Hydrocarbon-fueled internal combustion engines: "the worst form of vehicle propulsion… except for all the other forms"

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Introduction

Hydrocarbon-fueled internal combustion engines have been the workhorse of land, air and sea transportation system propulsion for nearly 100 years, for power levels as small as 0.005 hp (Figure 1, left) and as large as 100,000 hp (Figure 1, right). In this paper, the reasons why this is so and some of the challenges associated with changing the transportation system paradigm are discussed.

First a definition of an internal combustion engine is needed. For the purposes of this paper:

> *An internal combustion engine is a heat engine (a device in which thermal energy is converted into mechanical energy) in which the heat source is a combustible mixture that also serves as the working fluid. The working fluid in turn is used either to (1) produce shaft work by pushing on a piston or turbine blade that in turn drives a rotating shaft or (2) create a high-momentum fluid that is used directly for propulsive force.*

Examples of internal combustion engines include gasoline, LPG or natural-gas fueled premixed-

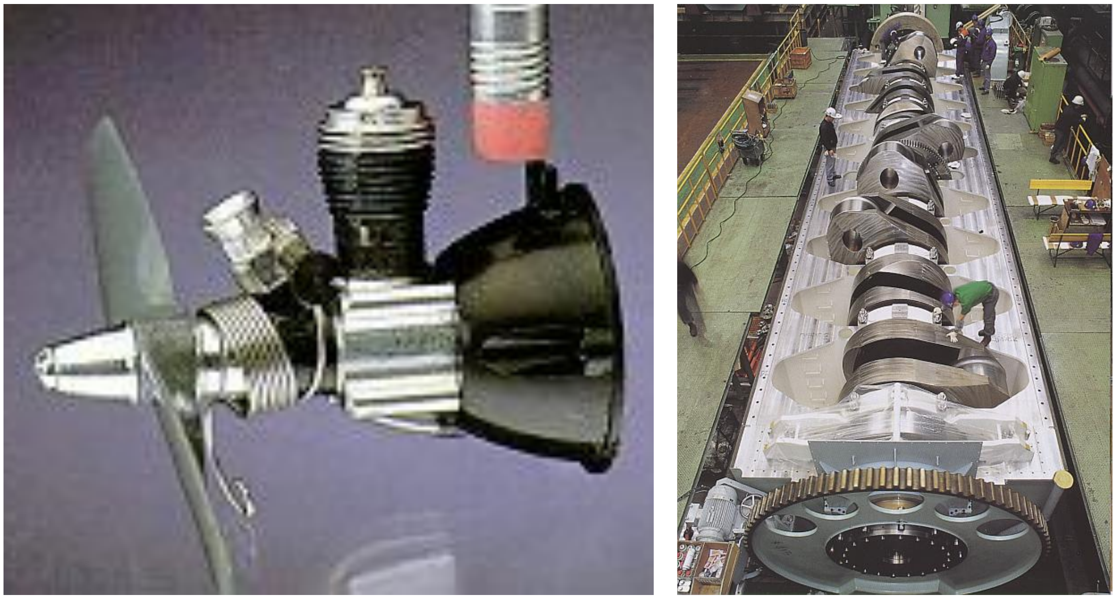

Figure 1. Worlds' smallest and largest commercially-available internal combustion engines. Left: Cox Tee Dee 010 two-stroke engine, used in model airplanes; specifications: 1 cylinder; weight 0.49 oz; maximum power about 0.005 horsepower at 30,000 rpm; fuel: castor oil (10 - 20%), nitromethane (0 - 50%), balance methanol; thermal efficiency less than 5%. *Right: Wartsila-Sulzer RTA96-C turbocharged two-stroke engine, built in Japan, used in container ships; specifications: 14 cylinders; weight 2300 tons; maximum power 108,920 horsepower at 102 rpm; maximum torque 5,608,312 ft lb @ 102 RPM; fuel: diesel; thermal efficiency 52%.*

charge reciprocating piston engines; diesel-fueled nonpremixed-charged reciprocating piston engines; gas turbines; and rocket engines. An “internal combustion engine family tree” is shown in Fig. 2. Examples of heat engines that are not internal combustion engines include coal, natural gas or solar-heated steam-cycle engines (because the working fluid is water, not a combustible mixture). Also, electric motors are not heat engines and thus not internal combustion engines.

