management protocols do not in themselves assist in the transport of packets over the network (except for those protocols that detect and correct collisions) but are present to assist those people administering the network. There is a lot of traffic on any network that is required to keep the network running well. There is a trade-off here such that if too much 'support' data exchange occurs, this negatively impacts on the available bandwidth for the data to be transferred.

Network controllers (routers and switches) and not the data packets themselves determine the movement of data through the network though the data packets contain their origin and destination network addresses. The routers know the destination of each packet that is received but may be unaware of exactly where that destination is. The cooperating set of protocols enables the routers to locate the next adjacent machine that is closer to the destination. In a properly configured network, the packet should eventually reach its destination.

Another 'simplifying' factor is that data packets do not choose their 'mode' of travel, there is no volition to use 'public' fibre backbones over 'private' ones or to use a particular carrier protocol. The various network topology information-gathering protocols can dynamically assign costs for routes between nodes of a network. Costs can be a conglomerate of different metrics such as bandwidth, reliability, speed, number of routers to the destination, load etc. As would be expected these costs are used by routers, or more specifically the route decision-making protocols operating within the routers, to choose a path. Further, network administrators can adjust the weighting given to each metric component of the cost. Hence the dynamic routing protocols operating within routers use this cost information to make path-determination decisions for each data packet.

Continued improvement in the optimising algorithms on which the network depends and improved performance of routers in particular (ie speed of decision-making and reduced propagation delay) have resulted in reduced data transmission times. Couple reduced transmission times with a greatly reduced total cost of ownership and more people are using the internet and data networks. Despite the increase in users, the performance of the network has not generally degraded (except on the odd occasion when the system is overloaded).

# Similarities and differences

Here we identify the first important difference between road networks and data networks: the moveable elements within a road network are self-aware. This self-awareness permeates through the three levels of route decisions. At the macroscopic level the self-aware elements in the traffic network control their ultimate origin-destination and the timing of the trip. At the mesoscopic level once the trip has begun, to a great extent they control the route they will choose to get there. At the microscopic level on the approaches to and at intersections traffic elements have little control over their physical placement. Indeed the timing of vehicle progress through that intersection is tightly controlled since the infrastructure is designed to maximise safety and efficiency in terms of vehicle progression. This is most evident in countries such as Australia, New Zealand, Canada, Japan, USA, Ireland, UK and much of Europe. This regimen applies to a lesser extent in the countries of SE Asia and some African and South American countries where vehicle placement and movement can often seem chaotic to an observer more use to rigid patterns of behaviour.

It is at the microscopic level that the elements of a road network can be viewed as being closest to the packets in a data network. In data networks, one view is that data packets have no self-awareness and do not choose their origin-destination nor do they choose the route they take to fulfil their travel requirements. Another view is that since the origin and destination addresses are contained within the data packet, they are self-aware only at the macroscopic level and must completely rely on the infrastructure to decide the path to be taken. The users of a road network only rely on the infrastructure in the sense of complete connectivity (network reliability) and useability (congestion less than totally clogged) and do not have to be provided with a selected path. Increasingly, the use of realtime road network information systems (Advanced Traveller Information Systems, VMSs, speed advisory signs etc) are helping road network users make on-the-fly route-choice decisions at the mesoscopic level.

There are similarities and differences in some of the cost measures for the suitability of links and routes in both networks. A fundamental difference between the two is in the viewpoint of the units/elements of each network. The people moving in a road network make cost calculations and route decisions whereas in a data network routers and not the packets make these decisions. Road users can make cost decisions on a link level whereas routers are more likely to make calculations on a route level. For example, a road network user may use a particular link due to the speed they can travel along that link thereby minimising an element of cost such as travel time. Bits in a data network travel along a given link at the same speed at all times. Propagation delay exists as the packet passes through the routers and switches due to the requirements of the software needed for these devices to perform their functions. These delays can be measured and are used in the costs associated with routes. People also make overall route cost calculations. Here similarities exist between the two types of networks where measures for the number of lanes and bandwidth are equivalent, as are load and congestion. While data network managers make adjustments to the weights of the metrics used in route scores that ultimately impact route decisions, road network engineers indirectly perform a similar operation when optimising traffic signals. That is, signals can be designed for minimisation of delay, number of stops, fuel consumption, length of queue or a weighted combination of these and through experience and on-the-fly perceptions and calculations people will make route decisions.

The two networks handle 'crippling' congestion in very different ways. While there are many instances or more specifically sets of circumstances where data packets are discarded, the same procedures cannot be adopted for any travelling elements of the road network. This means that one of the fundamental processes of networking, the best-effort delivery system, cannot be applied to the road system. It is reasonable therefore to think that the end-to-end route establishment algorithms of data networks could be applied to a route advisory system in the current road network and to an automated vehicle road system of the future. These algorithms operate on a slightly different premise than do the traffic assignment algorithms of road network analysis and planning. With data networks connectivity is not assumed and routes are established using the best available knowledge. This knowledge can change dynamically and quite radically as the network topology changes.

Data networks have a much higher proportion of management and support traffic (upwards of 15 per cent) than does the road network with its maintenance and policing vehicles. The incident-recovery techniques are arguably much quicker relatively speaking in a data network than they are in the road network. The speed of recovery of a road network from (say) a crash is to some extent a function of the speed of notification and the proximity of emergency service vehicles. In a localised sense the same is true for the network administrator when a serious event such as a crashed router occurs. On the other hand, road networks are, to some extent, self-healing in a way that data networks are not. Because drivers are self-aware in a way that data packets are not, drivers can react to congestion and to closed lanes to a limited extent even if there is not intervention by the emergency services. In the short term, drivers can find alternate routes. In the longer term drivers can retime trips or find different modes of travel which avoid the problem. A review of driver route and departure time choice can be found in Clegg (2004). Speed of recovery comparisons are therefore, dependent on defining the possible problem.

Data travel demand management (DTDM) is a concept for controlling the volume of unnecessary traffic propagating from smaller networks that are managed by various Internet Service Providers (ISPs) through to the larger network of networks (the internet). ISPs are often referred to by users as the 'gateway' to the Internet and as such are in a position to impact upon or control traffic flows. In the discussion that follows, the term gateway refers to the router(s) managed by the ISP.

One aspect of DTDM utilizes the concept of traffic quotas. This involves the monitoring of data traffic during a specified period - usually on a monthly basis. Once a quota limit has been reached, the governing entity of the traffic network, the ISP, may impose a restriction on usage. This may take the form of a reduced daily quota until the next monthly quota period commences. Alternatively, the throughput capacity of the traffic network may be limited to a much slower speed for the over-quota user. Restrictions may be removed of course by the user purchasing more capacity (increasing the quota). Similar ideas of travel demand management can be applied in automated road networks. A certain amount of travel by private vehicle can be purchased on a monthly basis with a reduced daily quota for the remainder of the month in which the limit has been reached. In the case of road networks, alternative modes may then have to be considered. In an automated road network, the speed of vehicles carrying over-quota users may be restricted. Travel quota increases could be purchased at any time.

