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Energy Use in Ground Transportation

DEPARTMENT OF
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Booz-Allen & Hamilton, Inc.
Bethesda MD 20814

June 1983
Final Report

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Urban Mass Transportation Administration

Office of Technical Assistance
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16. Abstract

This report is designed to serve as a handbook-type reference of the major factors affecting transit vehicle efficiency and energy consumption in automotive, bus, and urban rail transportation modes. It includes a summary of the various factors, both operational and equipment-related which impact energy consumption in transit vehicles. Special emphasis is given to subject content expected to be of greatest interest to individuals active in the field of transportation and energy management. Those desiring more detailed treatments in a given area are referred to the bibliography at the end of the report.

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PREFACE

This report reviews the principal technological factors which affect the three modes of transportation,-automotive, bus, and urban rail. The material for the report was compiled by Booz-Allen & Hamilton Inc. under a Task Directive (No. TTD 1744-015) with the Transportation Systems Center. Funding for this effort was provided by the Urban Mass Transportation Administration, U.S. Department of Transportation.

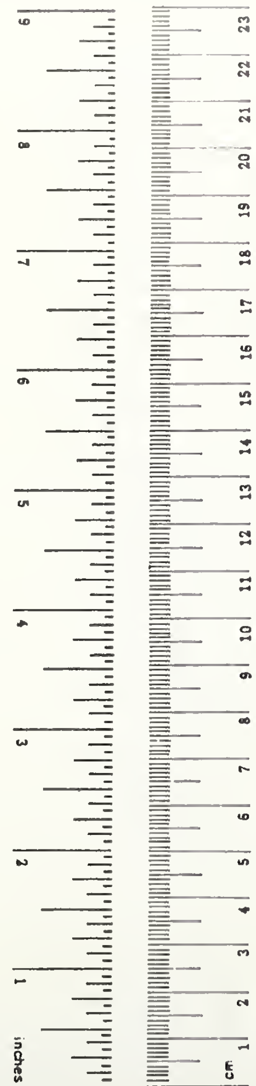
The contributors to the report include the following: Automotive Systems, Mr. Russell Zub, Transportation Systems Center and Mr. Arthur Karlin, Booz-Allen & Hamilton Inc.; Urban Bus Systems, Mr. Archie Riviera, Booz-Allen & Hamilton, Inc.; Urban Rail Systems, Mr. Michael McDonald and Mr. David Turner, Booz-Allen & Hamilton, Inc. Report editing was provided by Mr. John Stickler, Transportation Systems Center.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

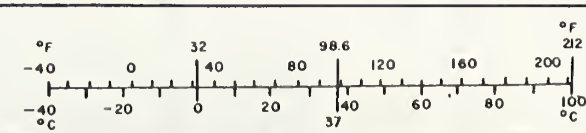


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

Transportation systems account for approximately twenty five percent of the country's total energy consumption. Such a large fraction of the nation's energy resources has prompted increased awareness of the role which transportation technology plays in the area of energy consumption. Of the different transportation modes, automobiles and trucks combine to consume approximately three-quarters of all transportation energy as of 1980. The importance of technologies aimed at reducing these large expenditures of our nation's resources cannot be minimized.

This report reviews the principal technological factors which affect the three modes of transportation,-automotive, bus, and urban rail, and seeks to provide the reader with a summary of the parameters which critically impact each mode. It is meant to serve as a handbook-type reference of the important factors affecting transit vehicle efficiency and energy consumption. The guideline for the selection of the material is the relative amount of technological information available in the given transportation field and the anticipated degree of interest in the given field. Individuals desiring more detailed treatments in any subject are referred to the bibliography at the end of the report.

2.0 ENERGY USE IN TRANSPORTATION SYSTEMS: OVERVIEW

Over the past 30 years, energy used in transportation has remained at approximately 25 percent of the country's total energy consumption (Figure 1). While the transportation share of U.S. energy consumption has remained relatively constant, annual consumption has increased from 7.2 quads (1 quad is 10^{15} Btu) in 1950 to 20.1 quads in 1980. Petroleum derivatives are the primary source of energy for transportation purposes, supplying nearly 97 percent of transportation energy requirements and making up 52 percent of total U.S. petroleum consumption.

Automobiles consumed approximately 49 percent and trucks about 26 percent of all transportation energy in 1980 (Table 1). Gasoline was the primary fuel used in transportation, representing 68 percent of all transportation energy.

Table 2 shows a range of values of primary fuel energy use for different modes. Fuel use per vehicle-mile is influenced by vehicle technology, system operating characteristics, and terrain. Fuel use per passenger-mile also depends on the typical vehicle load. Rail transit has the lowest fuel cost per passenger-mile, followed by commuter rail and buses. Autos have the highest costs,