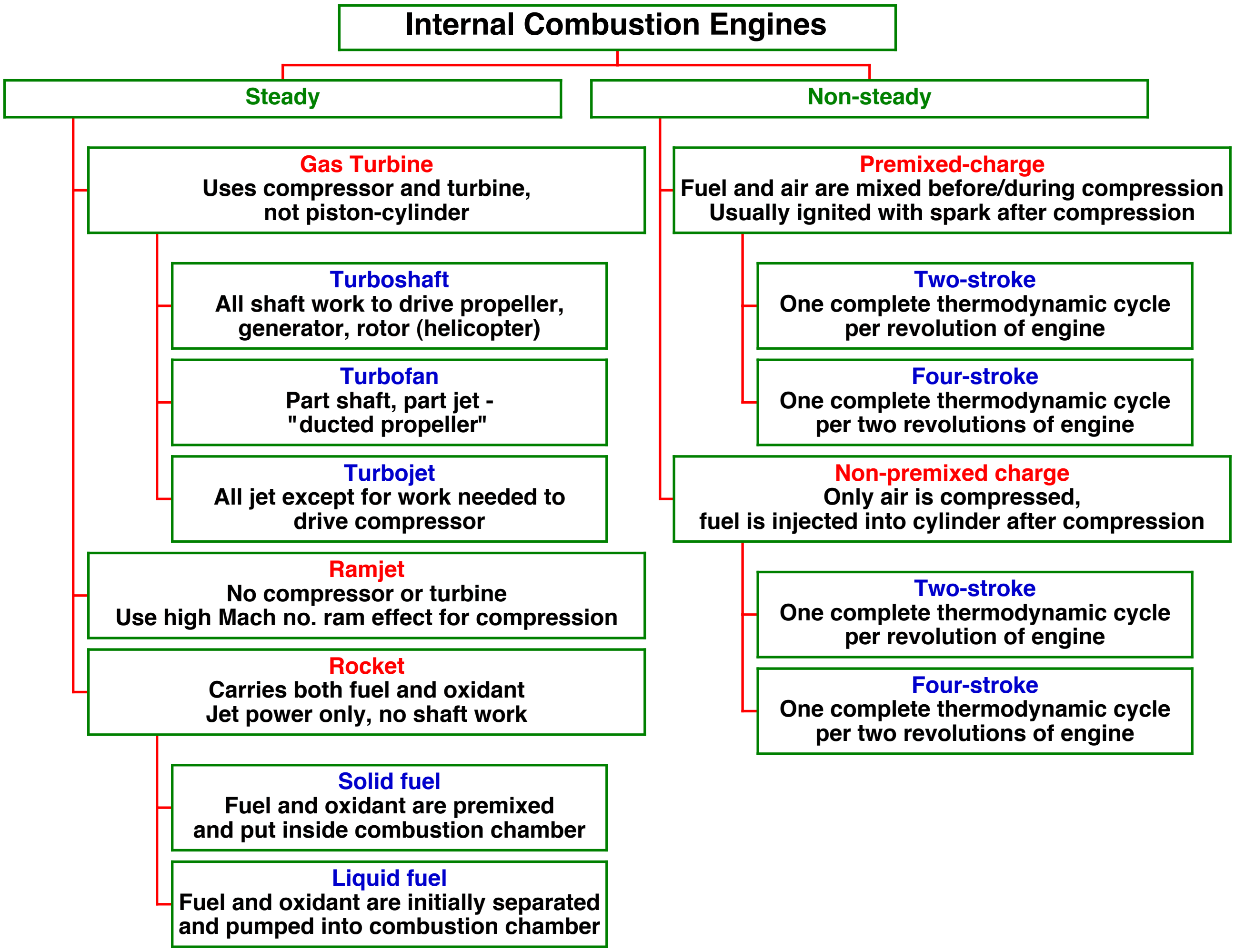

Figure 2. Internal combustion engine family tree

History

It is useful to start with a brief history of the internal combustion engine and some of the key technological and societal developments that have led us to the current state of technology and practice.

Perhaps the first major step towards the use of hydrocarbon fueled internal combustion engines was the discovery of “large” amounts of petroleum in 1859 at Drake’s Well, Titusville, Pennsylvania (Fig. 3, left). An “astounding” 20 barrels per day of oil was produced. This and subsequent petroleum discoveries led to the decline of the whale oil industry, but the significance to transportation was minimal at the time, since transportation engines were dominated by coal- or wood-fired steam engines for railroads and ships.

The next major step was the invention of the first practical internal combustion engine by Nicholas Otto in 1876. Otto's engine used a premixture of gaseous fuel (carbon monoxide and hydrogen, produced by burning coal under very air-deficient conditions) and air that was compressed in a piston/cylinder apparatus and ignited by a pilot flame. In 1885 Gottlieb Daimler and Wilhelm Maybach invented the carburetor and Karl Benz the spark ignition system, making possible the use of liquid fuels in moving vehicles. Essentially the same design (piston/cylinder with connecting rod and crankshaft; 4-stroke cycle; intake and exhaust valves; spark ignition) is used in automotive engines today. Otto's engine produced 2 horsepower (hp) and weighed 1250 pounds. Otto recognized that more compression of the fuel-air mixture would result in more power and better fuel efficiency, but the compression ratio was limited to 2.5:1 because of engine "knocking" (violent explosion of the fuel-air mixture during compression, before spark ignition) if higher compression ratios were tried. With this compression ratio, the measured thermal efficiency (ratio of useful work output to fuel energy input) was 14%, compared to a theoretical value of 27%. In other words, the theoretical efficiency was 1.9 times higher than the actual efficiency. Mainly because of better fuels, today's engines use a compression ratio of typically 8:1 and are still limited by engine knock. For this compression ratio, the typical efficiency is 30% compared to a theoretical value of 52%, thus the theoretical efficiency is 1.7 times the actual efficiency. Thus we have only achieved a very slight decrease (1.7 vs. 1.9) in the parasitic energy losses in the last 130 years.