Another aspect of DTDM utilizes dedicated gateways as a first port-of-call for data traffic originating from a local network and entering a larger network. These gateways provide a function for routing decisions to be made based on the destination of the traffic and act as a 'proxy server' for the intended destination by retaining in a cache information likely to be retrieved again. This method minimises the impact of continual connection to exterior networks by providing a local service of requests wherever possible. If the request cannot be serviced by the local gateway then the best path selection process to the wider network continues. These local gateway proxy servers have the distinct advantage that the traffic which flows to and from the local networks is often NOT metered or charged under a traffic quota. The data flow is deemed local. In a sense this 'default' gateway function has a parallel in road network TDM with the idea of informing residents of the existence of a service closer to home than the one they are already using (Ampt and Rooney, 1998; Ampt, 2003).

Data networks are very similar to road networks in that the users determine the destination and the time of the travel (peak, off peak etc). Pricing factors may well impact upon the nature of the travel. For data networks that are managed by ISPs, subscribers are encouraged to use dedicated gateways (routers) and servers for data traffic though users can still elect to by-pass their local gateway and servers and use a direct connection to the internet for every destination path. The encouragement to use the local services is achieved by the traffic quotas for all subscribers to the ISPs network. The more network capacity consumed, the higher the monetary subscription costs as users are charged for the capacity consumption of the larger network. The gateways (routers) assist in minimising 'unnecessary' traffic being diverted onto the Internet and causing potential congestion or 'slow downs' for data travel times.

A fundamental difference between road networks and internet networks is an environmental difference. The environmental burden caused by an internet network is generally perceived as minimal and does not change a great deal if that network is heavily used. On the other hand, the environmental damage done by road traffic is well known and, obviously, becomes greater if the network is more heavily used. This leads to a fundamental difference in attitudes to demand management. In road networks, reducing demand on the roads is often seen as an end in itself. A measure might sometimes be seen as successful if it reduces the demand on the road network (if it does not significantly inconvenience road users). In data networks, demand management is a technical fix for a network that has more traffic than it can carry. Reduction of data traffic volume is not an end in itself.

Quotas and pricing structures are an indirect means of making users more aware of the impact that their data path decisions have on the rest of the network infrastructure. This system makes users more responsible for their actions with the aim of better utilisation of infrastructure and resources.

The ISPs are required to purchase network capacity from the infrastructure owner (usually a telephone company). ISPs then offer local data traffic networks (subscribers) a means of utilising larger networks for data destination and network utilisation planning. Hence in data networks there are three types of entities involved; the users, the ISPs and the telephone companies. In the majority of road networks there are two types of entities; the road users and the government owners and maintainers of the network infrastructure. With the advent of private roads and tollways, a third type of entity, that of the builder and owner of the road or tollway, assumes importance. This is another instance of a policy applied to roads that influences travel decisions.

Designers, builders and operators of road and data networks endeavour to provide the highest reliability at lowest cost. To maximise data network reliability, engineers tend to add additional links (fibre/cable) to build 'redundancy' into the network. This cannot easily be replicated for a road network. Whereas the concept of road network vulnerability is relatively recent, the mechanisms of the internet were developed to at least reduce data communication vulnerability in the event of a malevolent act. In a local or even national sense data networks are not vulnerable just as in a connectivity sense urban road networks are generally not vulnerable. But if we step back and look at international connections, we see that since there are few gateways connecting each country to every other country, then at this scale the network is still vulnerable. This is analogous to the national strategic road network where the loss of a node or link could cause considerable disruption and delay.

# Future potential convergences

When discussing the future of road traffic networks it is beneficial to look at the developments that have been made since the first installation of signal control in 1868 (Clement, 1997) in terms of the human function in moving themselves and goods throughout a network. At the start of this period, humans were responsible for how the vehicles (horse-drawn, penny-farthing) were controlled and exactly when those vehicles could move safely. In the road networks with which we are familiar, control devices (roundabouts, stop signs, give way signs, traffic signals) have been introduced to regulate when vehicles can safely (and legally) move. The next step for improving intersection efficiency is for an automated driving system to control the timing of the movement of vehicles and the movements themselves to take greater advantage of the unused road space and time in and around signalised intersections (Clement, 2003). The theoretical Simple Platoon Advancement (SPA) system of Clement (2003) is designed to take advantage of the many Intelligent Transport Systems (ITS) technologies that have been developed in recent years in various countries of the world. The SPA system shows that through innovative use of ITS technologies, significant improvement in intersection performance in terms of vehicle throughput compared with the current road network can be achieved.

Though the SPA system proposes only to control vehicle movement for limited periods through intersections, a fully-automated system will need to be capable of catering to those who may not be interested in direct movement from A to B as quickly as possible, but who may choose the 'scenic' route. This adds complexity to any route optimisation algorithm (Vogiatzis, 2003) and may be the most difficult capability to build into a more automated road system.

Clement (2003) gives a comprehensive review of the systems and technologies being developed as stepping-stones towards automated driving systems. These have descriptive names such as Adaptive Cruise Control (ACC), Advanced Driver Assistance Systems (ADAS), Automated Highway Systems (AHS), Autonomous Intelligent Cruise Control (AICC), Autonomous Speed Assistant (ASA), Advanced Vehicle Control Systems (AVCS), Cooperative Intelligent Vehicle-Highway Systems (CIVHS), Intelligent Cruise Control (ICC), Lane Departure Avoidance (LDA). Lane Departure Warning Assistant (LDWA), Lane Keeping Support (LKS), Low Speed Automation (LSA) and all fall under the 'banner' of Intelligent Transport Systems (ITS). An early example of an AVCS is the original California PATH (Program on Advanced Technology for the Highway) program of the 1980s (Whelan, 1995) in which trials were conducted whereby vehicles were driven without human control on purpose-built sections of existing highways. A more recent example is Demo'97 from the National Automated Highway System Consortium (NAHSC) from the USA as reported in Bishop (2002) which showcased more than 20 fully automated vehicles moving along an Interstate highway in San Diego California. The increasing transfer of autonomous vehicle control, at least in some areas of the road network or under certain road conditions, from the vehicle occupants to an automated control system making control decisions based on information gathered from the transport environment, offers a diverse and interesting array of possibilities. Many of these developments will have the obvious objectives of improving traffic flow, reducing trip duration, minimising energy consumption (and possibly still the reduction of environmental pollutants, including noise) and avoiding chronic traffic congestion, but will have other potential applications as well. All have analogies in the data network arena and are applicable for similar underlying reasons.

While much of the underlying traffic network information processing will have the essential objective of improving overall traffic flow these also lend themselves to optimisations based on criteria other than basic traffic flow data. This already occurs in city vehicle networks in a relatively crude fashion. An obvious example is traffic signal control for Emergency Service Vehicles (ESVs), where vehicle movement from a central headquarters out through the denser traffic regions is facilitated by green-lighting a pre-determined route for the call-out. Another example is bus-only lanes and controlled intersection phases used to expedite public transport through the vehicle network. In data networking, the analogous concept is known as Quality Of Service (QOS) and provides preferential forwarding for indicated classes of datagram whose services rely on a timely and continuous flow of data. A common example is multimedia data streaming such as videoconferencing. In an automatic vehicle control system it is easy to conceive of ESVs and public transport vehicles being provided with optimal travel conditions for the full journey.

