Green Alternatives and National Energy Strategy

Gallman, Philip G.

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Gasoline and diesel together are responsible for 23% of our energy consumption, 23% of our greenhouse gas emissions, and 64% of our petroleum consumption. Road vehicles consume almost all of this. Improving the fuel economy of highway vehicles is the most important single step in reducing our consumption of gasoline and combating global warming. We can do this by nontechnological means, such as driving less or adopting efficient driving behavior, or by technological means, such as making automobiles more fuel-efficient or replacing gasoline with some other fuel. This chapter examines current automotive technology and explores which fuel-economy improvements are practical and how much improvement is possible without radical shifts in automotive technology.

Road transportation started expanding rapidly around 1950 with the convergence of two trends: oil and the automobile. Development of the modern automobile dates to the late 1700s with a model-sized self-propelled vehicle, followed by pedal power and some modern features in 1780, the internal combustion engine (fueled by hydrogen and oxygen) in 1806, and an electric car in 1881. The modern automobile dates from 1885 when German inventor Karl Benz patented the four-stroke internal combustion gasoline-fueled automobile. Benz began to sell his vehicles in 1888. German engineer Rudolf Diesel patented the diesel engine in 1892 and built the first one in 1897. By 1910, the field had shaken out, and the
four-stroke gasoline-fueled internal combustion engine had gained dominance over competing steam, electric, two-stroke gasoline, and diesel engines. The large-scale production line manufacturing of affordable automobiles was introduced by Ransom Olds in 1902 and expanded by Henry Ford in 1914. With the wide popularity of the internal combustion engine automobile, gasoline and diesel became the major products of crude oil.¹

The availability of affordable automobiles and inexpensive gasoline greatly influenced development of roads, housing, and cities. Started in 1956, the interstate highway system enabled Americans to travel great distances inexpensively and conveniently and has guided construction of cities for the past fifty years. Inexpensive personal transportation has molded the American lifestyle, where we live, where we work, where we shop, how far we are willing to travel to visit relatives, and how far we are willing to travel for vacations. It is foolhardy to think that we are going to restructure all of this in a few years.

The Department of Transportation estimates that there were 254 million highway vehicles registered in the United States in 2007.² The Environmental Protection Agency (EPA) estimates that between 11 million and 13 million cars go to the scrap heap each year. That is, drivers take 5% of vehicles off the road every year, junk them, and replace them with new ones. The EPA estimates that 38% of the vehicles on the road are more than ten years old. If this replacement rate remains constant, even if an ultraefficient car becomes available tomorrow and only the ultraefficient cars are sold from then on, it would still be at least twenty-one years before the overall fuel economy of automobiles on the highway settled down to the new ultraefficient value. Significant change in gasoline consumption will take decades.

Although some vehicles are gas hogs, some very fuel-efficient cars are available now. Over the entire fleet of new cars, fuel economy ranges from 10 miles per gallon (mpg) to 46 mpg, with an average about 22 mpg. The average fuel economy has remained nearly constant for the past twenty years.³
In order to meet the long-range goal of becoming independent of foreign oil, we have to eliminate or substantially reduce demand for gasoline. Simply improving the fuel economy of standard gasoline vehicles will not achieve this goal. It will reduce demand for gasoline and postpone the inevitable depletion of oil reserves, but it will not eliminate demand. Only replacing gasoline with something else will do that. However, developing alternatives to the internal combustion gasoline engine will be a lengthy process. In the short term, all we can do is improve current vehicle technology so that we can stretch the limited reserves of gasoline as far as possible while we develop alternatives. In this chapter, I describe the sources of inefficiency and possible engineering means for improving the fuel economy of the internal combustion gasoline engine. I do not discuss diesel engines here, not because they are not relatively common, but because the difference between diesel and gasoline engines is not great enough to warrant special treatment at the level of the discussion in this chapter. I discuss diesel engines and other alternatives to current gasoline vehicles in the next chapter.

