Transportation: Chapter 8

Freeways, cars, and trucks

- 220 million cars, trucks, and buses in U.S.
- 440 million parking spots!
- Roads cover more than 1% of entire country
- Most people drive to work alone
- Transportation 27% of all U.S. energy use
  - Cars, SUV's, light trucks: 61% of transportation energy
  - Big trucks: 19%
  - Airplanes: 8%
  - Pipelines: 4%
  - Railway: 2.5%
  - Buses: 1%

Interesting trivia: bicycle is most efficient known way to transport anything!

- Bike 3200 mi/million Btu (granola)!
- Walking: 1900 mi/million Btu
- Bus: 600 mi/million Btu
- Train: 300 mi/million Btu
- Car: 280 mi/million Btu
- Plane: 170 mi/million Btu

- Human on bicycle is more efficient than salmon swimming or albatross flying (all more efficient than any land animal walking)
- Million Btu ~ 8 gallons of gas

Physics of cars

- Four forces are important in understanding cars
- Remember: Energy = Force x distance (more force=> more energy)
  - Acceleration force: $F_{acceleration}$= m a
    - m is mass, a is acceleration (a = Delta v/ Delta t)
  - Climbing hills: F_{hill} = m g s (potential energy)
    - s= slope of hill, g = 9.8 m/s^2 (gravity)
  - F_{acc}=0 and F_{hill} = 0 going on level at constant speed
  - Rolling resistance: F_{roll}= C_{roll} m v
    - Cr coefficient of rolling: depends on type of tires, wheel bearings, etc
    - m is mass of car, v is speed of car, faster means more friction
    - Force in lbs
  - Aerodynamic drag force: F_{ad}= C_D A_f v^2 /370
    - C_D drag coefficient
    - A_f = frontal area of car or truck (in ft^2)
    - v is speed (MUST BE IN mph), Force in lbs

Drag coefficients (c_D)

• Square flat plate	1.17
• Ordinary truck	0.7
• 2003 Hummer H2	0.57
• Streamlined truck	0.55
• 1981 Cadillac	0.55
• Porche 928	0.45
• Jaguar XKE	0.4
• Ford Escort	0.39
• Camero/Datsun 280Z	0.35
• 1992 Ford Taurus	0.32
• 1997 Audi A8/Lotus Europa	0.29
• 2005 Toyota Prius	0.25
• VW research vehicle	0.15
• Boeing 747	0.031
• Teardrop	0.030

Example: calculate mpg of car at various speeds

- Consider Jaguar XKE going 75mph (area 28ft^2, c_D=.4)
  - F_{drag} = (.4)(28)(75^2)/370 = 170 lbs of force from wind drag
  - How about at 50mph? F_{drag} = 75 lbs (less than half as much!)
  - How about at 100mph? 75lbs (100mph/50mph)^2 = 300lbs
- Energy used is W = F d (efficiency)
  - Efficiency of cars: Carnot and waste heat in motor, drive train, tires on road (anything that gets hot wastes energy!)
  - Efficiency about 15% (can range from 10%-20%)
  - So energy used per mile for drag force only (at 75mph) is
    - E=(170 lbs)(5280ft)/.15 = 6 million ft lb/mile

- Now total force is sum: $F_{tot} = F_{acc} + F_{hill} + F_{roll} + F_{drag}$
  - On level ground at constant speed only F_{roll} and F_{drag} contribute
- Can estimate the miles per gallon; see how to design cars to get better mileage
- Suppose car weighs 3200 lb, c_D=0.35, Af = 28 ft^2, driving level freeway at 75 mph. Efficiency of motor/drive-train/etc. is 18%
  - Ftot = $F_{roll} + F_{drag} = 0.01\ m\ v + c_D\ A_f\ v^2/370$ (in lbs)
    - Problem with m in English units: m = w/g = lbs/32 ft/s^2
  - Ftot = $(.01)(3200/32)(75) + (.35)(28)(75^2)/370 = 75 + 149 = 224$lb
    - Most of force needed to fight wind resistance
  - Energy in one mile: E/mile = (5280ft)(224lb)/.18 = 6.5×10^6ft lb/mi
  - Convert to gallons of gas per mile (1.36J/1ft lb)(gal gas/1.32×10^8J) = .067 gal/mi. Take one over this to find 1/.067 = 14.9 mi/gal (Not too far off real answer)
  - Note if going 100mph, F_{roll} goes up to 75lb (100/75) = 100lb, while F_{drag} goes up to 149 lb $(100/75)^2$ = 264lb, so Ftot goes up to 364lb, and gas mileage goes down to 14.9mpg (224lb/364lb) = 9.1 mpg (See why speed limit was reduced to 55mph during 1973 oil crisis!)