To avoid the knocking problem, Rudolf Diesel introduced the non-premixed charge engine in 1897. In Diesel's engine, only air, not a fuel-air mixture was compressed, thus there was no knock-induced limitation on the compression ratio. Liquid fuel was injected directly into the cylinder after compression and spontaneously ignited due to the high temperature of the highly compressed gas. This higher compression ratio led to higher thermal efficiencies but, for reasons too lengthy to be discussed here, produced less power for a *given size and weight of engine*. (One typically thinks of Diesel engines as being more powerful than gasoline engines, but this is only because they are typically much larger than gasoline engines.)

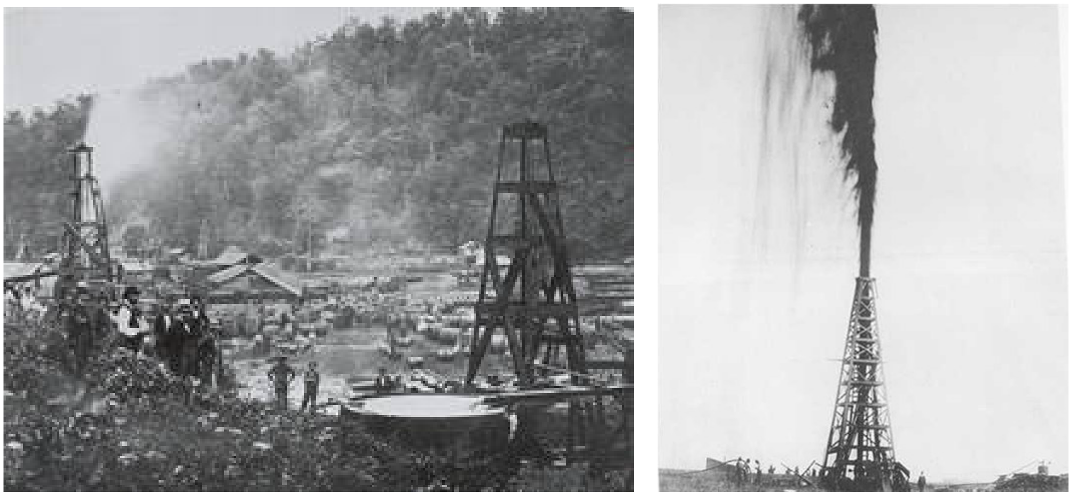

Figure 3. Left: Drake's Well, Titusville, PA; right: Spindletop Dome, TX.

A very important milestone in the evolution of internal combustion engines was the discovery in 1901 of a vast reservoir of oil at Spindletop Dome in east Texas. The Lucas #1 gusher (Figure 3, right) produced an astounding (note the lack of quotes this time) 100,000 barrels of oil per day, and virtually ensured that the "Second Industrial Revolution" would be fueled by oil, not coal or wood. That and the discovery of even more massive oil reserves in the Middle East in the 1930's are the cornerstones of our transportation economy today, not to mention the main driving force in the foreign policies of many countries.

Still, in the early 1900's, internal combustion engines had not emerged as the dominant transportation engine, there still being significant competition from steam and battery-powered vehicles. Though these alternatives were already in decline in the 1910's, the last nail in the coffin of these alternatives was the 1921 discovery at General Motors' research laboratories of tetraethyl lead as a remarkably effective antiknock fuel additive. Immediately compression ratios could be nearly doubled, leading to substantial increases in both power and efficiency.

The rise of the gasoline-fueled, spark-ignited internal combustion engine powered automobile through the 1950's is of course well known. Starting around the end of this period it became obvious that the skies of some metropolitan areas were being badly fouled by the emissions from the massive numbers of these engines, resulting in the formation of a brown haze of nitrogen dioxide (NO_2) as well as ozone (O_3), a colorless gas highly irritating to the respiratory system. In 1952, Prof. A. J. Haagen-Smit of Caltech showed that NO_2 and O_3 formed as a result of the reaction of nitric oxide (NO) and unburned hydrocarbons (UHCs) with oxygen and sunlight in the atmosphere to create a soup now called "photochemical smog." This led to the introduction of automotive emissions regulations in the 1960's. The U. S. automobile manufacturers were reluctant to accept that these regulations would not be repealed before the deadline for their introduction. Consequently, Detroit's initial stop-gap technology in the early 1970's (lean mixtures, exhaust gas recirculation, and retarded spark timing) led to poor fuel economy and performance. By a cruel twist of fate, around the same time the 1973 Arab Oil Embargo led to a rapid rise in oil prices and thus Detroit's large, inefficient gas-guzzling vehicles that were the joy of the American motorist just a year earlier were now virtual dinosaurs. Smaller, more efficient, technologically more sophisticated cars from Europe and Japan flooded the U. S. market. The problem was further compounded by the 1975 emissions standards on nitrogen oxides, which forced the use of 3-way catalytic converters requiring unleaded fuel. Detroit had no technology available and was forced to buy it from overseas. Moreover, in order to restore the antiknock properties (i.e., octane number) of gasoline to acceptable levels without the use of tetraethyl lead, more expensive fuel refining was needed, further aggravating the pressure on per-mile fuel costs.