Automobile Basics

When sitting at a stop sign or traffic light or stuck in a traffic jam, you are not going anywhere. If the engine is running and consuming fuel, all of the energy in the burned fuel is lost. As you drive away from the stop sign, your engine burns fuel to accelerate to the desired cruising speed. Some of the fuel energy goes to overcome engine and transmission-system losses. The rest is expended in maintaining the moving vehicle’s momentum. Heavier cars require more energy to accelerate than smaller cars and hence are less efficient. At cruising speed, the engine must provide enough energy to overcome external forces such as drag and tire rolling resistance in addition to overcoming the system losses to maintain the vehicle’s momentum. When you stop, you must counter the vehicle’s momentum by braking. Simply stated, braking increases frictional
losses (brake shoes rub on brake drums; brake pads rub on brake discs), converting stored energy into heat, which air flowing over the braking system removes from the vehicle. All the energy that was stored in momentum is lost to heat the atmosphere.

The two diagrams in figure 2.1 show the losses in a typical internal combustion gasoline engine automobile. One diagram applies to city driving and the other to highway driving. Highway driving usually involves higher speed, less frequent acceleration and braking, and less idling. I have calculated engine loss assuming an air standard Otto cycle engine with 10:1 compression ratio and 1.4 specific heat ratio. Other thermodynamic engine cycles are possible, but the Otto cycle is a good model for the typical automobile of the past decade. That is, the diagram is a good baseline for understanding recent engineering and estimating the potential for further improvement.

The single largest source of energy loss in a vehicle is the engine, which accounts for about 80% of the total loss. One might conclude that huge improvements in fuel economy are possible through engineering research and development (R&D). However, this conclusion is not valid. The thermodynamic efficiency of the Otto cycle internal combustion gasoline engine operating with typical air/fuel mixture and compression ratio is roughly 60%. Reducing engine losses below 40% is simply not possible. Nonetheless, there is plenty of room for improvement. Most of the reducible losses are those resulting from less-than-ideal fuel delivery, fuel burning, and exhaust. The EPA estimates that engineering improvements to fuel delivery and burning can reduce engine losses by around 30%, although such reductions require increased complexity and result in greater cost. Good engineering, good manufacturing, and improved design features, such as variable valve timing and lift, cylinder deactivation, turbochargers and superchargers, and direct fuel injection all contribute to improved fuel economy. The rest of the losses are due to friction. While friction may be reduced through good engineering, it is always a factor and increases with engine size, because with larger engines come larger rubbing surfaces, and
FIGURE 2.1 Energy Flow in Typical Midsize Gasoline Car: a, city driving; b, highway driving. These charts show where energy in the fuel is lost. The major loss is in the internal combustion engine and drivetrain. Some of this loss can be overcome by engineering improvements to the engine and the transmission. Some of this loss is inherent in the thermodynamics of the engine and cannot be reduced. Fuel waste during idling is a major source of loss in city driving, which could be overcome by turning the engine off when not needed. Major sources of loss in highway driving are aerodynamic drag, which could be addressed by streamlining, and tire rolling friction, which could be addressed by low-rolling-friction tires or simply by driving slower.

with speed, because driving faster means higher engine speed and thus higher engine friction. Engine friction can be reduced by making engines smaller and less powerful and by driving slower.

Idling losses are simply due to burning fuel to keep the engine running. After basic engine losses, idling is the leading loss factor in city driving, accounting for 17% of the overall loss. Turning the engine off when stopped would achieve huge savings, increasing typical fuel economy in city driving 4 mpg. Balancing the savings is the added fuel needed to restart the engine, the loss of engine-driven accessories while idling, and the inconvenience and delay of restarting. An integrated starter/generator system automatically turns the engine off at idle and starts it again with only a slight delay when the accelerator is pressed. Such a system could cut the losses at idle in half. Idling is not as large a source of waste in highway driving because there is less stopping. Nonetheless, eliminating idling would provide a noticeable improvement in efficiency even in highway driving.