How to make more fuel efficient car?

- Reduce F_{acc} =ma, by reducing mass and acceleration
  - Power to accelerate fast is paid for ALL THE TIME, so low power is good!
- Reduce F_{hill} =m g s, by reducing mass
- Reduce $F_{roll} = c_R$ m v, by reducing mass and by making car with less friction
  - Better tires can get extra 1-2 mpg, better engine design, etc.
- Reduce $F_{drag} = c_D\ A\ v^2/370$, by reducing frontal area and making more aerodynamic shape (to reduce c_D)
  - This is usually largest force, so most important! Need small area
  - Drag reduced by making car look like fish! e.g. Prius; this is shape of future whether you like look or not; think of a whale or 747 jumbo jet!
- Increase efficiency. Use lighter engine, better design, electric hybrid, etc.
  - Electric Hybrid has smaller gas engine, plus electric; uses electric motor to get enough F_{acc} and F_{hill}, so less wasted power. Also runs gas engine at optimal (most efficient) speed and charges battery. When braking, uses electric motor as generator to turn mechanical energy into electric and charge battery (usually goes to heating brake pads). Importantly is very light, low drag, and small frontal area.
- Car like Prius does all these and gets 45-55 mpg, Hummer does opposite of all these and gets 8 mpg
- Does a big hybrid SUV make sense?
- Future will be small, light weight, skinny cars with low power that look like fish!

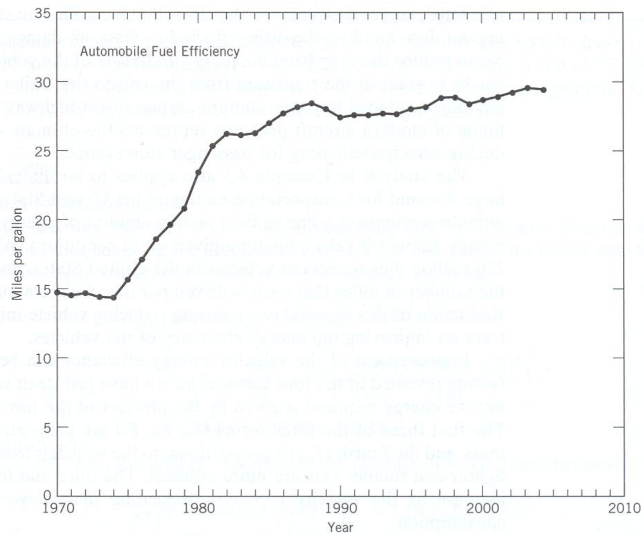

Figure 8.2 New car fuel efficiency in the United States since 1970. These are sales-weighted averages including domestic and imported passenger automobiles. Trucks, buses, light trucks, and sport-utility vehicles are not included. The increase since the minimum in 1974 is due to federally mandated standards for fuel economy as well as to technical advances in automobiles. (*Sources*: Oak Ridge National Laboratory, Light-Vehicle MPG and Market Shares System, Oak Ridge, TN, 1997; *Transportation Energy Data Book*, Edition 24, ORNL-6973, December 2004.)

Question

- Driving highway 5 and see sign: Next gas 33 miles; pass exit then notice cruising on empty! What should you do?