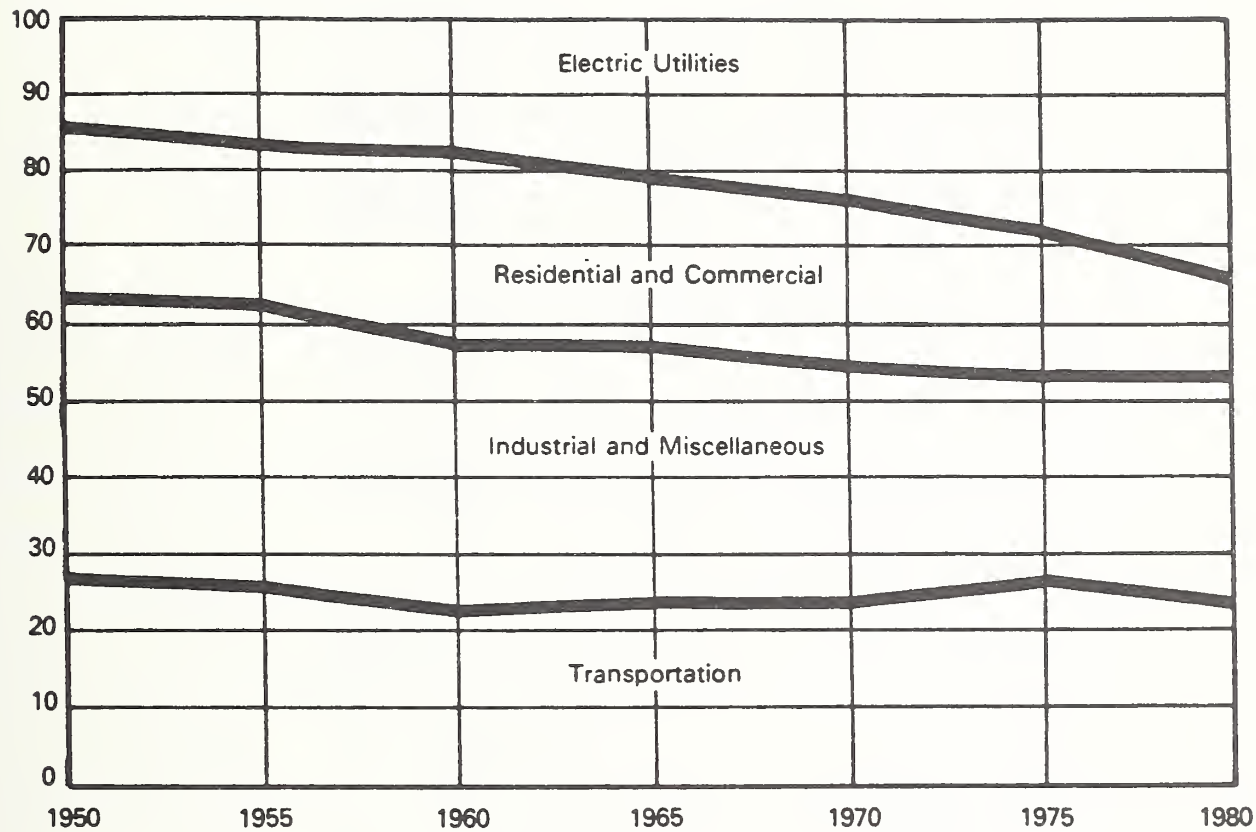


Figure 1. U.S. energy consumption, end use shares

Table 1. Energy consumption by mode and fuel type (1980, quads)

Mode	Gasoline	Distillate Fuel	Liquefied Gases	Jet Fuel	Residual Fuel	Natural Gas	Electricity	Total	Percent of Total
Motorcycle	0.1	--	--	--	--	--	--	0.1	0.5
Automobile	9.9	--	--	--	--	--	--	9.9	49.3
Recreational vehicle	0.1	--	--	--	--	--	--	0.1	0.5
Bus	--	0.1	--	--	--	--	--	0.1	0.5
Truck	3.3	1.8	0.1	--	--	--	--	5.2	25.9
Air	0.1	--	--	1.6	--	--	--	1.7	8.5
Marine	0.2	0.2	--	--	1.4	--	--	1.8	9.0
Pipeline	--	--	--	--	--	0.5	0.1	0.6	3.0
Rail	--	0.6	--	--	--	--	--	0.6	3.0
Total	13.7	2.7	0.1	1.6	1.4	0.5	0.1	20.1	100
Percent of total	68.2	13.4	0.5	8.0	7.0	2.5	0.5	100%	

Table 2. Energy use and energy cost per passenger-mile by mode

Mode	Equivalent Vehicle-Miles per Gasoline Gallon[1] (range of typical values)	Btu per Mile	Load: Passengers per Vehicle		Btu per Passenger-Mile[1]		Fuel Cost (cents) per Passenger-Mile[2]	
			Typical (range)	Maximum	At Typical Load	At Maximum Load	At Typical Load	At Maximum Load
Automobile	11.4	10,970	1.1-1.6	5	6,856-9,972	2,194	6.9-10.0	2.2
	15	8,330			5,206-7,572	1,666	5.2-7.6	1.7
	22.5	5,260			3,288-4,782	1,052	3.3-4.8	1.1
Bus	3.8	32,660	9.8-19.1	50	1,709-3,333	653	1.7-3.3	0.7
	4.8	26,310			1,377-2,685	526	1.4-2.7	0.5
Light rail	1.45	86,400	17-27	63	3,200-5,082	1,371	1.3-2.0	0.5
transit	2.17	57,750			2,139-3,397	917	0.9-1.4	0.4
Heavy rail	1.71	73,180	18-28	72	2,613-4,065	1,016	1.0-1.6	0.4
transit	2.23	56,175			2,006-3,120	780	0.8-1.2	0.3
Commuter rail	1.8	69,540	24-60	100	1,159-2,898	695	1.2-2.9	0.7
	2.90	43,150			719-1,798	432	0.7-1.8	0.4

Table 2. (continued)

Air (certi-fied carrier)	0.26	490,740	86	150	5,708	3,272	5.7	3.3

Sources: "Urban Transportation and Energy: The Potential Savings of Different Modes," Committee on Environment and Public Works, U.S. Senate, September 1977. "National Transportation Statistics," September 1980.

[1]Values are expressed in terms of energy content of primary fuels. Thus, for electrical modes (transit), energy requirements are three times the operating system electrical energy use to reflect 33 percent efficiency of electrical generation and distribution. 1 gallon of gasoline = 125,071 Btu.

[2]Fuel cost to operating authority. Electrical energy requirements for transit are divided by 3 to convert to actual electricity use. Costs are $1.30/gallon of liquid fuel (about 1 cent/1,000 Btu) and 4 cent/kwh of electricity (about 1.2 cents/1,000 Btu).

Note: 1 mpg = .425 km/l

1 Btu/mi = .000181 kwh/km

1¢/mi = 1.609344¢/km

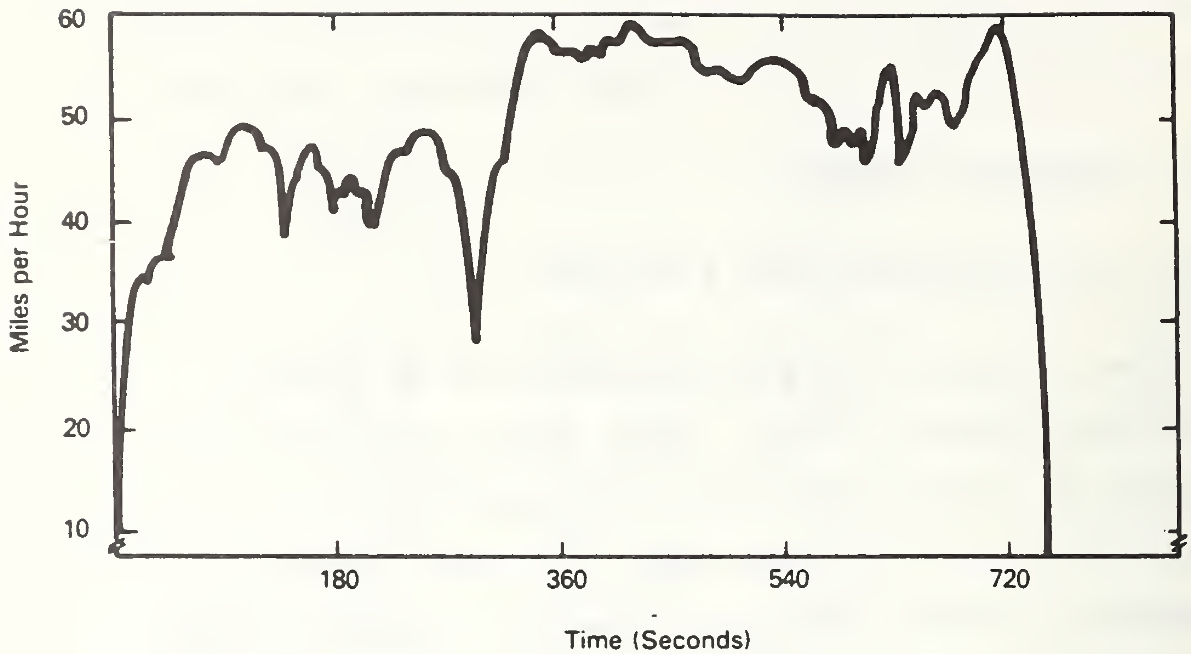
although new high-mileage vehicles can approach the costs of the mass transit modes in normal operating conditions.