Two other potential areas of convergence are networks within and between vehicles. Many modern vehicles contain networks that transmit data between on-board electronic devices using the same protocols used in the internet. This saves wiring and allows central control of a variety of devices within the vehicle. Another area of possible convergence is that of between vehicle ad-hoc networks (Blum, Eskandarian and Hoffman, 2004). These are networks of transmitters in cars that operate by transmitting data between each other with no centralised infrastructure. The idea is that the transmitters and receivers in vehicles form a low power network, the topology of which changes as vehicles move about the network.

With public infrastructure tending to be consumed to available capacity it is quite common for additional facilities to be provided, for an on-cost to the consumer of course, by the private sector. Examples of this abound, with privately funded, constructed and operated tollways (specifically a BOOT-style implementation) providing higher-speed, lower-duration point-to-point travel with fewer nodes of potential congestion (intersections). Slower, longer and more congested routes between the end-points are available and may be used without additional direct cost but if the funds are available and the vehicle operator desires or needs the advantages of the tollway route then it can be purchased as a premium travel option. Similar conditions and trends are seen in data networking. The obvious example is the difference in service between a low-cost dial-up connection to an Internet Service Provider (ISP) and the significantly more expensive broadband connection options providing much lower latency and higher bandwidth access. A move to broadband does not finish at the end-user connection. With the increasingly burdened public internet infrastructure not providing an acceptable level of service some organisations are implementing networks that parallel the internet backbone but provide the desired level of service to those willing and capable of paying for it. A recent example is Internet2 (Network Associates, 2004), a high-speed, high-capacity, low-latency network infrastructure connecting participating universities across continental USA and Hawaii. Similar purpose-built, parallel networks are appearing in Western Europe.

In economies increasingly offering 'premium' services on top of those provided as basic infrastructure it is conceivable that similar premium traffic conditions might be provided on a user-pays basis in automatic vehicle control networks. There are a number of extensions possible to the existing ESV and public transport services described above, however, the provision of optimal travel conditions based on other criteria is possibly of more interest. Some transport companies may wish to have their travel conditions organised to minimise energy consumption (a basic cost), while others, perhaps handling fresh or delicate product, may wish to minimise transit time. Private travellers might be able to purchase optimised travel, either as a one-off ("I need to get to grandma's house as quickly as possible") or as a premium vehicle registration category. Such travel is optimised against their desired characteristic; minimal travel time, reduced energy consumption, travel comfort (perhaps as measured by the number of controlled intersection waits), etc. The provision of a triple-zero emergency telephone analogy for vehicles, with an optimal journey being provided to the desired medical facility, might emerge as a component of a no-cost emergency service. The automatic management of the individual vehicle begins to involve Quality Of Transport Service (QOTS) considerations. These take into account traffic conditions and route, with some vehicles being less optimally moved through their journey, both in slower vehicle flows and less costly routes (no tollways for instance), while those subscribing to the premium service have the subscribed-to level of travel conditions provided.

This highlights a major difference between road and data networks in terms of topology. The internet is a ‘scale free’ network and also a ‘rich club’ network. A scale free network is one where the degree, *k* of nodes in the network (that is, the number of links which connect directly to a given node) approximately follows the distribution

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for some positive constants *C* and *α*. A ‘rich club’ network is one in which a node with high degree is more likely to connect to other nodes of high degree than would be the case if connections were made randomly. Road networks do not follow such a distribution, indeed, there are sound physical reasons why a node in a road network rarely has a degree of more than four (junctions become confusing if they are more complex than a crossroads). There exist a significant number of highly-connected nodes (the internet backbone) which form the mainstay of internet connectivity. Many mapping projects for the internet exist [www.caida.org] but the internet has grown so quickly that no centralised ‘map’ exists. With road traffic it is usually the case that the position of roads is well-known and mapped thoroughly. We can think of the internet backbone as being akin to Freeways or Motorways or Interstate Highways and individual computer connections as being akin to the roads outside our house or even the drive leading up to our garage. The infrastructure changes occur over a much longer time scale in road networks.

Data and road networks respond very differently to changes in the network. In the road network, if a link is extremely congested or closed then drivers may respond in the short term by looking for an alternative route and in the longer term by changing route, mode, destination or even electing not to travel. In data networks, if a link is broken or extremely congested then in the short term data is lost (packets dropped). This is responded to at two levels. If a link becomes extremely unreliable then routers may attempt to route data around the unreliable link. In addition, the sending node may send at a lower data rate under the assumption that the loss of packets was caused by congestion. In both cases, engineers may, at an even longer time scale, attempt to improve the network by providing more (or more reliable) capacity.

However in the case of both data networks and some tools used by traffic engineers where elements can be ‘dropped’, this same notion is not possible in a ‘live’ road network. For example, traffic microsimulation tools are able to, and sometimes do, drop virtual vehicles from the network if they have ‘crashed’ or if they have left the area of interest (Hidas, 2004). Hence any road traffic management system attempts to minimise the occurrence of ‘unit loss’.

For this integrated, automatic vehicle control system to be optimised for an overall journey, the vehicle network equivalent of the data network protocol infrastructure used to disseminate local information to non-local nodes in that network (the routers), will need to become increasingly sophisticated. Metrics suitable not only for optimising overall traffic flow but also the QOTS for individual vehicle requirements will need to be incorporated.

Conclusions

There are sufficient similarities between data and road traffic networks to encourage road traffic-engineering researchers to collaborate with physicists and data network engineering researchers in efforts to automate the road transport network. The units being moved in each network can be viewed in some instances with remarkable similarity at the macroscopic and microscopic levels. This, coupled with the gradual move to fully-automated vehicles within a road traffic network as ITS technologies become mature, embedded and prevalent in the road network infrastructure, suggests that there will be more interconnections between road and data traffic networks. The premise under which both will function is to move units from an origin to a destination efficiently. In this context, either an end-to-end route establishment algorithm or a virtual, on-the-fly route planning algorithm could be applied to an automated road system. This could extend to include the use of tollways in much the same manner that premium transmission services that provide preferential forwarding can be purchased in data networks.

Those responsible for designing, building and maintaining each of the networks have concerns about reliability and endeavour to provide the most efficient service for the least cost. Efficiency measures in road networks take a number of forms – throughput, number of stops, queue length, fuel consumption – whereas the measures for data networks are usually limited to throughput with some consideration for queue length. In the context of vulnerability, the data network was built to obviate this concern.

It is clear that experts in both fields have much to learn from one-another; however context is the key. In the case of real-life road networks, it is not possible to alleviate congestion through the ‘dropping’ of vehicles out of the network in the same way data networks can or in fact as some microsimulation packages do. Certainly the nature of vehicle and data packets on their respective networks is considerably different. One is self-aware, self-directed and intelligent, whereas data packets are not, so caution needs to be applied when attempting to make some interconnections; yet this should not hinder collaboration. It appears that if certain assumptions are made, such as data packets *are* the masters of their travel because they contain embedded within them their origin and destination and road users having similar information then the models grow toward each other quite comfortably.