A. Drive as slow as possible to try and make it 33 miles

B. Drive as fast as possible to get there quicker

C. Give up; just pull over and cry

D. Drive as slow as possible in the highest gear

E. Drive normal speed, it is all the same

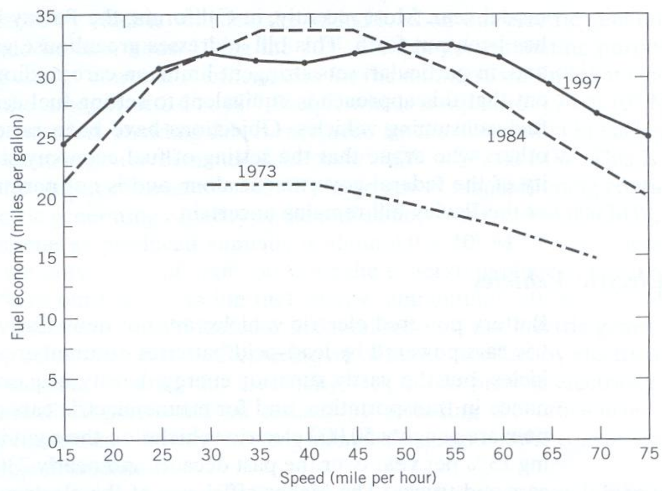

Figure 8.3 The dependence of fuel economy on speed. The results labeled 1973 are for an average of 13 vehicles from the model years 1970 and earlier. The 1984 test data are for 15 1981–1984 automobiles and light trucks; the 1997 data are for 9 1988–1997 automobiles and light trucks. Every one of the 37 tested vehicles showed a loss of fuel economy at 75 mph compared to 55 mph. (*Source*: *Transportation Energy Data Book*, Edition 24, December 2004. Stacy C. Davis and Susan W. Diegel. ORNL-6973, Oak Ridge National Laboratory.)

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The Relationship between Vehicle Weight, Size and Safety

Physics of Sustainable Energy:
Using Energy Efficiently and Producing It Renewably
Sponsored by American Physical Society's Forum on Physics and Society
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Improvements in both fuel economy and safety are possible

- Fuel economy improvement is cost-effective (Greene 2007, EEA 2006)…
  - technologies exist to raise fuel economy 50%, at current gas prices ($3.00/gallon)
  - includes some weight reduction in only heaviest pickups
  - does not include new powertrains (hybrid, plug-in hybrid, HCCI, fuel cells) or fuels (diesel, low-carbon fuels)
  - more technologies become cost-effective as gas price increases
- …but weight reduction is easiest, and least-costly, step to increase fuel economy
- Advanced materials (high-strength steel, advanced composites) may allow large weight reductions, and fuel economy improvement, without any sacrifice in safety
- Safety can be improved using new technologies, with little impact on weight or fuel economy
  - electronic stability control
  - better seat belts
  - stronger roofs
  - vehicle-to-vehicle communication

Definition of risk

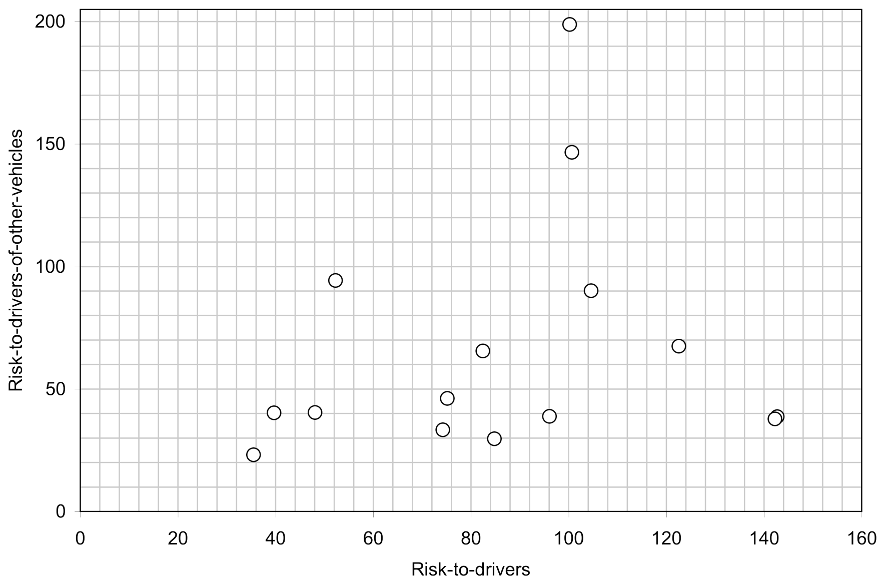
- "Risk": driver fatalities per year, per million vehicles registered as of Jan 2005
  - driver fatalities from NHTSA Fatality Analysis Reporting System (FARS)
    - FARS includes many details on all US traffic fatalities
  - registered vehicles as denominator, or measure of "exposure"
- Because it is based on actual fatalities, our definition of risk incorporates:
  - vehicle design
    - crash avoidance (sometimes measured by consumer groups)
    - crashworthiness (typically measured in artificial lab crash tests)
  - driver characteristics and behavior
  - road environment and conditions
- Therefore, all risks are "as driven"; as a result, our risks don't correlate well with lab crash test results

Two types of risk

- Risk to drivers of subject vehicle
  - from all types of crashes (total, and separately for two-vehicle crashes, one-vehicle crashes, rollovers, etc.)
- Risk imposed by subject vehicle on drivers of other vehicles (all types and ages)
  - often called vehicle “aggressivity” or “compatibility”
  - because from two-vehicle crashes only, risks to other drivers tend to be lower than risks to drivers
- Combined risk is the sum of the two