The 1980's saw the introduction of microcomputers and fuel injection systems to control engines, a sorely needed replacement for the increasingly sophisticated mechanical controls needed to adjust fuel/air mixture, ignition timing, etc. for varying speed, load, air temperature, altitude, etc. The computer control allowed operation to be tailored conveniently for best efficiency, power, emissions performance or a combination thereof. This more precise engine control, while still meeting emissions standards, enabled recovery of some of the performance and fuel economy lost to emissions controls in the previous decade.

In the 1990's reformulated gasolines containing oxygenated molecules such as MTBE were introduced in order to further reduce emissions. MTBE was somewhat successful in this regard and additionally improved antiknock performance at the expense of still higher refining costs and lower fuel economy (due to the lower heating value of MTBE compared to hydrocarbons.) However, the biggest problem with MTBE turned out to be its water solubility and extremely odiferous nature (a concentration of only a few parts per *billion* in water can be detected by the human nose) and possible toxicity, and soon groundwater supplies were contaminated in areas where underground gas station fuel tanks leaked. This led to an eventual ban on MTBE and its replacement by ethanol, which is less effective than MTBE but attractive to the farm lobby because of the use of agricultural products as a feedstock for producing ethanol.

Finally, in the new millennium hybrid vehicles have become a commonly used technology. The operating principle is that internal combustion engines operate most efficiently at near maximum power. Thus the engine is used both to propel the vehicle as well as power an electrical generator to charge a battery. When the battery charge level is sufficiently high, the engine is turned off and the electric motor / battery propels the vehicle. When the battery charge level drops too low, or if additional power is needed for climbing hills, passing, etc., the gasoline engine is started again. While hybrid vehicles are clearly more fuel-efficient, much more equipment is required and, as discussed later, it is not clear if fuel savings justify the extra capital and maintenance costs.

The case for internal combustion engines

One way of illustrating the merits of hydrocarbon-fueled internal combustion engines is to compare them to other forms of vehicle propulsion. In this section some of the alternatives to internal combustion engines are discussed.

"External combustion" engines

Many larger, stationary power generating devices use "external combustion" engines in which the exhaust products of a combustion process are used to heat a separate working fluid (typically water, to make steam) which is then expanded through a turbine (for steady flow) or piston/cylinder (unsteady flow) to produce useful work. One could even envision an apparatus similar to an internal combustion engine working this way, with heat transfer at the appropriate times to and from a trapped working gas inside the cylinders. An example of this type of system is the Stirling engine. There are several advantages to external combustion engines such as potentially higher thermal efficiency (because an optimized working fluid can be used) and the ability to optimize the combustion process separate from the power generation process (which means that potentially any fuel or heat source can be used, and emissions can be reduced.)

The main problem with external combustion engines is simply that *heat transfer is too slow.* One can roughly compare the rates of turbulent-flow heat transfer to and from a cylinder to the rate of heat generation in a turbulent flame propagating within the engine as follows. The rate of heat transfer per unit cross-section area (q) is given by $q = k(\Delta T/\Delta x)$, where k is the gas thermal conductivity, ΔT is the temperature difference between the gas and cylinder wall and Δx the distance across which the heat is transferred. The value of k for turbulent flows in engines may be 100 times that in still air, *i.e.* on the order of 4 Watts per meter per degree Centigrade. The temperature difference between combustion gases and the cylinder walls is typically 1500˚C. The distance across which heat must be transferred in a typical engine is about 1 cm. This leads to q = 600,000 Watts per square meter – a seemingly impressive value. Now compare this to the rate of heat release in a turbulent flame in an engine. In this case q can be estimated as $q = \rho Y_f Q_R S_T$ where ρ is the gas density (about 10 kilograms per cubic meter at the time of combustion in an engine), Y_f the fuel mass fraction (about 0.065 at the chemically-balanced ("stoichiometric") fuel-air ratio), Q_R is the fuel heating value (about 43,000,000 Joules per kilogram for gasoline or other hydrocarbon fuels), and S_T is the turbulent burning velocity (at least 2 meters per second at engine conditions). Thus for turbulent combustion, q = 55,900,000 Watts per square meter – **93 times that of heat transfer alone.** Consequently, for the same engine size and turbulence level, the flame can increase the gas temperature about 100 times faster than heat transfer alone. It is for this reason that 10 modern gas turbine engines of the type used in large aircraft can produce about 1 million horsepower, about the same as an entire coal-fired electrical generating plant, and steam-powered automobiles became obsolete nearly a century ago.

Battery-powered electric vehicles

Another possible alterative vehicle propulsion technology is electric motors. Electricity can be generated in a large central power plant at higher efficiency than is possible in individual internal combustion engines and this electricity can be distributed via the power grid to individual stations where batteries that power the vehicle's electric motors are charged. However, even when the lower efficiency of conversion of gasoline to shaft work compared to converting energy stored in batteries to shaft work is considered, the range of electric vehicles (not to mention the recharging time compared to refueling) has limited electric vehicles to short-range applications. For example, a representative Honda metal hydride electric vehicle battery [1] produces 0.07 kilowatt-hours or electricity per kilogram or 252,000 Joules per kilogram - 171 times less than hydrocarbon fuels. Even when the lower efficiency of conversion of gasoline to shaft work compared to converting energy stored in batteries to shaft work is considered (say 75% vs. 25%), it can be stated that 1 gallon of gasoline is equivalent to 349 pounds of batteries for same energy delivered to the wheels. Moreover, in addition to the batteries the electric motors required are about as heavy as gasoline engines of the same power.