Nonetheless it is likely that as the two systems draw closer together the proportion of management and support infrastructure on the road network will increase; it will be interesting to see if the level approaches that of today's data traffic network

Satellite control of vehicle operation for safe and fast travel

**UNIT V SUSPENSION, BRAKES, AERODYNAMICS AND SAFETY**

Air suspension

**Air suspension** is a type of vehicle [suspension](http://en.wikipedia.org/wiki/Suspension_%28vehicle%29) powered by an engine driven or electric air pump or [compressor](http://en.wikipedia.org/wiki/Gas_compressor). This pump pressurizes the air, using compressed air as a spring. Air suspension replaces conventional steel springs. If the engine is left off for an extended period, the car will settle to the ground. The purpose of air suspension is to provide a smooth [ride quality](http://en.wikipedia.org/wiki/Ride_quality) and in some cases [self-leveling](http://en.wikipedia.org/wiki/Self-leveling_suspension).

Vehicles that use air suspension today include models from [Maybach](http://en.wikipedia.org/wiki/Maybach), [Rolls-Royce](http://en.wikipedia.org/wiki/Rolls-Royce_Motor_Cars), [Lexus](http://en.wikipedia.org/wiki/Lexus_LS), Cadillac (GM), [Mercedes-Benz](http://en.wikipedia.org/wiki/Mercedes-Benz_600), [Land Rover/Range Rover](http://en.wikipedia.org/wiki/Land_Rover), [SsangYong](http://en.wikipedia.org/wiki/SsangYong_Chairman), [Audi](http://en.wikipedia.org/wiki/Audi), [Subaru](http://en.wikipedia.org/wiki/Subaru), [Volkswagen](http://en.wikipedia.org/wiki/Volkswagen), and [Lincoln](http://en.wikipedia.org/wiki/Lincoln_%28automobile%29) and [Ford](http://en.wikipedia.org/wiki/Ford), among others. [Citroën](http://en.wikipedia.org/wiki/Citro%C3%ABn) now feature Hydractive suspension, a computer controlled version of their Hydropneumatic system, which features sport and comfort modes, lowers the height of the car at high speeds and continues to maintain ride height when the engine is not running.

The *air suspension* designs from Land Rover, SsangYong, Subaru and some Audi, VW, and Lexus models, feature [height adjustable suspension](http://en.wikipedia.org/wiki/Height_adjustable_suspension) controlled by the driver, suitable for clearing rough terrain. The [Lincoln Continental](http://en.wikipedia.org/wiki/Lincoln_Continental) and [Mark VIII](http://en.wikipedia.org/wiki/Lincoln_Mark_VIII) also featured an air suspension system in which the driver could choose how sporty or comfortable they wanted the suspension to feel. These suspension settings were also linked to the memory seat system, meaning that the car would automatically adjust the suspension to the individual driver. The control system in the Mark VIII also lowered the suspension by about 25 m at speeds exceeding about 100 km/h for improved [aerodynamic](http://en.wikipedia.org/wiki/Aerodynamic) performance. Due to the many advantages air suspensions provide, and with the advancement of new materials and technologies, these systems are being designed on many future platforms. This is especially important as car manufacturers strive to improve gas mileage by reducing weight and utilizing active suspension technology to maximize performance.

In addition to passenger cars, air suspension is broadly used on semi trailers, [trains](http://en.wikipedia.org/wiki/Train) (primarily [passenger trains](http://en.wikipedia.org/wiki/Passenger_trains)) and buses, which are all transportation sectors that helped pioneer the use and design of air suspension. An unusual application was on [EMD](http://en.wikipedia.org/wiki/Electro-Motive_Diesel)'s experimental [Aerotrain](http://en.wikipedia.org/wiki/Aerotrain_%28GM%29).

##  Custom applications

Over the last decade or so air suspension has become extremely popular in the custom automobile culture: street rods, trucks, cars, and even motorcycles may have air springs. They are used in these applications to provide an adjustable suspension which allows vehicles to sit extremely low, yet be able rise to a level high enough to maneuver over obstacles and inconsistencies in the roadways (and parking lots). These systems generally employ small, electric or engine-driven air compressors which sometimes fill an on-board air receiver tank which stores compressed air for use in the future without delay. High-pressured industrial gas bottles (such as [nitrogen](http://en.wikipedia.org/wiki/Nitrogen) or [carbon dioxide](http://en.wikipedia.org/wiki/Carbon_dioxide) tanks used to store shielding gases for welding) are sometimes used in more radical air suspension setups. Either of these reservoir systems may be fully adjustable, being able to adjust each wheel's air pressure individually. This allows the user to tilt the vehicle side to side, front to back, in some instances "hit a 3-wheel" (contort the vehicle so one wheel lifts up from the ground) or even "hop" the entire vehicle into the air. When a pressure reservoir is present, the flow of air or gas is commonly controlled with pneumatic solenoid valves. This allows the user to make adjustments by simply pressing a momentary-contact electric button or switch.

The installation and configuration of these systems varies for different makes and models but the underlying principle remains the same. The metal spring (coil or leaf) is removed, and an air bag, also referred to as an air spring, is inserted or fabricated to fit in the place of the factory spring. When air pressure is supplied to the air bag, the suspension can be adjusted either up or down (lifted or lowered).

For vehicles with leaf spring suspension such as pickup trucks, the leaf spring is sometimes eliminated and replaced with a multiple-bar linkage. These bars are typically in a trailing arm configuration and the air spring may be situated vertically between a link bar or the axle housing and a point on the vehicle's frame. In other cases, the air bag is situated on the opposite side of the axle from the main link bars on an additional cantilever member. If the main linkage bars are oriented parallel to the longitudinal (driving) axis of the car, the axle housing may be constrained laterally with either a [Panhard rod](http://en.wikipedia.org/wiki/Panhard_rod) or [Watt's linkage](http://en.wikipedia.org/wiki/Watt%27s_linkage). In some cases, two of the link bars may be combined into a triangular shape which effectively constrains the vehicles axle laterally.

Often, owners may desire to lower their vehicle to such an extent that they must cut away portions of the frame for more clearance. A reinforcement member commonly referred to as a C-notch is then bolted or welded to the vehicle frame in order to maintain structural integrity. Specifically on pickup trucks, this process is termed "notching" because a portion (notch) of the cargo bed may also be removed, along with the wheel wells, to provide maximum axle clearance. For some, it is desirable to have the vehicle so low that the frame rests on the ground when the air bags are fully deflated.