Risks by vehicle type

Risks by vehicle type

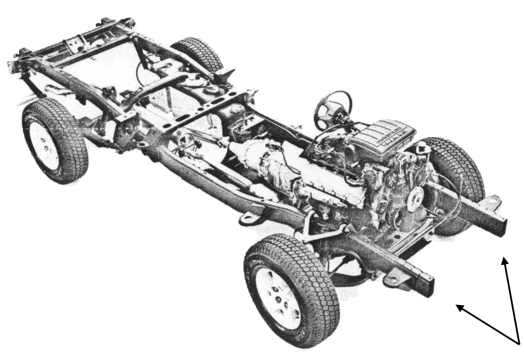


Risks by vehicle model

Effect of vehicle design on risk

- High risk to drivers of pickups and SUVs from their propensity to roll over
  - NHTSA's static stability factor (SSF): tw/2h
    tw = track width; h = height of center of gravity
  - average car SSF is 1.40, 12% chance of rollover in a crash
  - average SUV SSF is 1.15, 28% chance of rollover
- High risk to others from pickups and SUVs (and to a lesser extent minivans) associated with chassis stiffness and height
  - car driver fatality rate is 5x higher when struck in side by SUV (4x higher when struck by pickup) than when struck in side by another car
  - SUVs are built on pickup frames, whose rails often override car bumpers and sills and puncture car bodies
- Rollover risk in SUVs, especially crossovers, and risk to others from pickups are declining

Stiff frame rails of pickups and truck-based SUVs act as fork tines



MY02 Dodge Ram 150 pickup truck

Table 8.5 Fatalities in the United States by Type of Accident (2002)

Motor vehicle	42,000
Falls	16,000
Drowning	3,400
Fires	3,200
Electrocution	430
Lightning	75

Source: National Safety Council, 2005.

Table 8.6 Traffic Fatalities per Vehicle-Mile in the United States

Vehicle	Deaths per 10^8 Vehicle-Miles
Automobiles	1.5 (2002)
Automobiles on rural interstate highways	1.2 (2002)
Automobiles on urban interstate highways	0.6 (2002)
Bus	0.5 (2001)
Train	2.0 (2003)
Airline	0.000 (2002) 0.313 (2003)
Motorcycle	34 (2002)
Horses (26×10^6 horses, 1.3×10^{10} miles, 3850 deaths)	30 (1909)

Sources: Statistical Abstracts of the United States, 1996; U.S. Bureau of Transportation Statistics, 2003.

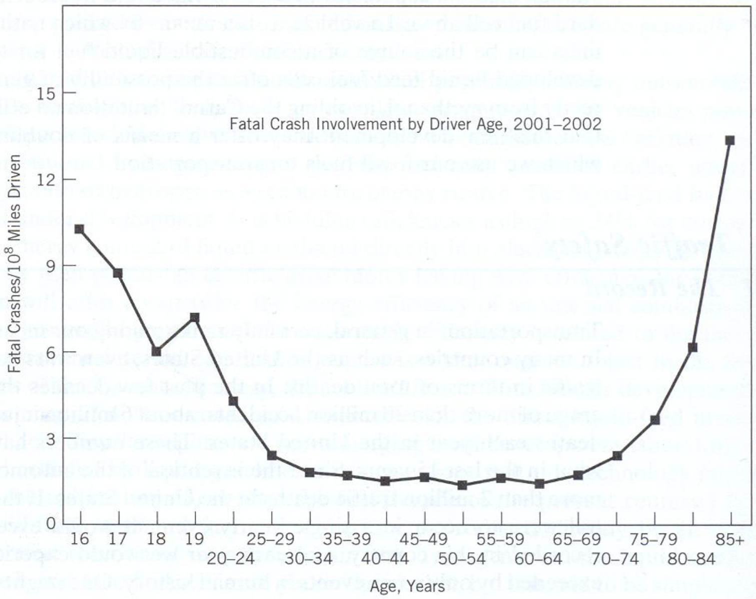


Figure 8.10 Fatal crash involvement by driver age. The high rates at the lower and higher ends of the age range are discussed in the text. (*Source*: Insurance Institute for Highway Safety, 2002.)