Another factor often discounted in the comparison of electric and conventional vehicles is the fact that electric vehicles are not pollution-free in the sense that emissions were produced where the power was generated (*i.e.*, the emissions are exported to a location other than where the vehicle is). Also, in addition to the energy storage (batteries) the weight of even the most advanced motors for electric vehicles is about 0.4 horsepower per pound [2] comparable to or lower than that of typical gasoline engines of the same power. Moreover, large quantities of toxic metals are needed for the batteries themselves. Finally, the lifetime of rechargeable batteries is far less than that of a typical automobile (say, 5 years vs. 10 years), thus the replacement cost of batteries before the end of the vehicle lifetime must be factored into the total vehicle operating costs.

One possible advantage of electric vehicles is that, because of the inherently lower energy density of batteries, electric vehicles are inherently smaller, more aerodynamically streamlined and constructed of lightweight materials. This could make smaller, lighter and thus inherently higher fuel economy vehicles more acceptable to the car-buying public that recently has favored ever- larger vehicles such as SUVs.

Fuel-cell vehicles

A variation on the electric vehicle theme is the fuel cell vehicle. Fuel cells are essentially batteries with a continuous feed of expendable reactants to convert fuel and air into electricity. Fuel cells can produce far more electrical energy per unit weight than batteries can, and thus are widely used in specialized applications where minimum weight is critical, *e.g.*, spacecraft. Additionally, fuel cells are not heat engines and thus are not subject to the thermodynamic limitations on efficiency that heat engines suffer. The Ballard Ballard HY-80 "Fuel cell engine" (Fig. 4) [3] produces 91 horsepower of electrical power and weighs 485 lb, for a horsepower to weight ratio of 0.19 hp/lb. The fuel-to-electrical conversion efficiency is 48%, and the fuel is hydrogen. To produce shaft power at the wheels, electric motors are required. Ballard's electric motors average 0.24 hp/lb at 90% electrical to mechanical energy conversion efficiency [4], thus the system performance (not including transmission gearbox(es)) is 0.11 hp/lb at 43% fuel to mechanical energy conversion efficiency. This compares to over 0.5 hp/lb for automotive engines and over 1 hp/lb for aircraft piston engines; many performance automobiles (e.g. Dodge Viper RT/10) produce more than 0.11 hp **per pound of total vehicle weight**. Moreover, 43% efficiency is only modestly better than IC engines (typically 25% to 30% for high-volume production vehicles). In fact, using lean hydrogen-air mixtures with lower flame temperatures and thus higher gas specific heat ratio, this 43% figure may nearly be reached in IC engines.

In addition to the performance benefits of internal combustion engines compared to hydrogen fuel cells, many of the environmental concerns of hydrocarbon-fueled IC engines are practically eliminated using hydrogen fuel. Because very lean hydrogen-air can produce the same burning velocity as stoichiometric hydrocarbon-air mixtures but with much lower flame temperatures, hydrogen-fueled engines can be run extremely fuel-lean at flame temperatures low enough that nitric oxide (NO) emissions are negligible. Furthermore, hydrogen fuel produces no hydrocarbons, carbon monoxide or carbon dioxide. Consequently, even within the context of a possible Hydrogen Energy Economy, internal combustion engines are likely to dominate other means of vehicle propulsion well into the future [5]. Thus, fuel cell engines are only marginally more efficient, much heavier for the same power, and require hydrogen that is very difficult and potentially dangerous to store on a vehicle. Additionally, fuel cell engines require large amounts of extremely expensive platinum catalyst (yet another advantage of internal combustion engines is that no expensive or toxic raw materials are required.) Consequently, *even if the issues of economical large-scale hydrogen production, distribution and on-vehicle storage are resolved, the most feasible use of hydrogen for vehicle propulsion will likely still be internal combustion (IC) engines*, as in the Ford Model U car [6].

A note on hydrogen

Hydrogen is an outstanding fuel in many ways. Its energy content per unit weight is nearly three times that of hydrocarbons (which is why it is used in rocket propulsion systems), it has outstanding electrochemical properties for use in fuel cells, and is an extremely clean-burning fuel. On the other hand, since hydrogen is not a fuel *per se* because it does not exist in nature in significant quantities. Rather, hydrogen is an *energy carrier* that must be made from something else, thus cost-effective production of hydrogen from energy "feedstocks" (coal, petroleum, nuclear energy, solar energy, biomass, etc.) is a very substantial barrier to any hydrogen-based economy. Additionally, while hydrogen is indeed very clean-burning, the environmental cost of producing the hydrogen must also be considered. Hydrogen is also easy to burn in internal combustion engines, even in very lean, low-temperature flames, but also has much more serious

Figure 4. Ballard HY-80 fuel cell engine.

explosion hazards than hydrocarbons. Also, being a very small molecule, it leaks out of tanks and through valves much more readily than other pressurized-gas fuels such as natural gas.