## [[edit](http://en.wikipedia.org/w/index.php?title=Air_suspension&action=edit&section=3)] Common air suspension problems

**Air bag or air strut failure** is usually caused by wet rot, due to old age, or moisture within the air system that damages it from the inside. Air ride suspension parts may fail because rubber dries out. Punctures to the air bag may be caused from [debris on the road](http://en.wikipedia.org/wiki/Debris_on_the_road). With custom applications, improper installation may cause the air bags to rub against the vehicle's frame or other surrounding parts, damaging it. The over-extension of an airspring which is not sufficiently constrained by other suspension components such as a shock absorber may also lead to the premature failure of an airspring through the tearing of the flexible layers.Failing of the Air bag may also result in completely immobilizing the vehicle. As the vehicle will rub against the ground or be too high to move.

**Air line failure** is a failure of the tubing which connects the air bags or struts to the rest of the air system, and is typically DOT-approved nylon air brake line. This usually occurs when the air lines, which must be routed to the air bags through the chassis of the vehicle, rub against a sharp edge of a chassis member or a moving suspension component, causing a hole to be formed. This mode of failure will typically take some time to occur after the initial installation of the system as the integrity of a section of air line is compromised to the point of failure due to the rubbing and resultant abrasion of the material. An air line failure may also occur if a piece of road debris hits an air line and punctures or tears it.

**Compressor failure** is primarily due to leaking air springs or air struts. The compressor will burn out trying to maintain the correct air pressure in a leaking air system. Compressor burnout may also be caused by moisture from within the air system coming into contact with its electronic parts.

In **Dryer failure** the dryer, which functions to remove moisture from the air system, eventually becomes saturated and unable to perform that function. This causes moisture to build up in the system and can result in damaged air springs and/or a burned out compressor.

Closed loop suspension, compensated suspension

Anti skid braking system

Retarders

Regenerative braking

A **regenerative brake** is an [energy recovery](http://en.wikipedia.org/wiki/Energy_recovery) mechanism which slows a vehicle by converting its [kinetic energy](http://en.wikipedia.org/wiki/Kinetic_energy) into another form, which can be either used immediately or stored until needed. This contrasts with conventional braking systems, where the excess kinetic energy is converted to heat by friction in the [brake linings](http://en.wikipedia.org/wiki/Brake_linings) and therefore wasted.

The most common form of regenerative brake involves using an [electric motor](http://en.wikipedia.org/wiki/Electric_motor) as an electric generator. In electric [railways](http://en.wikipedia.org/wiki/Rail_transport) the generated electricity is fed back into the [supply system](http://en.wikipedia.org/wiki/Railway_electrification_system), whereas in [battery electric](http://en.wikipedia.org/wiki/Battery_electric_vehicle) and [hybrid electric](http://en.wikipedia.org/wiki/Hybrid_vehicle) vehicles, the energy is stored in a [battery](http://en.wikipedia.org/wiki/Battery_%28electricity%29) or bank of [capacitors](http://en.wikipedia.org/wiki/Capacitor) for later use. Energy may also be stored via [pneumatics](http://en.wikipedia.org/wiki/Compressed_air_energy_storage), [hydraulics](http://en.wikipedia.org/wiki/Hydraulic_hybrid) or the kinetic energy of a rotating [flywheel](http://en.wikipedia.org/wiki/Flywheel_energy_storage).

**The motor as a generator**

Vehicles driven by [electric motors](http://en.wikipedia.org/wiki/Electric_motor) use the motor as a [generator](http://en.wikipedia.org/wiki/Electrical_generator) when using regenerative braking: it is operated as a generator during braking and its output is supplied to an electrical load; the transfer of energy to the load provides the braking effect.

Regenerative braking is used on hybrid gas/electric automobiles to recoup some of the energy lost during stopping. This energy is saved in a storage battery and used later to power the motor whenever the car is in electric mode.

Early examples of this system were the [front-wheel drive](http://en.wikipedia.org/wiki/Front-wheel_drive) conversions of horse-drawn [cabs](http://en.wikipedia.org/wiki/Cabriolet_%28carriage%29) by Louis Antoine Krieger (1868–1951). The Krieger electric [landaulet](http://en.wikipedia.org/wiki/Landaulet) had a drive motor in each front wheel with a second set of parallel windings ([bifilar coil](http://en.wikipedia.org/wiki/Bifilar_coil)) for regenerative braking. In England, the Raworth system of "regenerative control" was introduced by tramway operators in the early 1900s, since it offered them economic and operational benefits as explained by A. Raworth of Leeds in some detail. These included tramway systems at Devonport (1903), Rawtenstall, Birmingham, Crystal Palace-Croydon (1906) and many others. Slowing down the speed of the cars or keeping it in hand on descending gradients, the motors worked as generators and braked the vehicles. The tram cars also had wheel brakes and track slipper brakes which could stop the tram should the electric braking systems fail. In several cases the tram car motors were shunt wound instead of series wound, and the systems on the Crystal Palace line utilized series-parallel controllers. Following a serious accident at Rawtenstall, an embargo was placed on this form of traction in 1911. Twenty years later, the regenerative braking system was reintroduced.

Regenerative braking has been in extensive use on railways for many decades. The Baku-Tbilisi-Batumi railway (Transcaucasian railway or Georgian railway) started utilizing regenerative braking in the early 1930s. This was especially effective on the steep and dangerous Surami Pass. In Scandinavia the Kiruna to Narvik railway carries iron ore from the mines in Kiruna in the north of Sweden down to the port of Narvik in Norway to this day. The rail cars are full of thousands of tons of iron ore on the way down to Narvik, and these trains generate large amounts of electricity by their regenerative braking. From Riksgränsen on the national border to the Port of Narvik, the trains use only a fifth of the power they regenerate. The regenerated energy is sufficient to power the empty trains back up to the national border. Any excess energy from the railway is pumped into the power grid to supply homes and businesses in the region, and the railway is a net generator of electricity.

An [Energy Regeneration Brake](http://en.wikipedia.org/wiki/Energy_Regeneration_Brake) was developed in 1967 for the [AMC](http://en.wikipedia.org/wiki/American_Motors) [Amitron](http://en.wikipedia.org/wiki/Amitron). This was a completely [battery](http://en.wikipedia.org/wiki/Battery_electric_vehicle) powered urban [concept car](http://en.wikipedia.org/wiki/Concept_car) whose batteries were recharged by regenerative braking, thus increasing the range of the automobile.

Many modern hybrid and electric vehicles use this technique to extend the range of the battery pack. Examples include the [Toyota Prius](http://en.wikipedia.org/wiki/Toyota_Prius), [Honda Insight](http://en.wikipedia.org/wiki/Honda_Insight), the [Vectrix](http://en.wikipedia.org/wiki/Vectrix) electric maxi-scooter, and the [Chevrolet Volt](http://en.wikipedia.org/wiki/Chevrolet_Volt).

