A Physicist's View of the Automobile Engine

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Most first-semester university physics courses end with the chapter on the second law of thermodynamics, the Carnot cycle, and a brief introduction to the concept of entropy. My course and my final lecture are on the physics of the automobile engine. My students appreciate the application of the ideas of thermodynamics to an object that is an integral part of their lives, especially at a commuter school like mine. And the history of the automobile engine is a good lesson on the interaction between physics, engineering, economics, and environmental issues. It is a wonderful way to end the semester.

I start my lecture with the four-stroke Otto cycle and I calculate the peak gas temperature as a function of the compression ratio. From the Otto cycle, the compression stroke is taken to be an adiabatic, and PV^{γ} is a constant along an adiabatic, where P is the pressure, V is the volume, and γ is the heat capacity at constant P divided by the heat capacity at constant V. Substituting in the ideal gas law, $TV^{\gamma-1}$ becomes a constant along an adiabatic, where T is the temperature of the gas. Then

$$T_0 V_0^{\gamma-1} = T_f V_f^{\gamma-1}, \quad (1)$$

where T_0 and V_0 are the temperature and volume at the beginning of the stroke, and T_f and V_f, the temperature and volume at the end of the stroke. Rearranging Eq. (1),

$$T_f / T_0 = (V_0/V_f)^{\gamma-1}, \quad (2)$$

where V_0/V_f is the compression ratio. I then calculate the efficiency of the Otto cycle,

$$\text{efficiency} = 1 - 1/(V_0/V_f)^{\gamma-1}\,. \quad (3)$$

This material can be found in many introductory engineering physics textbooks.[1-4] The important point I make from these calculations is that with increasing compression ratios you have higher heat engine efficiency,[5] more power,[2] and higher peak gas temperatures. After this theoretical background, I begin a brief history of the automobile engine.

The golden years for the automobile engine lasted through the 1960s. It was an age of cheap oil, suburban sprawl, highway building, environmental indifference, decline of public transportation, and ascendancy of the automobile as the primary means of transportation. Automobiles became larger and more powerful, requiring larger engines operating at higher compression ratios to provide the needed power to accelerate these heavy cars. Because the engines were operating at higher compression ratios and thus at higher peak gas temperatures, they needed an anti-knocking additive in the gasoline to prevent the gasoline from preigniting before the piston reached the top of its stroke and the spark plug fired. The anti-knocking additive used was tetraethyl lead.[6]

Two major developments in the 1970s dramatically changed the automobile engine. The first was the oil embargo of 1973, which exposed this country's dependence on foreign oil and the political consequences of that dependence. This led shortly to the

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Table I. **Information from the U.S Bureau of Transportation Statistics.[7] The numbers of cars and light trucks are the total licensed. The average mpg is the weighted average of cars and light trucks.**

Year	# of cars (10^6)	mpg	# of light trucks (10^6)	mpg	Avg. mpg
1960	61.7	14.3			
1965	75.3	14.5			
1970	89.2	13.5			
1975	106.7	13.9	14.2	10.0	13.0
1980	121.6	13.9	20.4	10.5	13.6
1985	127.9	17.4	37.2	14.3	16.7
1990	133.7	20.2	48.3	16.1	19.1
1995	128.4	21.1	65.7	17.3	19.8
2000	133.6	22.0	79.1	17.5	20.3

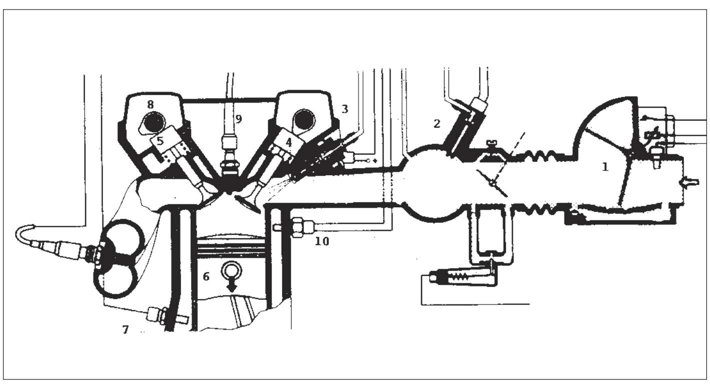

Fig. 1. Schematic diagram of a fuel-injection engine.[12] The air intake is at the right and the exhaust is at the left. The key elements are (1) air-flow sensor, (2) cold start injector, (3) fuel injector, (4) intake valve, (5) exhaust valve, (6) piston, (7) oxygen sensor, (8) cam shaft, (9) spark plug, and (10) temperature sensor.