2.1 AUTOMOTIVE SYSTEMS

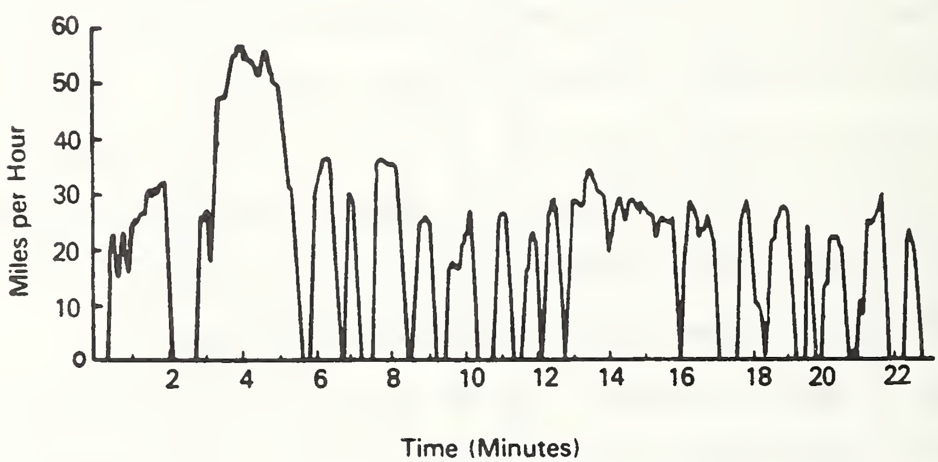
2.1-1 Duty Cycle and Fuel Efficiency

Fuel efficiency is greatly influenced by vehicle operating characteristics. To be useful, measurement methods for fuel economy must be repeatable and measurements must be taken under conditions normally expected in vehicle operation. For this reason, standard duty cycles and testing procedures have been developed. The repeatability of the standard tests allows comparison of vehicles and on-board vehicle systems.

Two commonly used duty cycles for measuring automotive fuel economy are the Environmental Protection Agency city (or urban) and highway driving cycles (Figure 2). The city cycle is 7.5 miles (12 km) long and has an average speed of 19.6 mph (31.5 kph), with approximately 2.3 stops per mile (1.6 km); the highway cycle is 10.3 miles (16.6 km) long and has an average speed of 48 mph (77.2 kph). Vehicle speeds and acceleration rates in the two cycles approximate survey data, although the cycles may be slightly biased toward slower speeds and lower acceleration rates than those that occur in actual practice. Both EPA tests assume level terrain.



Highway Cycle



City Cycle

Figure 2. EPA city and highway cycles

The combined EPA city and highway fuel economy rating is a weighted average of the EPA city and highway figures, proportioned 55 percent city and 45 percent highway:

$$\text{Composite mpg} = \frac{1}{\dfrac{0.55}{\text{City}} + \dfrac{0.45}{\text{Highway}}}$$

The Energy Policy and Conservation Act of 1975 established a corporate average fuel economy (CAFE) value for automobile manufacturers for the next 10 years based on the composite EPA fuel economy ratings. Table 3 shows the CAFE standards.

A duty cycle affects fuel economy in four major areas: vehicle speed, stops per mile, acceleration rate, and road grade.

Fuel consumption as a function of steady-state vehicle speed is shown in Figure 3. Vehicles at low speeds tend to have low fuel efficiency because of the poorer engine efficiency at low power and the increased relative importance of drive-train frictional losses. Vehicles at high speeds have poor fuel efficiency because of large aerodynamic losses. Also shown in Figure 3 is the effect of the number of stops per mile on fuel consumption. Stops reduce fuel economy because of the increased fuel consumption during repeated acceleration as well as the fuel consumed at idle. The acceleration rate affects fuel

Table 3. Corporate average fuel economy standards

Year	Automobile Fuel Economy (mpg)
1978	13.0
1979	19.0
1980	20.0
1981	22.0
1982	24.0
1983	26.0
1984	27.0
1985	27.5