In addition to the production and safety issues associated with hydrogen, its storage on a vehicle is extremely problematic. The only known weight-effective way of storing hydrogen at atmospheric pressure is as a cryogenic liquid at -424˚F, though even in this case the density of the liquid is very low, 14 times less than that of water, and certainly cryogenic hydrogen is both difficult and dangerous to manufacture, transport and store, hence its use only in specialized applications such as rocket propulsion. As a compressed gas, even with optimistic estimates of the tank weight assuming lightweight, high-strength materials, the weight of the tank will be about 15 times that of the hydrogen itself. Hydride solutions such as sodium borohydride ($NaBH_4$) in water produce hydrogen through the chemical reaction

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 \text{ (Borax)} + 3H_2$$

but even in this case the mass of the solution is 9.25 times that of the mass of the hydrogen produced. Hydrogen can also be stored in the interstitial spaces between palladium atoms, but the weight of the palladium is about 160 times that of the hydrogen produced. On the other hand, long-chain saturated hydrocarbons have the chemical formula $(CH_2)_n$ and thus the weight of the hydrocarbon is 7 times that of the hydrogen produced, which is better that that of the other storage methods described above. In other words*, by far the best way to store hydrogen is to attach it to carbon atoms and make hydrocarbons, even if the carbon is not used as an energy source!* And if the carbon is also used, the energy release increases from about 16,400,00 Joules per kilogram to 43,000,000 Joules per kilogram – more than double.

Solar and nuclear energy

The sun is frequently cited as the ultimate clean source of energy, and some solar-powered vehicles have been built (Figure 5). However, even in summer near the equator, the solar flux is only about 1000 watts per square meter. A vehicle cruising at 60 miles per hour and consuming fuel at the rate of 30 miles per gallon and uses 2 gallons (5.6 kilograms) of fuel in that hour, corresponding to a thermal power of 66,500 Watts. Thus, to have the same thermal power input as a gasoline engine at typical highway cruise condition, one would need a solar collector with an area corresponding of 66.5 square meters, corresponding to a square 27 feet on a side – assuming one only need to drive at noon, on clear days, near the equator. Of course, if the driver is willing to sacrifice some convenience, solar-powered vehicles such as that shown in Figure 5 do exist. This raises a point frequently overlooked in comparisons of conventional and non-conventionally powered vehicles – a fair comparison must evaluate vehicles of similar size, passenger comfort, speed and acceleration.

Nuclear power, on the other hand, while totally unsuitable for small vehicles, does have a tremendous advantage over other energy sources in that the energy stored in nuclear materials is enormous. For example fissionable uranium-235 contains about 82,000,000,000,000 Joules per kilogram of material - about *two million* times that of hydrocarbon fuels. Materials exhibiting radioactive decay produce much less energy per unit weight than fissionable uranium, but are still much higher than hydrocarbon fuels.

Figure 5. Typical solar-powered vehicle.

Hybrid vehicles

Hybrid vehicles save fuel because any internal combustion engine is most fuel-efficient at a particular operating condition, usually at or near the maximum power that the engine can produce. Vehicle engines must operate, however, over a very wide range of speeds and loads. In a hybrid vehicle, the engine is run at or near this best-efficiency condition and any power generated beyond that required to propel the vehicle is used to turn a generator which charges a battery. When the battery is fully charged then the engine is shut off and the vehicle runs off of electric motors, which operate efficiently over a wider range of speeds and loads than internal combustion engines. If more power is required than that which the battery and electric motors can provide, then the internal combustion engine is restarted. Also, during braking the motors can be operated as generators to recover some of the energy expended to accelerate the vehicle. While hybrid vehicles are clearly more fuel efficient because of the way that the internal combustion engine is used, significantly more equipment (generator, battery, motors, control system) is needed compared to a conventional vehicle drivetrain. More equipment also means more maintenance and part replacement costs, particularly the battery – a several thousand dollar item whose lifetime has not yet been determined. As a result of these factors, it is not clear whether hybrid vehicles provide is a net cost savings. In fact, a recent study in a major consumer magazine found that of seven vehicles from different manufacturers tested in their hybrid and non-hybrid models, only one showed a net savings in total operating cost over a 5-year period.

Additionally, the energy cost of the additional materials needed to manufacture hybrid vehicles is not trivial. For example, the energy cost of producing copper is about 71 million BTU per ton, which corresponds to 82,600,000 Joules per kilogram of copper produced [7]. This in turn corresponds to about 1.9 pounds of hydrocarbon fuel per pound of copper, or, for a representative 50 pounds of additional copper in a hybrid vehicle compared to a convention non-hybrid, 16 gallons of fuel. Thus, the energy cost of making the copper is equivalent to roughly 500 miles of additional driving. In a sense the situation is worse than this estimate since copper is typically smelted using coal, not petroleum, and burning coal yields about 35% more carbon dioxide emissions for the same energy produced. Similar arguments can be applied to other processed materials (e.g., in the battery) used in hybrid vehicles. Such considerations lead this author to modify a quote from the musician and actress Dolly Parton:

> "You wouldn't believe how much money it costs to look this cheap" – Dolly Parton

"You wouldn't believe how much energy we spend trying to save a little fuel" – PDR

Summary of the advantages

The conclusion of this section is that the use of hydrocarbon-fueled internal combustion engines for vehicle propulsion is a result of two key characteristics:

(1) the energy per unit weight of the energy storage medium (liquid hydrocarbon fuels)
(2) the power per unit weight or volume of the energy conversion device (i.e., the engine).