Accessories such as lights, windshield wipers, and instruments are unavoidable. One can also argue that air conditioning is necessary. Heating is not really an accessory, as most cars use heat from the engine normally dumped into the atmosphere and lost. Radios and other electronics also consume energy. We cannot do much about the energy lost to accessories.

The main loss element in the drivetrain is the transmission. An internal combustion engine operates efficiently over a rather broad range of crankshaft rotation speed, roughly 600 to 7,000 revolutions per minute (rpm). The wheels on my car rotate between 0 rpm at idle and 1,000 rpm at 80 miles per hour (mph). The transmission is required to match the optimal engine speed to the vehicle’s road speed. Transmission losses on the highway are generally slightly less than in city driving because most automobile transmissions provide optimum matching at the common highway cruising speed. For most cars built since the Arab oil embargo, the design speed is 55 mph. Manual transmissions may be up to 94% efficient, automatic transmissions as low as 70%. Of course, the efficiency of a
manual transmission in practice depends on the driver’s gear-shifting skill. The EPA estimates that using continuously variable transmissions or automatic manual transmissions, essentially a standard transmission shifted by the machinery rather than by the driver, could improve fuel economy 6%.\textsuperscript{6}

The energy needed to overcome inertia and accelerate to cruising speed increases with heavier cars and higher cruising speed. It is more significant for large vehicles on the highway because weight and speed are higher. Making cars lighter and reducing cruising speed mitigate some of the negative effect of inertia.

Large frontal area, boxy design, and high speed increase aerodynamic drag and the associated energy loss. Streamlining the car body, making the car small, and driving slower reduce drag and improve fuel economy. The speed penalty is severe. While drag increases as the square of velocity, the power required to overcome drag increases as the third power of velocity. That is, doubling speed requires an eightfold increase in power. Driving 70 mph requires twice the power and twice the fuel as driving 55 mph. A small streamlined car generally has much less drag than a large boxy one, but limiting speed has much more effect and is easier to achieve.

Tires get hot when we drive because of resistance as the tires roll over the road. Low-rolling-resistance tires minimize rolling resistance and losses but give a harsher, less comfortable ride.

Where does this leave us with regard to improving fuel economy? Many aspects of the engine are amenable to engineering advances, and this is where most of the effort is going. Engine designers have a good grasp on friction, and I would not expect much improvement here. All we can do is reduce friction by reducing the size and speed of the engine. Losses at idle can be reduced by turning off the engine when the car is not moving, despite some inconvenience. High-tech transmissions, such as the continuously variable transmission or automatic manual transmission, can decrease transmission losses markedly, although they do cost more. Inertia is not amenable to change in the internal combustion en-
engine (though regenerative braking in electric-drive cars can recoup something). Reducing frontal area, streamlining the car, and reducing top speed all reduce drag losses. High-tech tires can reduce, though not eliminate, rolling resistance at the expense of a harsher ride.

How much improvement can we expect? First, let us look at engineering tweaks. Assume that good engineering eliminates three-quarters of the engine engineering losses, reducing engineering losses in city driving from 22% (as shown in fig. 2.1) to 5% and total engine loss from 62% to 45%. This is about a 30% reduction in engine loss as estimated by the EPA. It also means that the engine would be operating close to the theoretical maximum possible efficiency, which is a stretch, and leaves little room for further improvement. Then assume that three-quarters of transmission loss is eliminated by high-tech transmissions, three-quarters of tire loss is eliminated using low-rolling-resistance tires, and three-quarters of the drag loss is removed with streamlining. Overall, this would eliminate 26% of the losses in city driving and 39% of the losses in highway driving. That is, fuel economy of a typical 20 mpg car would increase to 27 mpg city and 33 mpg highway, close to the fuel economy of the Chevrolet Aveo: 27/34/31. (In this standard way of representing fuel economy, the first number is mpg in city driving, the second is mpg in highway driving, and the third is a composite number assuming 55% city driving and 45% highway.)

We have already made most of the possible engineering improvements to the internal combustion gasoline engine and automobile. There is not much room for additional improvement as long as we continue with the standard internal combustion gasoline engine.