NOTE: 1 mpg = .425 km/l

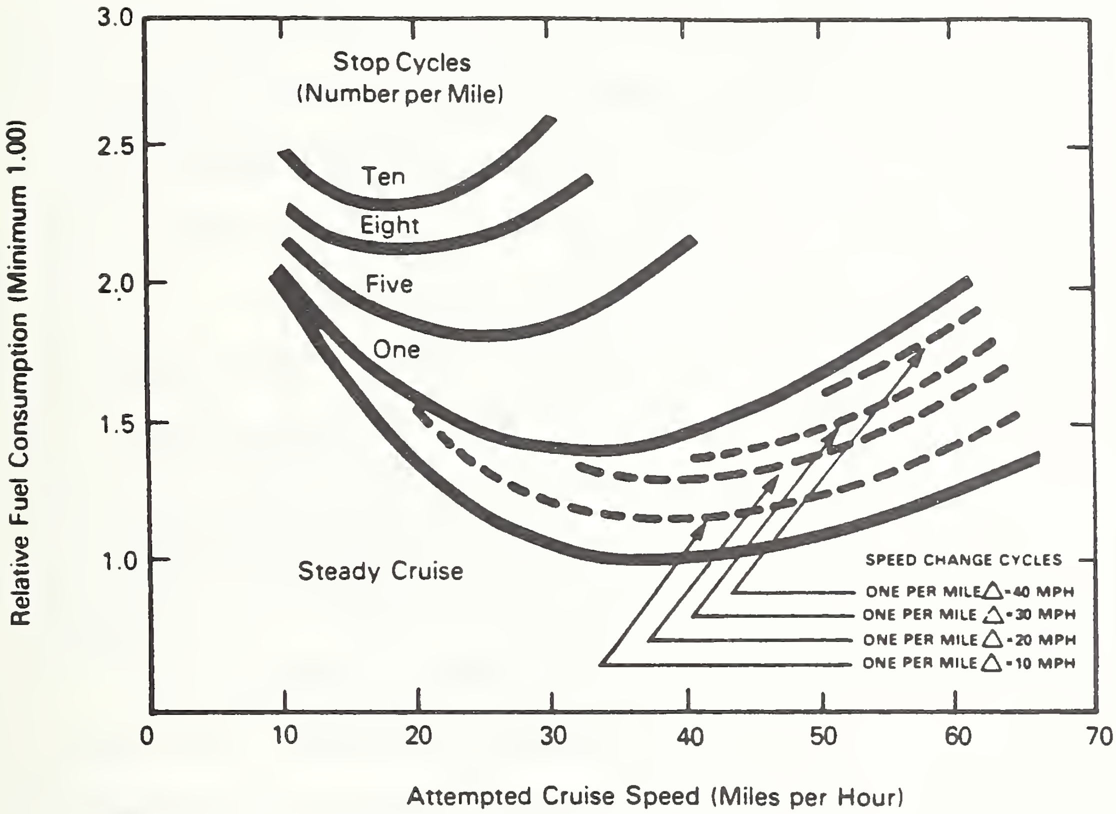


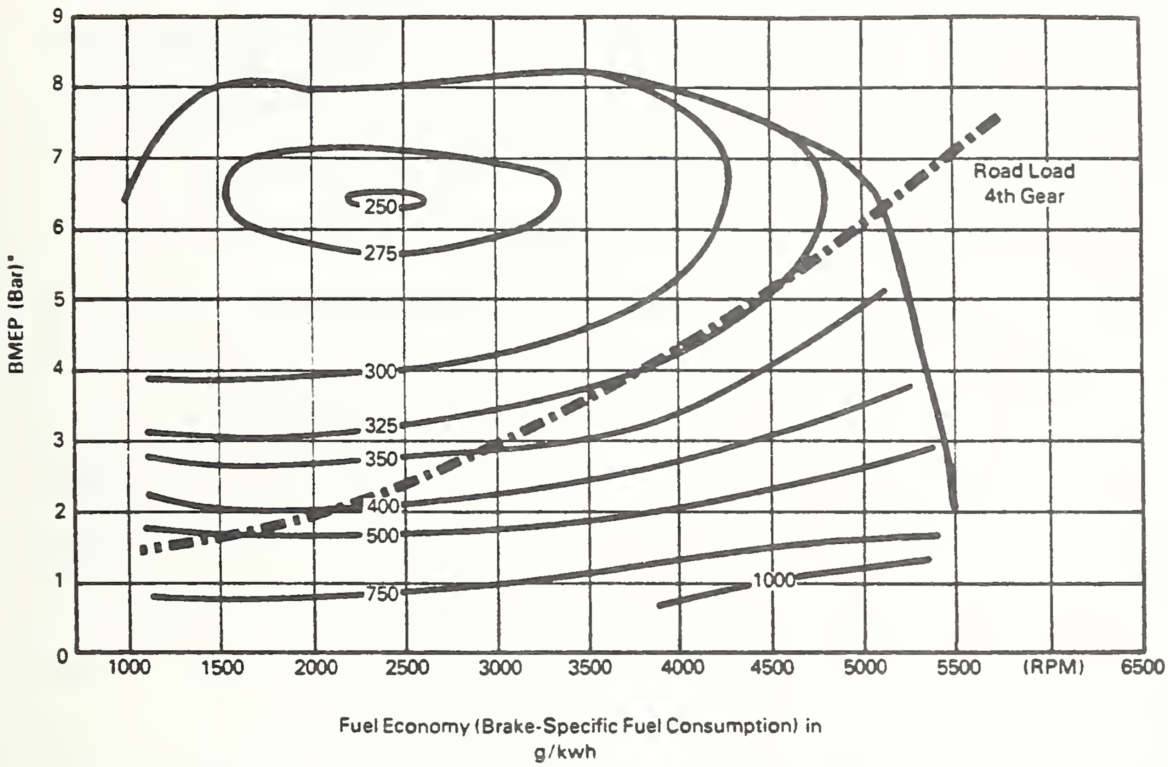
Figure 3. Effects of stops and speed variations on fuel consumption

economy since it affects engine operating parameters (load and speed) and efficiency and changes the vehicle speed distribution during the driving cycle. The effect of road grade on fuel economy depends on vehicle speed and grade level. In steep terrain there is a slight reduction in fuel economy because energy saved on downhill travel does not quite equal increased uphill energy use.

EPA combined city and highway vehicle fuel economy figures have consistently overstated, by about 15 to 20 percent, the mileage that cars actually achieve on the road. This is due to the non-ideal nature of the travel environment in terms of temperature, wind, road gradient, and road surface conditions, as well as some of the non-typical aspects of the EPA driving cycles, non-ideal vehicle condition, and inaccuracies in the test procedure. The EPA city/highway figures will probably continue to overstate actual fuel economy by about 20 percent.

2.1-2 Energy Budget of the Automobile

The brake-specific fuel consumption (BSFC) of an internal combustion engine is defined as the amount of fuel mass required per unit of engine energy output. An engine's fuel consumption is a function of both load and engine speed and can be presented as an engine map. In the sample shown in Figure 4, the engine BSFC ranges from



*Brake mean effective pressure (engine load)

Figure 4. Typical engine map (Volkswagen Rabbit Diesel)

Source: P. Hofbauer and K. Sator, "Advanced Automotive Power Systems, Part 2: A Diesel for a Subcompact Car," SAE Paper 770113, Feb. 1977.

250 to 1,000 g/kwh, with the greatest efficiency at about 3/4 load and an engine speed of 2,500 RPM.

The energy delivered from the engine must accelerate the vehicle and the drive train against air resistance, rolling resistance, drive-train friction, and power accessory resistance forces.

A simplified overall energy balance equation for an automobile can be expressed as

$$P_{eng} = \left[\underset{(1)}{\frac{C_D}{2} \rho A V^2} + \underset{(2)}{C_R M g} + \underset{(3)}{M g \sin \theta} + \underset{(4)}{M a} \right] V + \underset{(5)}{P_a} + \underset{(6)}{P_L} + \underset{(7)}{P_I}$$

Equation 1

where: P_{eng} is power from the engine; V is vehicle velocity; A is vehicle frontal area; ρ is density of air; M is vehicle mass; g is acceleration of gravity; a is vehicle acceleration; P_a is accessory power; P_L is drive-train friction losses; P_I is power required to accelerate the drive train; θ is grade angle; C_D is drag coefficient; and C_R is rolling resistance coefficient;

Term (1) represents the **aerodynamic resistance** and is a function of the velocity squared and the vehicle frontal area. The drag coefficient, C_D, is determined by the vehicle's shape, load distribution, and external items. **Term (2)** represents the **rolling resistance.** This term is predominantly proportional to vehicle weight, although there is some effect from vehicle speed. The rolling resistance coefficient, C_R, will also be affected by road surface conditions and tire pressure. **Term** (3) is the force required to move a vehicle on a grade, and **Term** (4) is the force needed to accelerate a vehicle. Both of these terms are directly proportional to vehicle weight. **Term** (5) is the power of accessories such as fans, pumps, air-conditioning, and alternators and depends on the specific accessories and their use. This is not a simple function of weight or vehicle speed, although it can be affected by driving cycle. For instance, certain cooling fans are now designed to shut off at high vehicle speeds. Air-conditioning power requirements vary with the duration of compressor operation. **Term** (6) represents friction losses in the torque converter, transmission, and other parts of the drive train. These losses are also not simple functions of weight or speed but depend on gear, vehicle speed, and load. **Term** (7) represents power required to accelerate the engine, drive train, and wheels.