**Limitations**

Traditional [friction](http://en.wikipedia.org/wiki/Friction)-based braking is used in conjunction with mechanical regenerative braking for the following reasons:

* The regenerative braking effect drops off at lower speeds; therefore the friction brake is still required in order to bring the vehicle to a complete halt. Physical locking of the rotor is also required to prevent vehicles from rolling down hills.
* The friction brake is a necessary back-up in the event of failure of the regenerative brake.
* Most road vehicles with regenerative braking only have power on some wheels (as in a [two-wheel drive](http://en.wikipedia.org/wiki/Two-wheel_drive) car) and regenerative braking power only applies to such wheels because they are the only wheels linked to the drive motor, so in order to provide controlled braking under difficult conditions (such as in wet roads) friction based braking is necessary on the other wheels.
* The amount of electrical energy capable of dissipation is limited by either the capacity of the supply system to absorb this energy or on the state of charge of the battery or capacitors. No regenerative braking effect can occur if another electrical component on the same supply system is not currently drawing power and if the battery or capacitors are already charged. For this reason, it is normal to also incorporate dynamic braking to absorb the excess energy.
* Under emergency braking it is desirable that the braking force exerted be the maximum allowed by the friction between the wheels and the surface without slipping, over the entire speed range from the vehicle's maximum speed down to zero. The maximum force available for acceleration is typically much less than this except in the case of extreme high-performance vehicles. Therefore, the power required to be dissipated by the braking system under emergency braking conditions may be many times the maximum power which is delivered under acceleration. Traction motors sized to handle the drive power may not be able to cope with the extra load and the battery may not be able to accept charge at a sufficiently high rate. Friction braking is required to dissipate the surplus energy in order to allow an acceptable emergency braking performance.

For these reasons there is typically the need to control the regenerative braking and match the friction and regenerative braking to produce the desired total braking output. The GM [EV-1](http://en.wikipedia.org/wiki/General_Motors_EV1) was the first commercial car to do this. Engineers Abraham Farag and Loren Majersik were issued two patents for this [*brake-by-wire*](http://en.wikipedia.org/wiki/Brake-by-wire) technology.

**Electric railway vehicle operation**

During braking, the [traction motor](http://en.wikipedia.org/wiki/Traction_motor) connections are altered to turn them into electrical generators. The motor fields are connected across the main traction generator (MG) and the motor armatures are connected across the load. The MG now excites the motor fields. The rolling locomotive or multiple unit wheels turn the motor armatures, and the motors act as generators, either sending the generated current through onboard resistors ([dynamic braking](http://en.wikipedia.org/wiki/Dynamic_braking)) or back into the supply (regenerative braking).

For a given direction of travel, current flow through the motor armatures during braking will be opposite to that during motoring. Therefore, the motor exerts [torque](http://en.wikipedia.org/wiki/Torque) in a direction that is opposite from the rolling direction.

Braking effort is proportional to the product of the magnetic strength of the field windings, times that of the armature windings.

Savings of 17% are claimed for [Virgin Trains](http://en.wikipedia.org/wiki/Virgin_Trains) [Pendolinos](http://en.wikipedia.org/wiki/British_Rail_Class_390). There is also less wear on friction braking components. The [Delhi Metro](http://en.wikipedia.org/wiki/Delhi_Metro) saved around 90,000 tons of [carbon dioxide](http://en.wikipedia.org/wiki/Carbon_dioxide) (CO2) from being released into the atmosphere by regenerating 112,500 megawatt hours of electricity through the use of regenerative braking systems between 2004 and 2007. It is expected that the Delhi Metro will save over 100,000 tons of CO2 from being emitted per year once its phase II is complete through the use of regenerative braking.

Another form of simple, yet effective regenerative braking is used on the [London Underground](http://en.wikipedia.org/wiki/London_Underground) which is achieved by having small slopes leading up and down from stations. The train is slowed by the climb, and then leaves down a slope, so kinetic energy is converted to [gravitational potential energy](http://en.wikipedia.org/wiki/Gravitational_potential) in the station.

Electricity generated by regenerative braking may be fed back into the traction power supply; either offset against other electrical demand on the network at that instant, or stored in [lineside storage systems](http://en.wikipedia.org/wiki/Kinetic_Traction_Systems) for later use.

**Comparison of dynamic and regenerative brakes**

Dynamic brakes ("rheostatic brakes" in the UK), unlike regenerative brakes, dissipate the electric energy as heat by passing the current through large banks of variable [resistors](http://en.wikipedia.org/wiki/Resistor). Vehicles that use dynamic brakes include [forklifts](http://en.wikipedia.org/wiki/Forklift_truck), [Diesel-electric](http://en.wikipedia.org/wiki/Diesel-electric_transmission) [locomotives](http://en.wikipedia.org/wiki/Locomotive), and [streetcars](http://en.wikipedia.org/wiki/Tram). This heat can be used to warm the vehicle interior, or dissipated externally by large [radiator](http://en.wikipedia.org/wiki/Radiator)-like cowls to house the resistor banks.

The main disadvantage of regenerative brakes when compared with dynamic brakes is the need to closely match the generated current with the supply characteristics and increased maintenance cost of the lines. With DC supplies, this requires that the voltage be closely controlled. Only with the development of [power electronics](http://en.wikipedia.org/wiki/Power_electronics) has this been possible with AC supplies, where the supply frequency must also be matched (this mainly applies to locomotives where an AC supply is [rectified](http://en.wikipedia.org/wiki/Rectifier) for DC motors).

A small number of [mountain railways](http://en.wikipedia.org/wiki/Mountain_railway) have used [3-phase](http://en.wikipedia.org/wiki/Three-phase) power supplies and 3-phase [induction motors](http://en.wikipedia.org/wiki/Induction_motors). This results in a near constant speed for all trains as the motors rotate with the supply frequency both when motoring and braking.

**Kinetic Energy Recovery Systems**

Kinetic Energy Recovery Systems (KERS) were used for the motor sport [Formula One](http://en.wikipedia.org/wiki/Formula_One)'s [2009 season](http://en.wikipedia.org/wiki/2009_Formula_One_season), and are under development for road vehicles. KERS was abandoned for the 2010 Formula One season, but re-introduced for the 2011 season. As of the 2011 season, 9 teams are using KERS, with 3 teams having not used it so far in a race. One of the main reasons that not all cars use KERS is because it adds an extra 25 kilograms of weight, while not adding to the total car weight, it does incur a penalty particularly seen in the qualifying rounds, as it raises the car's center of gravity, and reduces the amount of [ballast](http://en.wikipedia.org/wiki/Ballast_weight) that is available to balance the car so that it is more predictable when turning. FIA rules also limit the exploitation of the system. The concept of transferring the vehicle’s kinetic energy using [flywheel energy storage](http://en.wikipedia.org/wiki/Flywheel_energy_storage) was postulated by physicist [Richard Feynman](http://en.wikipedia.org/wiki/Richard_Feynman) in the 1950sand is exemplified in complex high end systems such as the [Zytek](http://en.wikipedia.org/wiki/Zytek), Flybrid. Torotrak and Xtrac used in F1 and simple, easily manufactured and integrated [differential](http://en.wikipedia.org/wiki/Differential_%28mechanical_device%29) based systems such as the Cambridge Passenger/Commercial Vehicle Kinetic Energy Recovery System (CPC-KERS).