Additional factors include

(3) the distribution and handling convenience of liquids is a compelling reason for using petroleum-based hydrocarbons in vehicles instead of gaseous (e.g., natural gas or LPG) or solid (e.g., coal) fuels
(4) the fact that internal combustion engines are made almost entirely of relatively inexpensive materials (i.e., steel) compared to, for example, the precious metals (i.e. platinum) needed for fuel cells.

Room for improvement

The above discussion might lead one to conclude that there is no room for improvement in internal combustion engines. Certainly this is not the case, but before one invents the zero-emission, 100 mile per gallon, 1000 horsepower engine, revolutionizes the automotive industry and shops for his/her retirement home on the French Riviera, there are a few simple facts about engines that need to be considered.

Efficiency

The ideal thermodynamic model of the premixed-charge (usually called "gasoline" or "spark-ignited" internal combustion engine) is the so-called "Otto Cycle" whose thermal efficiency depends on only two factors: the compression ratio and a property of the gas mixture called the "specific heat ratio." Since the latter factor is not an adjustable design parameter, only the compression ratio may be adjusted. As discussed earlier, higher compression ratio improves both thermal efficiency and power but is limited by engine knock. At a typical compression ratio of 9, the maximum possible Otto Cycle efficiency is about 50%, whereas the actual efficiency is closer to 30%, meaning that there theoretically almost a factor of two room for improvement, possibly even more with different thermodynamic cycles such as the "complete expansion" or "Atkinson" cycle.

Of course, practically speaking this much improvement will never be realized. The differences between the actual and theoretical efficiencies is a result of several factors, the most important typically being, in order of decreasing importance [8]:

- *Heat losses to the cylinder walls.* About 25 – 35% of the energy contained in the fuel winds up being lost to the cylinder walls and rejected as waste heat through the radiator. Many studies, for example Leidel [9], have shown that so-called "adiabatic engines," which are really just "coolant-free" engines with high wall temperatures, do not in fact improve efficiency; what is needed is a way to reduce all heat transfer to or from the cylinder walls (via lower turbulence, etc.)

- *Friction losses.* About 10 - 20% of the energy contained in the fuel is used to overcome rubbing friction losses in the engine.
- *Throttling losses* (at part-load operation). When less than the full power output of the engine is required (which is most of the time), a throttle is used to control power output. It does so by creating a pressure drop across the throttle valve, which in turn decreases the density of the fuel-air mixture entering the cylinder. This pressure drop results in pumping work being required to draw the mixture into the cylinder. The energy loss associated with throttling varies from 0% at wide-open throttle (maximum power) to 15% at typical highway cruise conditions to 50% at idling. Some schemes such as "displacement on demand" technology [10] and throttleless engines [11] have been developed as a result.
- *Non-ideal combustion* effects such as slow burning and incomplete combustion of the fuel generally have lesser impacts on efficiency.

It should also be noted that the majority of power used to propel a vehicle at highway speeds is used to overcome air resistance. As a result, smaller, more aerodynamically streamlined vehicles will always have better fuel economy, even if the weight is the same as a larger vehicle.

Emissions

Unlike efficiency, there is almost unlimited room for improvement in emissions performance – *other than carbon dioxide*. This is because *pollutants other than carbon dioxide are a non-equilibrium effect.* What this means is that ideally the burning hydrocarbon fuels with air (mostly oxygen (O_2) and nitrogen (N_2)) at stoichiometric or fuel-lean conditions results in the production of carbon dioxide (CO_2) and water vapor (H_2O) only:

$$\text{Fuel} + O_2 + N_2 \rightarrow H_2O + CO_2 + N_2$$

for which the only environmental concern is the CO_2. However, this ideal condition requires *infinite time* for the combustion products to adjust to this ideal composition. In reality, because of the very limited time available for combustion, expansion and cooling of the products in an internal combustion engine, the products additionally include undesirable components such as carbon monoxide (CO), nitric oxide (NO) and unburned hydrocarbons (UHCs):

$$\text{Fuel} + O_2 + N_2 \rightarrow H_2O + CO_2 + N_2 + CO + NO + \text{UHCs}$$

In essence, the problem is that at combustion conditions, CO, NO and UHCs always form. During the expansion stroke and the resulting cooling of the gases, if adequate time is allowed these products will be converted to H_2O, CO_2 and N_2, but this time is not available. All emissions control techniques are essentially aimed at either (1) modifying the combustion conditions so that less of the undesirable products are formed, (2) driving the products toward their equilibrium state more quickly within the combustion chamber or (3) driving the products toward their equilibrium state in the exhaust stream.

Modern engines are actually extremely clean in comparison to older engines built before the age of emissions regulations. By far the worst problems are during cold starting conditions, changes in speed or load, and especially old or out-of-tune vehicles.