**CAFE Standards**

Congress established the Corporate Average Fuel Economy (CAFE) standard in 1975, in response to the 1973 Arab oil embargo. CAFE is the average fuel economy of a manufacturer’s fleet of pas-
senger cars and light trucks for the current model year. The goal of the original CAFE standard was to increase new-car fuel economy to 27.5 mpg by model year 1985. The CAFE standard has changed several times since it was established. The current standard is 27.5 mpg for cars and 22.2 mpg for trucks with a gross vehicle weight rating (GVWR) of 8,500 pounds or less. Vehicles with GVWR greater than 8,500 pounds (i.e., the large sport-utility vehicles [SUVs]) were exempt.

In May 2009, President Obama raised the fuel economy standard. Under the new rules, the mandated average economy of each manufacturer’s fleet of new cars and light trucks increases to 35.5 mpg (39 mpg for cars, 30 mpg for trucks), with the increase being phased in between the 2009 and 2016. This is very laudable and a huge step in the right direction, but we have to understand the details.

First, the improvement will not happen overnight. It will be seven years before the standard reaches 35.5 mpg, and it will take at least two decades from then for standard-satisfying fuel-efficient vehicles to replace all cars on the road. Figure 2.2 illustrates the difference between the CAFE standard that applies to new vehicles and the average fuel economy of actual vehicles on the road. The figure shows the CAFE standard and actual fuel economy over the past thirty years. Although the CAFE standard has been 27.5 mpg since 1985, actual fuel economy has only reached 22.4 mpg. The figure also shows my projection of how the actual fuel economy will respond to the 2009 CAFE standards. I assume that we continue to replace 5% of vehicles on the road each year with vehicles meeting the then-current fuel economy. The year 2006 was the last year for which actual data were available, so the projection starts in 2007. The projection shows that it will be 2053, almost forty-five years from now, before we achieve 34 mpg actual fuel economy, still short of the 35.5 mpg CAFE standard.

Second, the CAFE standard will not accomplish its goal if the public does not buy the cars. One estimate says that the new efficiency standards will add $1,300 to the price of each car, on av-
Fuel cost savings will recover some of this, but the amount of saving will depend on the price of gasoline. If the benefit is too little, people may not continue to replace cars at the 5% rate. Consequently, the projection may be optimistic, and it might be more than thirty years before the on-road fleet is completely converted to fuel-efficient vehicles.

Third, the CAFE standard will not accomplish its goal if manufacturers do not comply. Even though manufacturers pay stiff penalties for not meeting the standards, several manufacturers do not meet the current CAFE standards. They have decided that it is better for them economically to pay the penalty than to invest in

**FIGURE 2.2**  Average US Fuel Economy. This chart shows how slowly actual fuel economy of cars on the road responded to CAFE standards over the past thirty years since CAFE standards were instituted. The chart also shows the projected fuel economy response to new standards, assuming a 5% replacement rate. Although the CAFE standard rises to 35.5 mpg in 2016, on-road fuel economy will not reach 34 mpg until at least 2053. That is, oil consumption would be reduced about a third in fifty years if the total number of cars on the road does not increase and the annual replacement rate remains at 5%.

improving fuel economy. European manufacturers consistently pay millions of dollars in penalties a year. Asian and most large domestic manufacturers usually pay no penalty.

Finally, raising the actual fuel economy from 22.4 to 34 mpg reduces gasoline consumption by only 34%, barely enough to cut our foreign oil imports in half.

The new CAFE standard is a step in the right direction and is achievable, but we need to do much more.

EPA Fuel Economy Ratings

This is a good time to describe how EPA determines fuel economy. The test vehicle is put on a machine called a dynamometer that simulates the driving environment, just as exercise bikes and treadmills simulate physical activity. The dynamometer controls the resistance provided by the rollers under the drive wheels, simulating acceleration, hills and so on, while the operator controls the speed to follow the established test protocol. The amount of fuel consumed during the test is the fuel economy for that particular vehicle model and test schedule. The EPA used only city and highway test schedules up to 2007. Three additional schedules (high speed, air conditioning, and cold temperature) are used today in an attempt to get fuel economy ratings that are better matches to actual highway performance. Figure 2.3 shows the highway test protocol.