Xtrac and Flybrid are both licensees of Torotrak's technologies, which employ a small and sophisticated ancillary gearbox incorporating a [continuously variable transmission](http://en.wikipedia.org/wiki/Continuously_variable_transmission) (CVT). The CPC-KERS is similar as it also forms part of the driveline assembly. However, the whole mechanism including the flywheel sits entirely in the vehicle’s hub (looking like a drum brake). In the CPC-KERS, a differential replaces the CVT and transfers torque between the [flywheel](http://en.wikipedia.org/wiki/Flywheel), drive wheel and road wheel.

Safety gauge air bags

Crash resistance

Aerodynamics for modern vehicles

Most of the information about car aerodynamics seems to be centered around generating downforce. While this may be needed for race cars, the average 3000+ pound car driving at speeds below 90 MPH does not need to be concerned with downforce. If you are trying to improve the efficiency of your vehicle, reducing the coefficient of drag (Cd) should be the main concern.

**Rationale**
In this day and age of expensive fuel and inefficient vehicles, it makes sense both economically and ecologically to conserve as much fuel as possible. To accomplish this, you could go out and buy another car with better mileage, but there are other options. This article focuses on how to optimize your current vehicle.

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| The example vehicle is a 1998 Nissan Maxima. This is a rather boxy 4 door sedan with quite a lot of ground clearance and a 190hp 6 cyl engine, that is rated at 26MPG highway by [fueleconomy.gov](http://www.fueleconomy.gov/), but gets around 21MPG in mixed driving.   | http://www.recumbents.com/car_aerodynamics/maxima_side.jpg1998 Maxima Before mods |

For highway driving conditions, it is estimated that driveline uses about 15% of the total energy to required to push your vehicle down the highway, tire rolling resistance represents about 25%, and *air drag is about 60%!*  While the traditional sources advocate saving fuel by driving less or driving slower, there are greater gains that can be made by modifying the aerodynamics, engine, and rolling resistance of  the vehicle. These modifications are not without cost, but are within reach of even those of us with meager incomes. All of the aerodynamic modifications mentioned here can be performed for under $1000, providing you are willing to do the work yourself.

It may take a couple of years for the dollars expended in making the modifications to be paid for by the savings of gas, but a payback in that timeframe is easy to rationalize to yourself, and others.

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| **Vehicle** | **Configuration** | **MPG** | **Gas cost/year** | **Savings/Year** |
| 6cyl sedan | stock | 26 | $1615 | $0 |
| 4cyl econobox | stock | 40 | $1050 | $565 |
| 4Cyl hybrid | stock | 50 | $840 | $755 |
| 6cyl sedan | aero mods | 34.5 | $1215 | $400 |
| Savings using the 6cyl sedan as "baseline", and using gas costs of $2.80/gal and 15,000 miles/year |

As seen in the table above, purchasing a 4cyl econobox or a 4cyl hybrid to replace your comfy (and paid for!) 6cyl sedan would save a bunch of money every year, but not enough to pay for the replacement. If you can afford it, it does make the best sense from an environmental point of view, but purchasing an expensive new car just to save $900 per year in gas is not an option many of us can afford.  To most of us it makes more sense economically to keep driving our current gas guzzler. Modifying the sedan to get 25% better mileage, for under $1000 would start paying back after only two years. None of the modifications below in itself will provide a huge change in efficiency, but 3% here and 5% there all add up to big numbers eventually.

The 25% mileage improvement figure above is an estimate based on results I have seen of a [70 MPG Honda Civic](http://www.wisil.recumbents.com/wisil/Bryant.jpg) (Bryant Tucker), and a 32 MPG truck, (Phil Know).  This would be an improvement in highway mileage only. The $1000 project cost estimate would be spent on:

* Eibach height adjustable springs - ~$300.
* Aluminum sheet and hardware to build a belly pan and other aero mods - ~$300
* The remainder would be for other stuff like [measuring the mileage](http://www.recumbents.com/car_aerodynamics/#Measuring%20your%20mileage).

Manufacturers design most cars for looks, with aerodynamics as an afterthought. As such, much can be gained by tweaking the aerodynamics of these vehicles. The unit of measurement for aerodynamics is called the "coefficient of drag" or Cd. The Cd value tells us how efficiently the vehicle slips through the wind. Another common measurement multiplies the Cd times the total frontal area of the vehicle. This is called CdA. Check [this site](http://www.mayfco.com/tbls.htm) for the Cd value for different cars. Lower Cd means better Mileage!

**Here are** **things that can be done to improve your vehicle's aerodynamics:**

* Lower the car - Lowering the car reduces the effective frontal area, increasing efficiency. Note that this only works up to a certain point. There will be an ideal ride height for each car. According to [this article](http://www.wisil.recumbents.com/wisil/demma/aero_review.htm), 2.7" ground clearance is a good minimum height to shoot for. According to Mercedes, "Lowering the ride height at speed results in a 3-percent improvement in drag."
* Remove that wing - Many "sports" cars have a non-functional wing on the back. Removing it will improve the fuel economy. The exceptions are the small rear fairings that are designed to detach the airflow from a rounded trunk.
* Clean up the underside of the car. - Installation of a "body pan", while a labor intensive operation, will provide a significant improvement in mileage. [More..](http://www.recumbents.com/car_aerodynamics/#Body%20pan%20notes:).
* If a body pan is not practical, an air dam will redirect air that would normally pile up under the car causing drag. Not as good as a body pan, but better than nothing. Should be combined with side fairings.
* Fair the wheel wells. - Yeah, this looks funny, but completely covering the rear wheel well will help improve efficiency. While the front wheel can not easily be completely faired due to clearances needed for turning, a partial fairing can be made. In addition, fairings can be added in front and behind the tires to help transition the air around these large appendages.
* Clean up the front of the car. Basically the smoother the better. If the car has a large air intake under the bumper, it may not need that opening above the bumper (they are often just styling cues). An aerodynamic plastic, composite, or foam and duct tape panel can be built to cover the opening.
* Remove the side view mirrors and instead use a remote camera system.
* Replace large whip antennas with smaller powered antennas.
* Vehicles with steep windshields can benefit from a hood fairing to help smooth the transition of air between the hood and windshield.
* A small "tail cone" can be affixed the the rear bumper to help transition the air from under the car.
* Side fairings can be used to clean up the lower half of the body between the tires. [More...](http://www.recumbents.com/car_aerodynamics/#Car%20side%20fairings)


1998 Maxima after proposed modifications. Hover mouse over body mods to see notes.

**Additional mods for trucks:**
If you need the utility of a truck, there are things that can be done to improve their efficiency in addition to the items noted above. Most notably, cover the bed! A flat hard cover will help some, but a custom aero cover is much more efficient. Experimentation has shown that simple removal of the truck bed door does not provide better mileage.