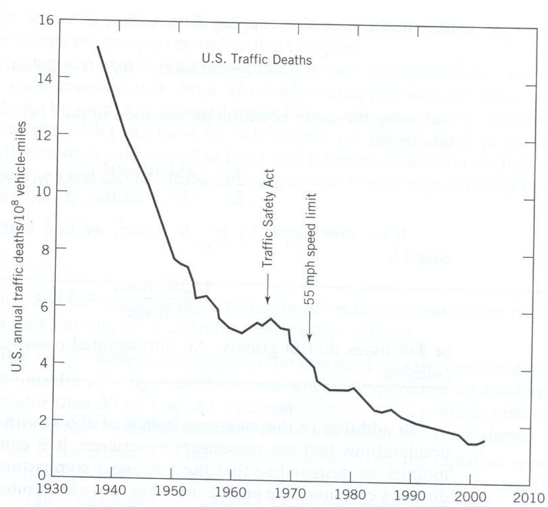


Figure 8.11 A 70-year record of U.S. traffic deaths per 100 million vehicle miles. From 1936 to 1960 there was a rapid decline due to improvement of vehicles, roadways, and driver licensing. After 1960 the rate started to turn up again until passage of the Traffic Safety Act. A further drop after 1973 is often attributed to the 55 mph speed limit. In 1988 the speed limit on some interstate highways was increased to 65 mph. In 1995 it became 75 mph in some locations. Over the time period shown on this graph the number of vehicle-miles in the United States each year increased more than ten times. (*Sources*: *Statistical Abstracts of the United States*; U.S. Bureau of Transportation Statistics, 2003.)

Future cars: Hydrogen

- What about hydrogen cars?
  - H is most common element in Universe! (75%!), but on Earth does not exist in pure state (lighter than He, rises and escapes atmosphere into space)
  - Lots of in in H_2O, but takes energy to get it out; can also get from hydrocarbons like methane (CH_4), etc.
  - Once have it out burns very clean ($H + O_2 \rightarrow H_2O$); no nasty pollution
  - Is very concentrated form of energy
    - Hydrogen has 38 kWh/kg (remember 1 gallon of gasoline has 36.6 kWh)
    - Gasoline has 13 kWh/kg
    - Flywheel has 0.9 kWh/kg
    - Lead acid battery has 0.03 kWh/kg (see why electric cars have problems!)
  - In gaseous forms takes lots of volume.
    - 1 kg with energy of 1 gal gas takes ~1000 gallons of volume
  - Gasoline is always used in heat engine (Carnot efficiency limited), but Hydrogen can be used in fuel cell: Direct conversion of H to electricity. Can get efficiency of 65%-80%, much better than gas engine

Future cars: Hydrogen

- Hydrogen cars continued
  - Hydrogen is very dangerous; burns and explodes much more easily than gasoline
    - e.g. nat gas explodes only when between 5%-15% concentration in air, while Hydrogen explodes at any concentration between 4%-75%; explosion is also 15 times more powerful
    - Hydrogen is also invisible when it burns!
- Conclusions:
  - Hydrogen not source of energy, more like a battery, and even with fuel cell not more energy efficient than Prius!
    - Total efficiency is 30%-40% to make electricity from coal/nat gas
    - Times 65% to make H gas from H_2O
    - Times 65%-80% to turn H back into electricity
    - Times 90%-95% electric motor in car
    - Total is efficiency is 11%-20%, about same as a regular car!
    - But far more expensive

Future cars: Hydrogen

- However, if H gas is produced from solar electricity rather than coal or nat gas, then reduces use of fossil fuel and produces no CO_2
- Could be good in future, but would require completely new infrastructure for transporting and fueling H gas (or liquid H which would take even more energy to produce)
- Currently fuel cells used in space craft but way too expensive for cars (e.g. $1 million)
- Hydrogen probably not going to be very important in near future

Future cars: Flex cars/Ethanol

- We talked about ethanol before: Study by Farrell, Kammen, et el., Science, 311, 506 (2006)
- Ethanol made from corn, sugar cane, etc. Contains 2/3 energy content of gasoline (24 kWh/gal vs. 36.6 kWh/gal)
- Compared 6 studies of U.S. corn based ethanol:
  - These found NET energy of -6 kWh/gal to 11 kWh/gal; Farrell, et al. corrected these to common assumption and got a range -4 kWh/gal to +9 kWh/gal. Their best estimate was 4 kWh/gal
  - That is, out of 24 kWh in one gallon of ethanol, 20 kWh, all but 4 kWh, went into producing it.
    - Net energy Ratio is therefore 24/20 = 1.2 for ethanol
  - For gasoline, about 7% of energy in gallon for production
    - Ratio is therefore 36.3/(.07x36.6) =14.2
  - Worst is that 2 out of 6 studies showed net energy loss!
- Conclusion: Corn ethanol only exists because of govt. subsidies and regulations: not good for environment, etc.