Figure 5 shows the key energy losses for a vehicle moving at various constant speeds. Table 4 shows the energy dissipation of a recent vehicle on the urban and highway EPA cycles.

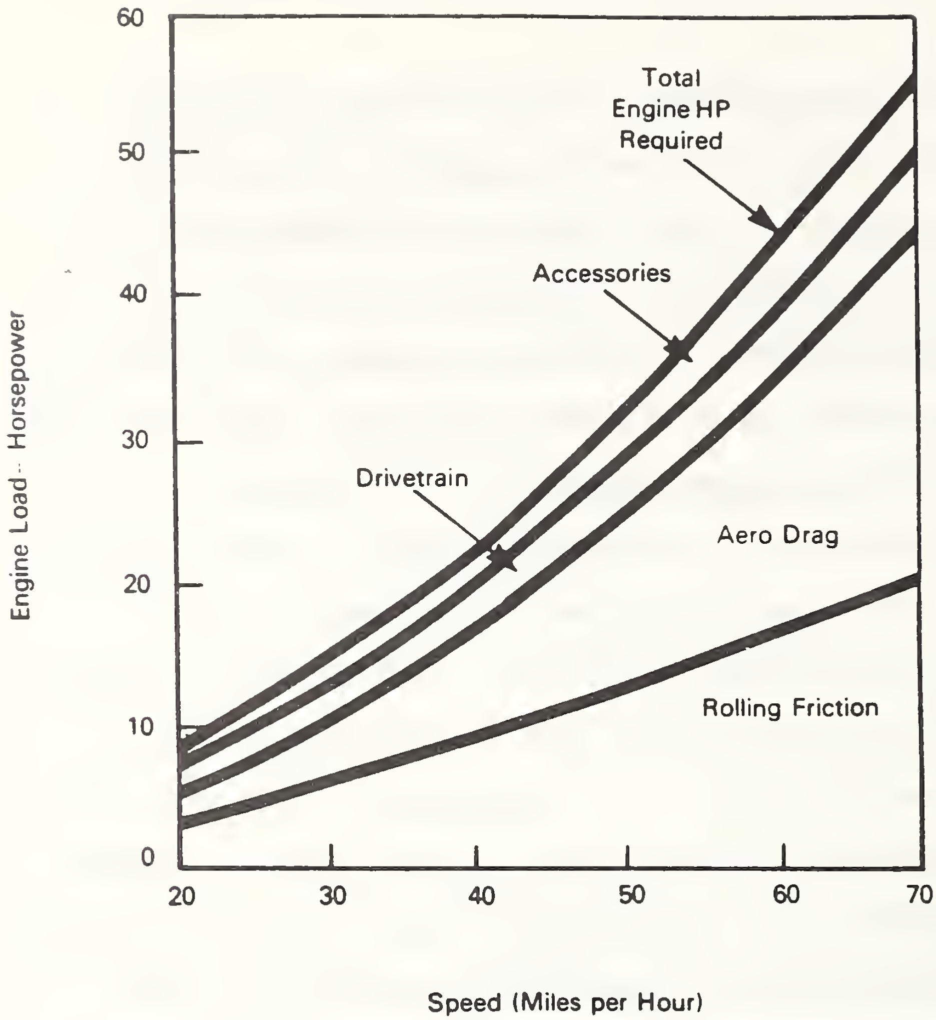


Figure 5. Effect of speed on power requirements (standard size car)

Source: Jet Propulsion Laboratories, "Should We Have a New Engine? An Automobile Power Systems Evaluation," August 1975.

Table 4. Percent of total energy output for a 1981 2,400-pound vehicle

Component	Urban Cycle	Highway Cycle
Accessories	8	4
Transmission	3	2
Differential	3	3
Aerodynamics	25	56
Rolling Resistance (tire)	27	28
Braking (weight-dependent)	34	7

2.1-3 Chassis and Body Characteristics

The effect of **aerodynamics** on automobile fuel economy over the composite drive schedule is about 2 to 3 percent for each 10 percent reduction in aerodynamic drag. C_D values (see Equation 1) vary depending on vehicle shape, load distribution, and shape of vehicle trim. The range of C_D values for current automobiles is on the order of 0.3 to 0.5, but research vehicles such as the Ford Probe III and Volkswagen Auto 2000 have drag coefficients of 0.22 to 0.25. The techniques used to achieve these low coefficients include a squared-off tail, rear spoiler, underbody panel, and flush side windows.

Weight is the most important design parameter affecting fuel economy. As can be seen in Equation 1, weight directly affects rolling resistance, power required for acceleration, and power required for grades. Figure 6 shows how fuel economy changes with weight. Weight reduction is accomplished in vehicles through downsizing and material substitution. Between 1977 and 1981, average vehicle weight in the United States dropped from 3,830 pounds (1,737 kg) to 3,080 pounds (1,397 kg). Further weight reduction will require greater use of lightweight materials such as aluminum, high-strength steel, and plastic.

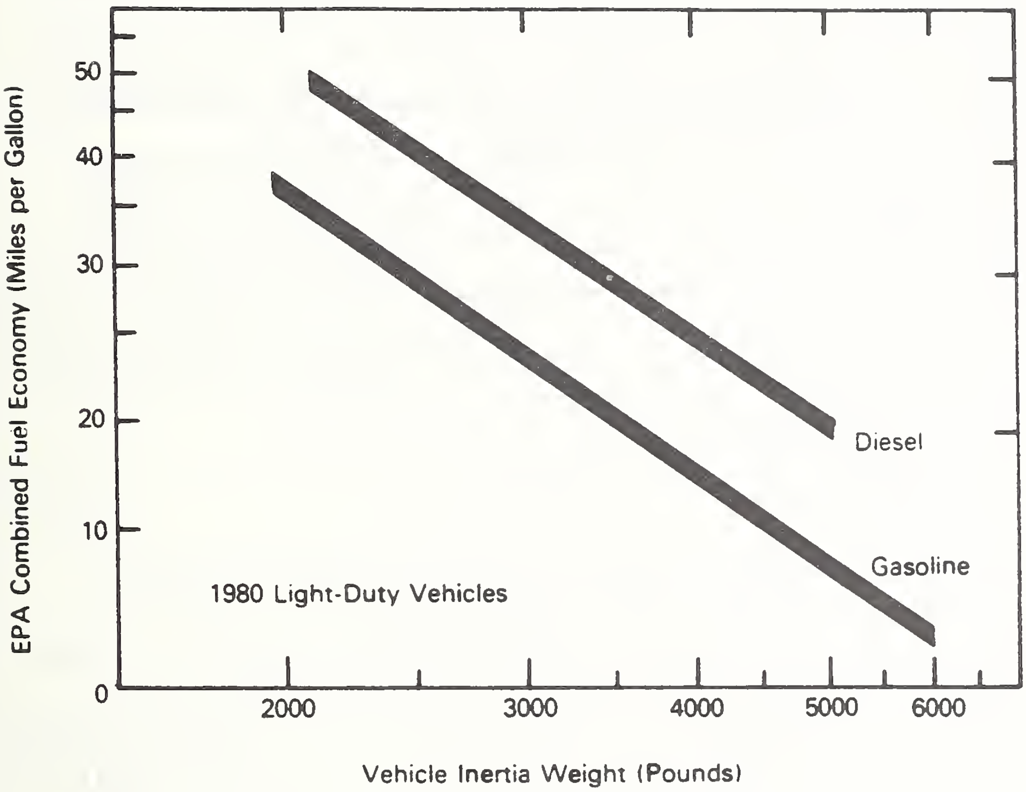


Figure 6. Average 1980 EPA combined—schedule fuel economy for light-duty vehicles powered by gasoline and diesel engines