Energy Policy and Conservation Act of 1975, which set a limit to the consumption of gasoline by passenger vehicles to an average of 27.5 miles per gallon by 1985. These fuel consumption standards are known as CAFE (Corporate Average Fuel Economy). Table I lists the number and average efficiency (miles per gallon, mpg) of licensed automobiles and light trucks (those having two axles) in the United States as a function of time.[7] In the last five years, the weighted average efficiency for cars and light trucks has barely increased due to the dramatically increasing number of SUVs and minivans, which are covered under the lower CAFE standard for light trucks.

The second major development was a growing awareness of the environmental damage created by automobile exhausts. This led to the Clean Air Act of 1970, which specified emission standards for passenger cars that became more stringent with time. The higher standards made the three-way catalytic converter unavoidable, and by the mid 1980s all new automobiles had them. In turn, since even small amounts of lead poisoned the catalytic converter, by the mid 1980s all new automobiles were using unleaded gasoline.

In order for automobiles to increase their fuel efficiency, many changes in the automobile occurred. Cars became significantly smaller, lighter, and more aerodynamic. Plastics replaced steel. Front-wheel drive cars with their short, efficient transaxles[8] replaced rear-wheel-drive cars with their lengthy, heavy, and inefficient transmission systems. Fuel-injection systems replaced carburetors, so that fuel could be injected into the cylinder with the optimum air-fuel ratio and in a way that maximized fuel combustion.[9] New formulations of gasoline were developed that included new non-lead, anti-knocking additives so that engines could operate at higher compression ratios and thus higher engine efficiencies.

The three major air pollutants of the automobile engine are carbon monoxide (CO) and unburned hydrocarbons (HC), which are byproducts of unburned gasoline, and nitrogen oxides (NO), which are created by the burning of N_2 in the engine cylinder. The new clean air emission standards for all three pollutants have been met by the introduction of the three-way catalytic converter.[10] The active layer in the catalytic converter consists of platinum and rhodium.[11] The platinum mainly induces oxidation reactions, which reduce the concentrations of carbon monoxide and unburned hydrocarbons through the following reactions :

$$CO + 1/2\ O_2 = CO_2$$

$$2\ HC + 5/2\ O_2 = H_2O + 2\ CO_2\ .$$

The rhodium reduces the nitrogen oxides (NO) in

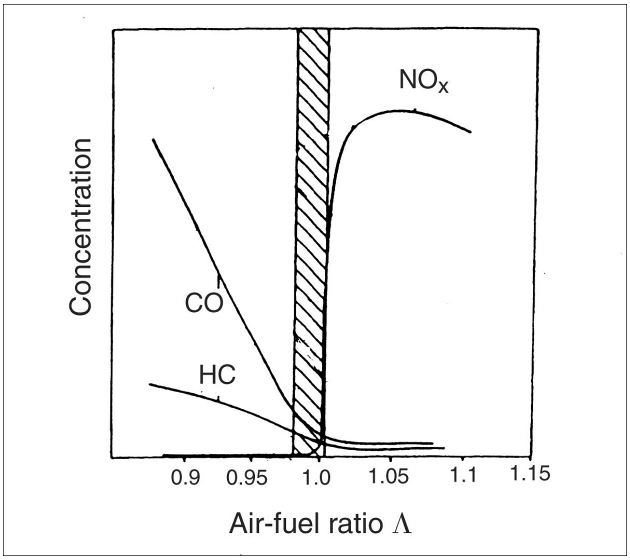

Fig. 2. Concentration of the major pollutants of a typical automobile engine equipped with a catalytic converter as a function of the air-fuel ratio, Λ.[10] The shaded area is the Λ window, where the fuel-injection engine operates. A Λ of 1 is approximately 14.6 kg of air to 1 kg of fuel.

the following reaction:

$$2\,NO = N_2 + O_2\,.$$

The higher the compression ratio, the higher the peak gas temperatures in the cylinder, and the higher the amount of nitrogen oxides produced. The catalytic converter is called three-way because it reduces the three major automobile pollutants, CO, HC and NO. But it could really be called four-way, because it also forced the elimination of tetraethyl lead from gasoline and thus lead from the air.