Future cars: other Bio fuels

- Ethanol from sugar cane
  - Much higher energy ratio's since more energy produced and less energy used in production. Brazil has replaced nearly all cars with ethanol cars, and has greatly reduced oil imports.
  - What will be affect on rainforests and CO_2?; jury still out; probably not good
- Celluosic ethanol: from switchgrass or wood chips, etc.
  - Big money going into developing (BP/Monsanto)
  - So far not practical, but could have much better energy ratio than corn ethanol, if chemistry problems are solved
- Convert vegetable oils into bio-diesel fuel?
  - Too soon to tell; very popular in Europe where there are big govt. subsidies. Net energy ratio can be better than corn ethanol, but net CO_2 may be worse than just burning gas. Plus land used for food is displaced causing food prices to increase.

Future cars: Electric

- Seems like an ideal solution: No pollution, efficiency of electric motor can be 95%, much better than 15-18% of gasoline engines (but hybrids are better than normal gas)
  - BUT NO GOOD BATTERY!
    - Lead acid batter can only hold 0.03 kWh/kg
    - Compared to gasoline: 13 kWh/kg, 400 times less energy density than gasoline => very heavy (big m =>bad) or very short driving range
    - Lithium batteries are much better, but currently very expensive
    - Maybe technology will save situation?
  - Also currently, energy used by electrics is NOT MUCH LESS than gas cars! (consider electricity made by burning coal or nat gas)
    - Power plant ~30%-40% efficiency
    - Transmit electricity over power lines (~92% efficiency)
    - Charge lead-acid batteries (60-80% eff)(Li ion 86%)
    - Electric motor, etc. (90-95%)
    - Total is: 15%-30% efficiency before counting tires, drive train, etc. but for high efficiency need very expensive Li-ion batteries (Tesla)
- Eventually invent better battery and get electricity from solar, etc.

Future cars: Flywheels, other?

- Flywheels can store 0.9 kWh/kg (30 time more than current batteries, but 10 times less than gasoline)
- Idea is old, seems good, but no one is seriously developing
- Can be dangerous

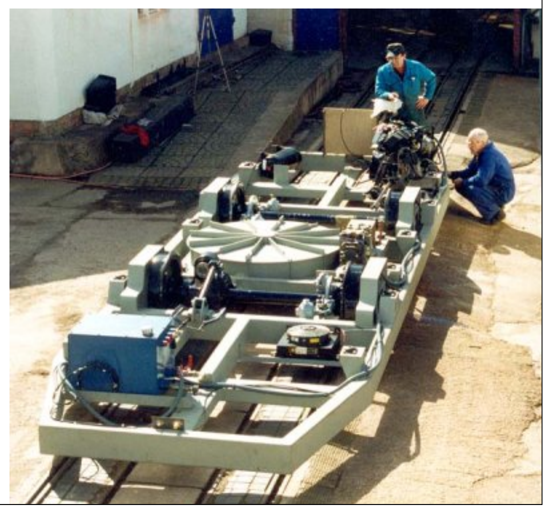


Table 8.1 Energy Used in U.S. Transportation (2002)

Mode	Btu (10^{12})	Percent
Automobiles	9,326	35.4
Motorcycles	24	0.1
Buses	191	0.7
Light trucks	6,842	26.0
Other trucks	5,027	19.1
Air	2,213	8.4
Water	1,185	4.5
Pipeline	935	3.5
Rail	621	2.4
Total	**26,364**	
	(4.7×10^9 bbl petroleum)	

Source: Transportation Energy Data Book, Edition 24, ORNL-6973, December 2004.

Table 8.2 Energy Efficiency Estimates for Various Forms of Transportation

Passenger Transportation	Passenger-Mile/10^6 Btu
Bicycle (8 mph)	3200
Walking (3 mph)	1900
Bus, intercity	1100
Bus, transit	240
Automobile	280
Train	210–370
Airplane, commercial passenger	270
Freight Transportation	**Ton-Mile/10^6 Btu**
Ocean oil tanker	12,500
Pipelines	3300
Railroad	2900
Waterway	2100
Truck	385
Aircraft	32

Source: Richard C. Dorf, *The Energy Factbook*, McGraw-Hill, 1981; *Transportation Energy Data Book*, Edition 24, ORNL-6973, December 2004.