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| **Additional mods for Vans and SUVs::**A new spoiler design has been shown to reduce  drag and lift significantly on bluff-backed vehicles such as minivans and SUVs. Simulations showed that aerodynamic drag on a mini-van moving at 67 mph were reduced by 5% when the new spoiler was attached. This rear spoiler acts like a diffuser when it is attached to the back of a vehicle, making the pressure on the back of the vehicle higher than without it. That's a good thing![Full technical paper](http://www.sae.org/technical/papers/2006-01-1631) | http://www.recumbents.com/car_aerodynamics/Inchul_Kim_van_spoiler_sm.png |

**Body Pans:**
A body pan fairs the underside of the vehicle. This becomes increasingly important as the vehicle gets closer to the ground. The pan ideally covers the entire underside of the car, but this may be impractical in many cases, so the idea is to make it as smooth as possible. Covering the exhaust system can lead to heat buildup between the belly pan and the floorboards. In general it's a good idea to create a heat shield/tunnel extending from the engine compartment to the rear of the vehicle. This will serve to seal in as much of the heat as possible. High pressure from the engine compartment will force air down the tunnel and out the rear of the car. Also, louvers may be cut into the body pan in areas where more heat needs to be released, such as along the route of the exhaust pipe. NACA ducts do not work well for this application as they are designed as devices to scavenge incoming air without disturbing the airflow, not as an air exhaust device. Engine airflow needs to be retained, but generally there are large enough opening between the engine compartment and the front wheels to give good engine airflow, even with the underside of the engine covered.

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|  | Be sure to make the areas where maintenance will occur easily accessible, especially oil pan drain and oil filter access. The belly pad should be parallel to the ground until just past the rear axle, then it should gradually curve upward to meet with the underside of the rear fascia of the car. Even the most aerodynamic cars manufactured today, for example the Toyota Prius pictured here which is touted as having a full body pan, can be cleaned up extensively.  |

**Car side fairings - "ground effects":**
Most car bodies slope inward at the sides until they are inside of the tires toward the bottom of the vehicle, leaving a large gap between the tires. Mud flaps are spiffy but only serve to make the gaps bigger. This all adds up to a lot of aerodynamic inefficiency. Side fairings "fill the gap", transition the air around the tires and keep side winds from flowing under the car. If you are driving 60 MPH with a 20MPH side wind, 33% of the wind forces are on the side of the car, so making the side of the car aerodynamic is almost as important as improving the aero qualities of the car front. Stylists have created "ground effects" that claim to be aerodynamic, but really aren't. Instead, a flat panel slightly wider than the tires can be installed to help fair the sides of the car. Check out the side of NASCAR vehicles for reference. This panel should extend down to meet with the body pan. The corner where the two panels meet should be rounded if possible. The hardest part of this task will be the door cutouts and clearances.  Side fairings also transition the air around those large appendages called tires.

**Turbulators, etc:**
In areas where the body transitions at a rate of more than 12 degrees, turbulator strips, vortex generators, diffusers, very short fairings or other devices can be used to "trip the airflow".

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| The idea is that areas like the transition between the roof and rear window on the average car creates a large vortex. Any large vortices effectively grab the car and try to hold it back as it tries to slip through the air. If the air that makes up the vortex can be "tripped" before it leaves the back of the car, it will make smaller vortices, which will have a smaller effect on the overall aerodynamics of the vehicle. Measurement of the effects of these devices at highway speeds has been difficult to obtain. | http://www.recumbents.com/car_aerodynamics/diffuser_sm.jpgVortex generator above a Mitsubishi rear window (photo by Mitsubishi) |

**Tires:**
Tire rolling resistance (RR) also plays a large part in the mileage of a vehicle. Running your tire pressure at higher pressures will help somewhat (do not exceed rated pressures printed on the side of the tire), but specially designed low RR tires will help more. The typical 20% reduction in RR from a low RR tire can result in fuel savings of  2% to 4%. Here are some [low rolling resistance tires tested by Green Seal](http://www.greenseal.org/resources/reports/CGR_tire_rollingresistance.pdf) and a [report by the US government](http://books.nap.edu/openbook.php?record_id=11620&page=60). Green Seal notes that a typical Ford focus can increase it's mileage by 2 MPG (from 30 to 32MPG) just by replacing the stock tires with low RR tires. A caveat however, is that low RR tires do not handle as well as normal "sport" tires.

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| **Wheel covers:**Unfortunately, the coolest looking chrome spoked wheels are really bad aerodynamically. The best wheel cover is a slightly convex, completely smooth cover that fits flush with the tire. "Racing disks" like the one pictured here from [JC Whitney](http://www.jcwhitney.com) or something similar can be snapped onto most wheels for a quick aero fix. |  |

**Temperature**Air temperature has a large effect on gas mileage. Part of this is due to rolling resistance. Because tires lose one PSI for every 10 degrees, and tires lose elasticity in colder weather, rolling resistance increases as temperature decreases. This means the tires don't roll as well when it's cold out. Air density also increases as temperature drops. Ralph Kenyon worked out the math to calculate how much this effects gas mileage [here](http://www.xenodochy.org/ex/index.html?abstract/mileage). His works suggests that gas mileage drops 2% for every 10 degrees F below 90 degrees due to air density alone. This means that at 40 degrees F there will be a 10% decrease in mileage.

**Engine efficiency:**
Modern engines are fairly efficient. Plenty of claims for products to improve your vehicles engine efficiency have been made, but few do anything worthwhile. The ones that do work are generally pricey. If you want to spend the bucks, you can:

* Install headers or a "Y pipe" to scavenge the exhaust gasses. Do not remove the catalytic converter.
* Install efficient mufflers. Note that engines do require backpressure to function properly.
* Install Under-drive pulley. Note that this will reduce engine cooling and and battery recharging. Most vehicles are designed for worst case scenarios though, so this is usually ok unless you have a 3 kilowatt stereo.
* Install a cold air intake. Most air intake systems are designed to be quiet, not efficient.
* Install a high flow air filter.
* If the radiator fan is driven off of the engine by belts, replace it with thermostatically controlled electric fans.
* Install a transmission with taller gears. Once you have made your vehicle more aero, it won't need the power that the extra RPMs provided. Taller gears mean that the engine RPMs will be lower, which equates to less gas used.

Note that due to differences in how engines operate, changing the intake or exhaust system may not help the mileage. Generally they don't hurt it, but you may get lower mileage due to the tendency to drive more aggressively when you can hear the engine making cool noises. Measuring is key.

**Measuring your mileage:**
So, you have decided to terrorize your car, and are not too concerned about what your neighbors will think. Now, how do you figure out if what you did helps or hurts your mileage? You have a couple choices.

* Record the amount of gas and your mileage and do the math. Here's how:
  1) Fill up your car. Record the mileage.
  2) Next time you fill up, record the mileage and the amount of gas.
  3) Latest mileage minus original mileage = number of miles driven
  4) Number of miles driven divided by amount of gas = miles per gallon
This is the cheapest thing to do, but takes a long time and is not very granular.
* Buy a mileage measurement device. [I like the Scangauge II](http://www.scangauge.com/). $159 and it just plugs into the OBD port of your car. It works on almost all cars newer than 1995. New is the [PLX Kiwi MPG](http://www.plxkiwi.com/) device for only $90, though they seem to always be on backorder.

Safety systems, materials and standards