Source: "Passenger Car Diesels," PT-24, Introduction, SAE, Warrendale, PA.

As shown in Equation 1, the **rolling resistance** is a function of vehicle weight for a given tire and pressure. The rolling resistance is also a function of tire type and air pressure. Automotive rolling resistance coefficients C_R are around 0.010 to 0.015. Radial tires are generally 15 percent lower in rolling resistance than bias tires. For tires at constant load, the variation of rolling resistance with tire pressure tends to follow the equation:

$$F_r = F_{ro} \left[1 + C_p \left(\frac{P_o}{P} - 1 \right) \right]$$

where F_r is the rolling resistance, F_{ro} is the initial rolling resistance, P is the final pressure, and P_o is the initial pressure. C_p is a constant that is about 0.5 for many applications. For example, an 8-psi (55,158-Pascal) decrease in pressure on a 30-psi (206,843.61-Pascals) tire will increase rolling resistance by about 18 percent. As a rule of thumb, each 10 percent reduction in rolling resistance will improve fuel economy by about 2 percent. Table 5 shows several measurements of the effect of tire pressure on fuel economy.

Surfaces other than dry, well-maintained concrete or asphalt decrease fuel economy. This is apparently due to an increase in both rolling resistance and aerodynamic drag caused by vehicle pitch and yaw. Gravel and sand can reduce fuel economy 5 to 20 percent at slow speeds and 5 to

Table 5. Effects of tire pressure on fuel economy

Test	Percent Improvement per psi	Study Parameters
Grugett et al.	0.33	Radial tires, 1979 Chevy Novas, composite urban-highway driving cycle
Goodyear	0.30	Radial tires, full-size sedan, constant 45 mph
	0.75	Bias tires, full-size sedan, constant 45 mph
Corporate Tech	0.38	Radial tires, GM X-cars, combination city-highway driving cycle
	0.5	Radial tires, GM X-cars, constant 30 mph

Note: 1 psi = 6894.787 Pascals

1 mph = 1.62 kph

50 percent at high speeds. Wet surfaces and snow can also reduce fuel economy 5 to 30 percent.

2.1-4 Power Train

The two primary **power plants** for automobiles are 4-cycle gasoline and diesel engines. As shown in Figure 7, diesel engines exhibit better fuel economy than gasoline engines, primarily because of the higher energy content of diesel fuel, their higher compression ratios, and the absence of throttling losses at part load. When 1980 diesel cars are compared to gasoline-engine cars of the same inertia weight, the average combined city and highway fuel economy advantage is about 25 percent.

Current automotive diesels use indirect fuel injection. Direct-injection passenger-car diesels are being developed and will likely be able to improve fuel efficiency by another 10 to 20 percent.

Improvements in the efficiency of current engines include electronic engine controls, turbochargers, and friction-reducing lubricants. **Electronic engine controls** are microprocessor-based systems that monitor engine parameters such as engine speed, exhaust oxygen content, and air intake. The systems can be used to control emissions and improve fuel economy at reduced emission standards by optimizing spark timing, air/fuel ratio, and

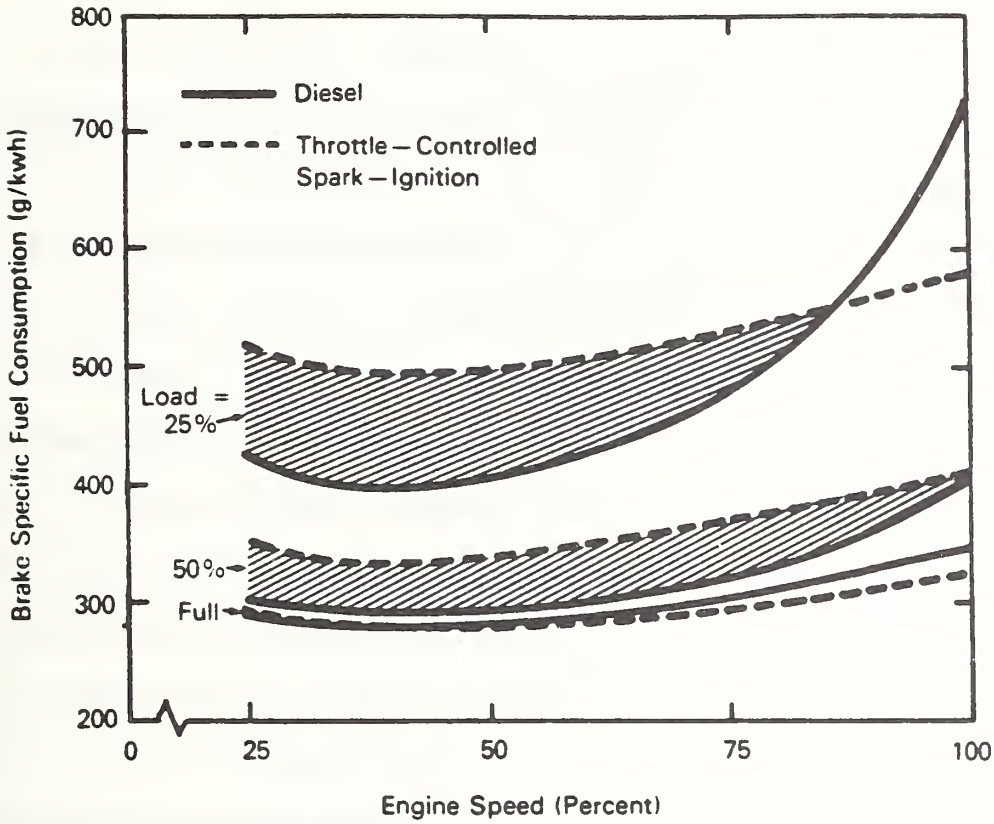


Figure 7. Brake-specific fuel consumption comparison — diesel versus spark-ignition engine

Source: "Passenger Car Diesels," PT-24, Introduction, SAE.

exhaust gas recirculation. One report indicated the electronic control system improved vehicle fuel economy by 7 percent.