The performance of the catalytic converter is dramatically improved with the use of a fuel-injected engine and emission-control computer. A schematic of a fuel-injection engine is shown in Fig. 1.[12] The key idea behind the fuel-injected engine is that the air-fuel mixture ratio, Λ, is monitored by an oxygen sensor in the exhaust system, whose output is used by the emission-control computer to adjust the amount of fuel injected into the cylinder, so the Λ is controlled to less than a one percent variation. In Fig. 2, the concentrations of the major pollutants are plotted against Λ.[10] Notice in the region where Λ is between 0.98 and 1.0, the reduction of all pollutants is dramatically optimized. A further step to reduce these pollutants is the addition of ethanol to the gasoline. The oxygen atoms in ethanol increase the fraction of the fuel that is completely oxidized.

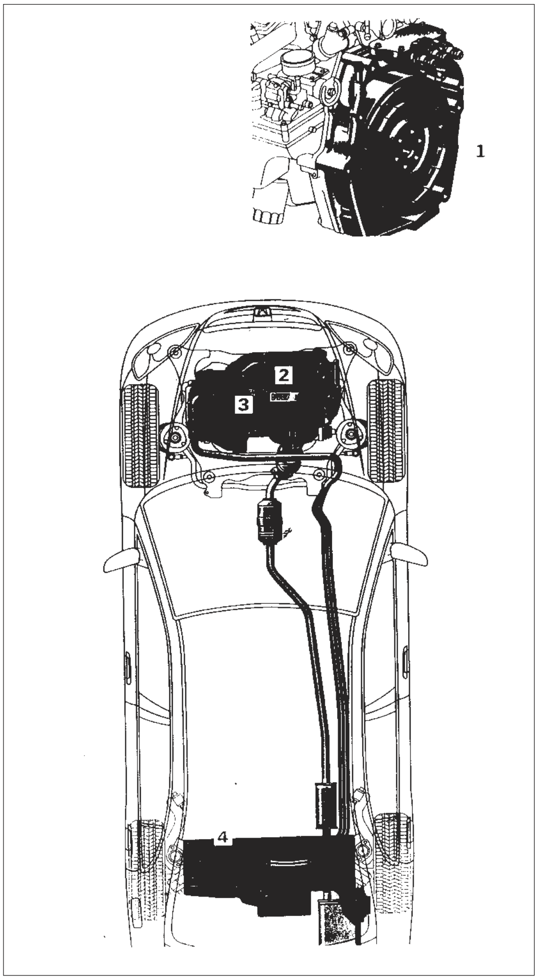

Fig. 3. Schematic diagram of the Honda Civic Hybrid, showing the major components: (1) electric motor, (2) 1.3-liter 4-cylinder gasoline engine, (3) transmission, and (4) nickel-metal hydride rechargeable battery pack.[13] The electric motor is located between the gasoline engine and the transmission.

When catalytic converters were first introduced and tetraethyl lead was removed from gasoline in the mid 1980s, the compression ratios of cars were dropped from over 10 to under 8 in order to avoid pre-ignition and minimize the production of NO. Consequently, the automobile engine efficiency and performance (acceleration) of cars were dramatically reduced. However, because automobiles became much lighter and more aerodynamic, automobile efficiencies actually increased.[5] With the advent of the fuel-injection engine and reformulated gasoline, those compression ratios are now around 10. The air-fuel ratio and the engine timing are regulated to minimize pre-ignition, making the fuel-injection engine even more efficient.

Finally, let me conclude by briefly mentioning two recent developments in automobile engines: hybrid engines and hydrogen gas fuel cells. A schematic of a hybrid engine is shown in Fig. 3. The automobile is powered by a small gasoline engine and an electric motor acting together.[13] These hybrid cars have good performance in comparison to electric cars, because during acceleration both the electric motor and the gasoline engine are providing power. They also have outstanding efficiencies (60 mpg), because when the car is braking or not moving the gasoline engine is either charging up the batteries or is turned off. When the car is braking, the batteries are recharged by the regenerative braking. Time will tell whether these hybrid engines are the automobile engines of the future or not.