Power

In contrast to efficiency and emissions performance, there is almost no room for improvement in engine power. Fundamentally this is because internal combustion engines are air processors – the fuel requires very little volume compared to the air. Moreover, adding fuel in excess of the stoichiometric mixture with air does not increase power because in that case there is insufficient oxygen to burn the additional fuel. Thus, to a good approximation, air flow corresponds to power. The most fundamental limitation on air flow is due to "choking" of the air flow past the intake valves – that is, gas cannot flow through a restriction such as the intake valves at a speed faster than a value related to the speed of sound, regardless of how low the pressure is downstream (*i.e.* in the cylinders, due to their downward motion on the intake stroke). Engines (in particular intake ports) are designed so that this limitation occurs only at very high rotational speeds, *i.e.*, near their maximum designed rotation rates.

In order to increase air flow and thus power, essentially the engine designer must either

- Increase engine rotation rate (and if necessary to avoid choking, increase intake valve port area)
- Increase engine displacement (cylinder bore, piston stroke or number of cylinders)
- Increase intake mixture density and thus pressure (i.e. via turbocharging or supercharging.)

The future – practical alternatives

In this paper it has been argued that hydrocarbon-fueled internal combustion engines will be the preferred vehicle power source for many years to come, for a number of fundamental technical reasons far beyond the simple fact that the capital investment, *i.e.*, the required industries and supporting technologies, is enormous. If this is in fact the case, and thus the world will continue to move by hydrocarbon-fueled internal combustion engines, what can be done to reduce the negative impacts of their usage? The 3 most significant negative impacts are probably

1. Global warming
2. Global balance of power shift and lack of U. S. energy independence
3. Environmental pollution

It could be said that there has been very negative progress with respect to (1) in the past 30 years, moderately negative progress with respect to (2), and very positive progress with respect to (3). Thus, positive progress on (1) is the most immediate and compelling societal need – if one believes that global warming is anthropogenic in nature.

Reducing the rate of global warming would require a decrease in CO_2 emissions. Realistically, no decision can be made on what the best course of action should be until it is decided whether there will be a tax on CO_2 emissions in the US. If no CO_2 tax is forthcoming, which essentially means denying or ignoring the global warming issue, petroleum use will continue unabated because it will not become cost-prohibitive for decades. In fact, forecasts have frequently suggested that the world is 40 years away from "running out of oil" – for the last 150 years.

Technology improves, and oil that was previously un-recoverable becomes economically feasible. Oil is still by far the most economical, practical fuel for transportation, which is why it is so ubiquitous. In the still-longer term, the next follow-on to petroleum (and tar sands, oil shale, etc.) is likely to be Fischer-Tropsch (FT) fuels [12] (liquid fuels made from coal or natural gas). Currently it is competitive with petroleum at about $75/barrel, but this price point would need to be sustained for a very long period of time before FT plants would be seen as a profitable investment. FT fuels are somewhat cleaner than conventional petroleum-based fuels because they are comprised almost entirely of saturated hydrocarbons (single bonds between carbon atoms) with very small amounts of olefins (hydrocarbons with double bonds between some carbon atoms) and aromatics (molecules with benzene-ring structures), but are not an environmental "silver bullet." A very serious problem with FT fuels, however, is that the energy feedstock will generally be coal, which is nearly pure carbon. For a given energy release, coal yields more carbon dioxide release than oil or natural gas, roughly in the ratio

Coal : oil : natural gas = 2 : 1.5 : 1.

The same warning applies to electric vehicles also – since most new electrical generating capacity is added in the form of coal-fired power plants, electric vehicles actually *increase* CO_2 emissions compared to gasoline- or diesel-powered vehicles.

If a substantial CO_2 tax is forthcoming, then energy consumption will gravitate towards natural gas for transportation and nuclear power for stationary power (electricity). Solar and biomass will fill some niche applications but even under the most optimistic near-term projections will not make a significant dent in global energy consumption - the sun's energy just isn't concentrated enough to recover in a way that is economically feasible compared to fossil fuels or nuclear power. In the short term, the use of natural gas is by far the simplest way to decrease CO_2 emissions. On an equivalent-energy basis, the cost of natural gas is about 25% that of electricity and 50% that of gasoline or diesel fuel. Natural gas is also somewhat cleaner than gasoline or diesel, but again no environmental silver bullet. The primary drawback of natural gas is its lower energy storage density – even stored as a compressed gas at high pressure (3000 pounds per square inch) the energy per unit volume (not mass) is about 25% that of liquid hydrocarbon fuels. While the energy density per unit weight of fuel is slightly higher for natural gas than liquid hydrocarbons, when the weight of the tanks, regulators and fittings is considered, the energy per unit weight is significantly lower than liquid hydrocarbons. This lower energy density reduces the range of natural gas vehicles, thus limiting their application primarily to fleet vehicles such as urban buses, shuttle vans, taxis, etc. where range is less of an issue.

A final point to be considered is that when comparing hydrocarbon-fueled internal combustion engines to its alternatives, typically "constant-technology" is assumed for the internal combustion engines whereas for the alternatives, improving technology is assumed. It must be appreciated that *internal combustion engine technology is always improving too*, perhaps not as rapidly as alternatives in their infancy, but improving nonetheless.

Thus, to paraphrase Winton Churchill, it can be stated that

> *Petroleum-fueled internal combustion engines are the worst form of vehicle propulsion… except for all the other forms.*

As a consequence, internal combustion engines are likely to be in widespread use for many years to come. A related point to be made is that, because of the convenience of using petroleum fuel:

> *Oil costs way too much, but it's still very cheap.*

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