Turbochargers use exhaust gas to compress intake air and thus increase the power capability of an engine. Fuel economy improvements with turbochargers come from two sources: an overall efficiency improvement of the engine and an increase in its power-to-weight ratio. Thus turbocharging becomes an attractive option to give vehicles higher power. Turbocharging is particularly attractive for diesel engines, where peak power is less than for an equivalently sized gasoline engine because of the difficulty of using all available oxygen at high power levels.

The transmission is a significant factor in automotive energy consumption. The efficiency of the automatic transmission can be improved by reducing energy losses in the torque converter, extending the gear ratio range, or modifying the shift logic. An effective method of reducing torque-converter losses is by bypassing the converter. Usually, the upper gears are locked up (converter-bypassed) completely or locked up at some predetermined speed and the first gear power path remains through the torque converter. This allows the torque converter losses at cruising speeds to be reduced while low-speed drivability and torque multiplication are maintained. Depending on the type of lockup scheme used, the composite fuel economy improvement for a 3-speed automatic transmission can be 1.5 to 3.5 percent over a baseline 3-speed automatic transmission.

The gear ratio range can be extended to increase fuel economy. The increase, which is limited by the number of gears, gear spacing, and engine and transmission matching, allows the engine to operate at a lower fuel consumption in the top gears. This improvement can approach 20 percent. In determining the effect of transmission modifications on fuel economy, the main parameter is the span of the gearbox. The improvement of a 4-speed versus a 3-speed transmission has been measured at 3 percent in the urban cycle and 21 percent in the highway cycle. More recently, the introduction of the 4-speed automatic transmission has improved fuel economy 2.5 to 3 miles per gallon (1.06 to 1.28 km per liter).

The shift logic for an automatic transmission is set by the manufacturer. By making the transmission shift earlier, fuel economy can be improved. The shift logic for a manual transmission is determined by the driver. One manufacturer has installed a light on the dash that signals when to shift for best fuel economy. The improvement with this upshift indicator is 7 percent in the urban cycle.

An innovative transmission concept is the continuously variable transmission (CVT). This transmission allows the engine to operate at maximum efficiency by continuously varying the transmission gear ratio. Fuel economy improvement utilizing a CVT is on the order of 10 to 20 percent over an automatic.

Vehicle maintenance is another factor in vehicle energy use. Engines out of adjustment with respect to the manufacturer's recommendations suffer fuel economy penalties. Table 6 shows the impact of specific malfunctions on vehicle fuel economy for certain test vehicles. Tests of groups of in-use vehicles have indicated an average urban fuel economy improvement of 1 to 5 percent with vehicles receiving minor tune-up adjustments. The table also shows that tampering with some emission-control devices can result in slight changes in vehicle fuel economy.

Vehicle accessories, including the fuel pump, alternator, cooling fan, air conditioner, and power steering, contribute significantly to fuel consumption, particularly during low-speed operation. The most energy-intensive accessory is the air-conditioning compressor, but there is no consensus on the magnitude of the effect of air conditioning on fuel economy because of the wide variation in its operation. The EPA dynamometer

Table 6. Percent effect on fuel economy of indicated malfunction

Malfunction	City	Highway
One spark plug misfiring	-13	-15
Air/fuel ratio too rich	-11	-12
Ignition timing retarded (8^{o})	-6	-4
Idle air/fuel rich	-2	+1
Plugged PCV	-4	-3
Choke rich	-2	-1
Idle RPM high	-4	-2
Distributor vacuum low	-1	-1
Ignition timing advanced (5^{o})	+2	+1
EGR disabled	+1	+1
Air pump disabled	+1	+1
Choke heater disconnected	*	+2
Idle RPM low	+3	*

* = insignificant effect (less than 0.5 percent)

test procedure simulates air conditioning by increasing the road load horsepower absorbed by the dynamometer by 10 percent, which translates into a 2 percent fuel economy penalty. Actual road tests determined that air conditioners usually result in a 10 percent reduction in fuel economy during full power operation.

Because there is usually no need for a radiator cooling fan at higher vehicle speeds, belt-driven fans waste energy. Two solutions to this energy waste are thermostatically activated clutch fans and electric fans; both reduce the duty cycle of the fan. Efforts to improve fans further include more efficient blade design and lighter blade materials.

The use of power steering will depend on the size of the vehicle, drive-train configuration, and consumer demand. The energy used in the power steering pump is influenced by its design. For example, one manufacturer, utilizing a radial piston design, has developed a pump that consumes only about 61 percent of the power of those commercially used in the United States in 1979. Further development of this system is projected to reduce pump fuel consumption to 0.04 gallons per 100 miles (.09 liters per 100 km).

The energy used by the alternator is dependent on the electrical demand on the vehicle. Computer-simulated alternator loads representing night-driving lighting conditions yielded a 1 to 3 percent decrease in fuel economy over the composite cycle.

One technique to reduce belt-driven accessory energy consumption is to limit the accessory speed, thereby lowering parasitic horsepower. This technique is accomplished by utilizing a controlled speed accessory drive (CSAD), which serves as a power takeoff for all accessories normally driven from the engine crankshaft.

2.1-5 Alternate Fuels

Major alternatives to gasoline and diesel fuels include propane, methane, methanol, and electricity. Propane and methane (natural gas) vehicles are currently operated commercially by fleets and some private owners, and methanol and electric vehicles are being tested in several parts of the country. Methanol-fueled vehicles currently appear to be the likely replacement for gasoline-powered vehicles if petroleum supplies are exhausted, since methanol can be readily produced from coal. Propane, methane, and methanol vehicles all operate with a spark-ignition, throttle-type engine. The fuel efficiency of these engines theoretically can be somewhat superior to gasoline-fueled vehicles since high octane numbers of these fuels allow higher compression ratios without harmful knock (see Table 7). Electric vehicles currently have only a limited role in transportation because of their short range between charging. Batteries currently being researched could improve the range of electric vehicles from the current 40 to 60 miles (64 to 96 km) to 150 miles (241 km) .

2.2 BUS SYSTEMS

The basic vehicle power-train relationships in buses are nearly the same as those in automobiles, but with fundamental differences in the physical characteristics of size, shape, and payload. To gain a better understanding of the energy intensity of the transit bus, the previous section on automotive systems should be reviewed before this section is examined.

2.2-1 Duty Cycles

The standard duty cycle used in most testing procedures to estimate power utilization and fuel consumption is the composite advanced design bus (ADB) cycle. This cycle is a combination of three operating phases: central business district (CBD), arterial (ART), and commuter (COM). The cycle is performance-based; acceleration is limited only by the capabilities of the vehicle.