The purpose of the EPA fuel economy ratings is to determine whether manufacturers satisfy the CAFE standards. The ratings do not necessarily say much about the gasoline mileage a driver should get from a car, and the ratings are inadequate for comparing different engine technologies. Let me explain.

The dynamometer test is a strictly defined and controlled test procedure. Because the EPA rates all cars with the same test schedule, one can compare test results and say that a certain model is better than another model, slightly better, not as good, and so on. But the test cannot account for how a particular person drives (a
heavy foot on the accelerator, poor gear shifting skill, etc.), how much excess cargo they have in the car adding to weight, how the car is maintained, what the driving environment is (temperature, snow, rain, etc.), and so on. The EPA rating for a gasoline car is only a rough guideline for actual fuel economy. However, the actual fuel economy of two models with the same EPA rating should be roughly the same as long as the same driver operates them with the same level of maintenance, loading, environment, and so forth. Recently defined additional test protocols attempt to match common driving conditions to give a better indication of actual fuel economy and quiet consumer complaints about EPA fuel economy ratings.

We must be careful about comparing different automobile technologies using the fuel economy ratings. The following three examples should be thought-provoking. The Volkswagen Jetta, discussed in more detail in the next chapter, is a good example. The EPA rating for the diesel version is 36 mpg, while the rating for the gasoline version is 26 mpg. Concentrating on the EPA ratings, one might get the impression that the diesel is better than the gasoline model. However, when we consider consumption of crude oil, the
source of both gasoline and diesel, the result is different. Although the diesel consumes less refined fuel than the gasoline model, a barrel of crude oil has less diesel fuel than gasoline, and the diesel consumes more crude oil than the gasoline vehicle. If the chief concern is consumption of crude oil, the gasoline Jetta is more crude-efficient than the diesel model. I return to this topic in the next chapter when I discuss diesels.

Flex-fuel vehicles burning E85 ethanol fuel (consisting of 85% ethanol and 15% gasoline) provide a second example. According to the EPA ratings, flex-fuel vehicles generally get 25% poorer fuel economy than straight gasoline vehicles. In particular, a midsize Dodge Avenger gets 23 mpg on gasoline and 17 mpg on E85. However, if we are concerned about consumption of gasoline and crude oil, one should consider the composition of E85 fuel. Since only 15% of it is gasoline, 17 miles per gallon of E85 is equivalent to 113 miles per gallon of gasoline. While the EPA has a procedure for adjusting fuel consumption ratings for flex-fuel vehicles, the purpose is to document adherence to the CAFE standards and does not necessarily indicate how much gasoline one is using or saving.

My last example is the electric vehicle. General Motors has stated that EPA tests show that the Chevrolet Volt gets 230 mpg,\(^\text{10}\) which is a truly impressive fuel rating. However, the EPA test protocols are not set up to handle cars that get some motive power from batteries and some from gasoline, as is the case with the Volt. A more realistic figure is 50 mpg. I discuss the Volt’s fuel economy in detail in chapter 3.

Nonengineering Approaches to Fuel Economy

What can we do to save fuel without buying high-tech cars? First, we can drive fewer miles. But driving less might be difficult because decades of cheap fuel have led to the development of our highway system and separation of living and working centers, requiring long commutes, having to drive children to activities, and so on. More-
over, driving less consumes less gasoline but does not improve fuel economy per se. Second, we can drive smaller, lighter, less powerful cars. There is a clear advantage to doing so, but Americans must overcome their love of macho driving. Third, we can drive smarter. The EPA website lists several techniques for driving efficiently:

- Stop aggressive driving. This could improve fuel economy 5% to 33%.
- Drive at good speed. Fuel economy suffers significantly at speeds slower than 25 mph or faster than 55 mph. Save 7% to 23%.
- Reduce what you carry in your car. Each one hundred pounds of load changes fuel economy by 2%.
- Reduce excessive idling. Seventeen percent of fuel energy is lost to idling in city driving.
- Use cruise control and overdrive gear on the highway.
- Keep tires properly inflated. Fuel economy suffers 0.3% for each 1 psi difference from optimum in all four tires.
- Keep the engine tuned up. Not doing so can cost 4% in fuel economy.\textsuperscript{11}

These EPA guidelines are understandable in light of figure 2.1, showing energy losses in the internal combustion engine. Aggressive driving puts a lot of energy into vehicle momentum that is lost if it has to be removed by braking. Acceleration is essentially inefficient. High speed contributes directly to air resistance and indirectly to engine friction losses because high road speed requires high engine speed. The effect of weight is obvious, as greater load requires more work. Keeping tires inflated properly minimizes the frictional losses in tire rolling resistance. Idling is also an obvious loss.

There seems to be no consensus about how much the average driver can improve fuel economy by practicing all of the EPA suggestions, especially because many of us already follow some of
the recommendations. Still, widespread good driving habits could markedly raise national average fuel economy. A recent fad indicates what is possible. “Hypermiling” is the name given to driving techniques that markedly increase fuel economy. Some of these techniques, such as turning the engine off and coasting down inclines are dangerous and not to be encouraged. Still, hypermilers have claimed fuel economies of 76 to 213 mpg. The success of the fad shows strongly how much driving-behavior modification can influence fuel economy, much more in some respects than engineering developments can.

Summary

Examining energy losses for a typical late twentieth-century gasoline automobile provides insight into where R&D efforts should go to improve efficiency. While there is room for improvement, and raising the CAFE fuel economy standard is definitely a step in the right direction, it will take over forty-five years for the average fuel economy of cars on the road to rise to 34 mpg, 1.5 mpg less than the new CAFE standard. Indeed, if the new fuel-efficient cars cost more than current vehicles, there will be a resistance to purchasing new cars, and it will take longer for the fleet of cars on the road to transition to higher economy. The efficiency of current conventional gasoline automobiles is probably about as good as we can expect from internal combustion engines. There is not much more room for engineering improvement, and additional improvement will depend on further reducing size, weight, power, and drag. Overall, we have gotten about as much out of the internal combustion gasoline engine as possible. Meeting the new CAFE standard will require some additional engineering improvement in gasoline automobiles, balancing less fuel-efficient vehicles with smaller and lighter cars and adding advanced technology to the mix. Further improvement will require different technology. Even if we meet the 35.5 mpg goal, it will be about 2070 before we do so. Moreover,
increasing from 20 mpg to 35.5 mpg only reduces demand for gasoline 43%, not nearly enough by itself to eliminate the need to import foreign oil. We need additional improvements, such as the alternative vehicles discussed in the next chapter.

Distinct from increasing fuel economy by engineering changes, we can decrease demand for gasoline by modifying our behavior. Driving less and driving less aggressively would each have a marked effect on gasoline consumption. However, I am not sanguine about our doing so. The American lifestyle has developed over the past hundred years based on ready availability of inexpensive gasoline and the acceptance of a lot of driving. Changing this will not be easy. Many Americans are habituated to aggressive driving and will not give up such habits without a struggle. It may be possible to mandate sedate driving by enforcing limits on vehicle size, speed, power and so on, but any effort to do so would encounter substantial resistance. Requiring a 35.5 mpg CAFE standard for some vehicles while exempting gas-guzzlers also will not accomplish our goals.

Much of the improvement in fuel economy comes from reducing automobile size and weight, and many people are rightly concerned about the safety implications of mixing small fragile cars with large, heavy SUVs, trucks, and vans. Numerous studies, including recent crash tests of the very small Smart car, verify that the small cars do not do well in crashes with large cars. It is essential that efforts to make our highways safer for small cars accompany any efforts to downsize automobiles.