Secondly, the U.S. government and the automobile industry are putting a great deal of effort into developing a hydrogen gas-powered automobile engine.[14] One of the major attractions of this engine is that it would not exhaust CO_2, the primary greenhouse gas, and the other major attraction is that it would not use gasoline. On the other hand, one of the major obstacles facing the hydrogen gas engine is how the hydrogen gas will be produced. If fossil fuels are burned to generate electricity that hydrolyzes water into hydrogen gas, you have gained nothing for the environment. On the other hand, if hydrogen can be extracted from coal without the release of any CO_2, then this technology may make sense.

This is essentially the concluding lecture of my introductory physics class. I have found it well received and it generates numerous questions. Many students, especially engineering students, are fascinated by automobile technology. All students should have some idea of how an automobile works and the key ideas behind its evolution. I hope this short essay provides you with the material for an outstanding discussion to end your first-semester physics class.

References

1. H.D. Young and R.A. Freedman, *Sears and Zemansky's University Physics* (Addison-Wesley, San Francisco, 2000). I found this textbook's treatment of the automobile to be outstanding. There is a section on Automotive Power (p. 181) that includes sketches of the early 1970s car and the 1990s car, as well as a section on the Internal-Combustion Engines (p. 563) that includes a brief discussion of real automotive engines.
2. R.A. Serway and R.J. Beicher, *Physics for Scientists and Engineers*, 5th ed. (Saunders, Fort Worth, 2000), p. 679.
3. S.M. Lea and J.R. Burke, *Physics: The Nature of Things* (Brooks/Cole, Pacific Grove, CA, 1997), p. 721.
4. P.A. Tipler, *Physics for Scientists and Engineers*, 4th ed. (W.H. Freeman, New York, 1999), p. 602.
5. The textbooks define heat engine efficiency as the fraction of the heat from the burned fuel that is converted into work (kinetic energy of the pistons, assuming no mechanical losses). I define automobile engine efficiency as the fraction of the fuel's potential energy converted into real work. Automobile engine efficiency is less than the heat engine efficiency, because a real engine does not fully burn all of its fuel (unburned hydrocarbons and carbon monoxide are two primary automobile pollutants) and has various mechanical losses. I will also refer to automobile efficiency, which is measured by the average miles traveled per gallon of gasoline used (mpg).
6. For a fascinating article on the history of the discovery of tetraethyl lead as an anti-knocking additive, see M. Bernstein, "Thomas Midgley and the law of unintended consequences," *Inv. Technol.* **17**, 38 (Spring 2002).
7. U.S. Bureau of Transportation Statistics; http://www.bts.gov/publications/nts/html.
8. The modern transaxle with a lock-up torque converter and automatic overdrive has dramatically decreased the energy losses in transmitting power from the engine to the wheels and is a very significant factor in the increased automobile efficiency in the last 30 years.
9. In a fuel-injection engine, the fuel injector is located right behind the intake valve (see Fig. 1), so the gasoline is injected into the center of the cylinder and away from the cooler cylinder walls, where incomplete oxidation is more likely to occur.
10. F. Schafer and R. van Basshuysen, *Reduced Emissions and Fuel Consumption in Automobile Engines* (Springer-Verlag, Wien, 1995). Most of the material in this paper on automobile emissions, including Fig. 2, was taken from this outstanding reference book.

11. How a catalytic converter works on the atomic level is very poorly understood. See, for example, R.J. Farrauto and R.M. Heck, "Catalytic converters: State of the art and perspectives," *Catalysis Today* **51**, 351 (1999).
12. Robert Bosch GmbH, 70442 Stuttgart, Germany.
13. American Honda Motor Company, 700 Van Ness Ave., Torrance, CA 90501.
14. Joan M. Ogden, "Hydrogen: The fuel of the future?" *Phys. Today* **55**, 69 (April 2002). See also the letters in response to this article: *Phys. Today* **55**, 12 (Nov. 2002). For fuel cell proof-of-concept cars, see F. Markus, "Driving Impression: GM Hy-Wire," *Car and Driver* **48**, 77 (March 2003), and J. Dunne, "Fuel cells from sea to shining sea," *Pop. Mech.* **180**, 78 (Jan. 2003).

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