Table 7. Alternate fuel characteristics

Fuel	Octane (research)	Cetane	Btu/16 Lower Heating Value	Btu/Gal	Storage
Methane	130	0	21,518	*	Stored as gas at high pressure (2,400 psi)
Propane	111	--	19,944	84,563	Stored as liquid at moderate pressure
Methanol	110	0	8,570	56,900	Stored as liquid at atmospheric pressure
Gasoline	91-95	16-19	18,900	115,800	
Diesel	15-35	45-55	18,400	130,300	

*23.626 ft^3/lb. @ 60^oF, 14.7 psi

Note: 1 BTU = .0002931 kwh

1 psi = 6894.787 Pascals

The CBD phase consists of 7 consecutive stops per mile (1.6 km) over a 2-mile (3.2 km) course with accelerations from 0 to 20 mph (0 to 32 kph). This phase simulates the boarding and exiting of passengers in the business district, where frequent stops must be made and heavy traffic is encountered. The ART phase consists of accelerations from 0 to 40 mph (0 to 64 km/h) and 1 stop per mile (1.6 km) over a 2-mile (3.2 km) course. Passenger activity in less congested areas where traffic is lighter and higher vehicle speeds are attained is represented in this phase. Finally, the COM phase has one 0- to 55-mph (88.5-km/h) acceleration and deceleration activity and close to 4 miles (6.4 km) of highway-speed operation over a 4-mile (6.4-km) course. This phase models boarding of passengers in surburban areas and transportation to metropolitan areas. Table 8 and Figure 8 present the composite ADB cycle and its components in greater detail.

The Society of Automotive Engineers (SAE) has developed a series of procedures for measuring fuel economy. Currently, the most common of these procedures for measuring basic highway vehicle engine performance and fuel consumption for both spark ignition and diesel vehicles are the June 1980 SAE J1312 and the joint TMC/SAE fuel consumption test procedure, Type II, SAE J1321 of

Table 8. Composite ADB duty cycle.

	Phase							
	CBD	Idle	Arterial	CBD	Arterial	CBD	Commuter	Total
Stops/Mile	7	-	2	7	2	7	1 stop for phase	
Top Speed (mph)	20	-	40	20	40	20	Maximum or 55	
Miles	2	-	2	2	2	2	4	14
Approximate Acceleration Distance (ft)	155	-	1,035	155	1,035	155	5,500	
Approximate Acceleration Time (sec)	10	-	29	10	35	10	90	
Approximate Cruise Distance (ft)	540	-	1,350	540	1,350	540	2 mile + 4580 feet	
Approximate Cruise Time (sec)	18.5	-	22.5	18.5	22.5	18.5	188	
Approximate Deceleration Rate (fpsps)	6.78	-	6.78	6.78	6.78	6.78	6.78	

Table 8 (continued)

Approximate Deceleration Distance (ft)	60	-	255	60	255	60	480	
Approximate Deceleration Time (sec)	4.5	-	9	4.5	9	4.5	12	
Approximate Dwell Time (sec)	7	-	7	7	7	7	20	
Approximate Cycle Time (min-sec)	9-20	5-0	4-30	9-20	4-30	9-20	5-10	47-10
Total Stops	14	-	4	14	4	14	1	51

Note: 1 mi = 1.609344 km

1 mph = 1.62 kph

1 ft = 0.31 m

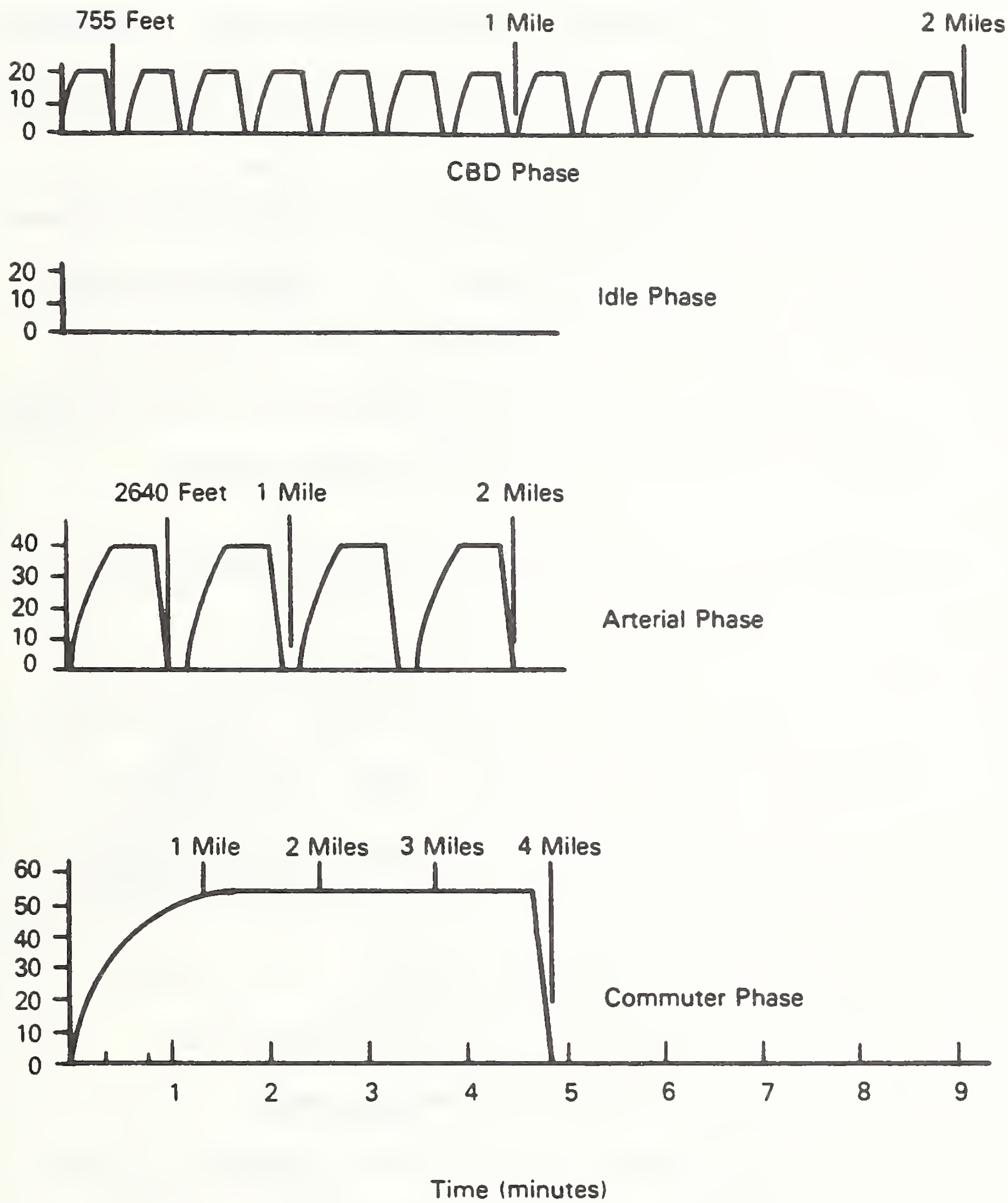


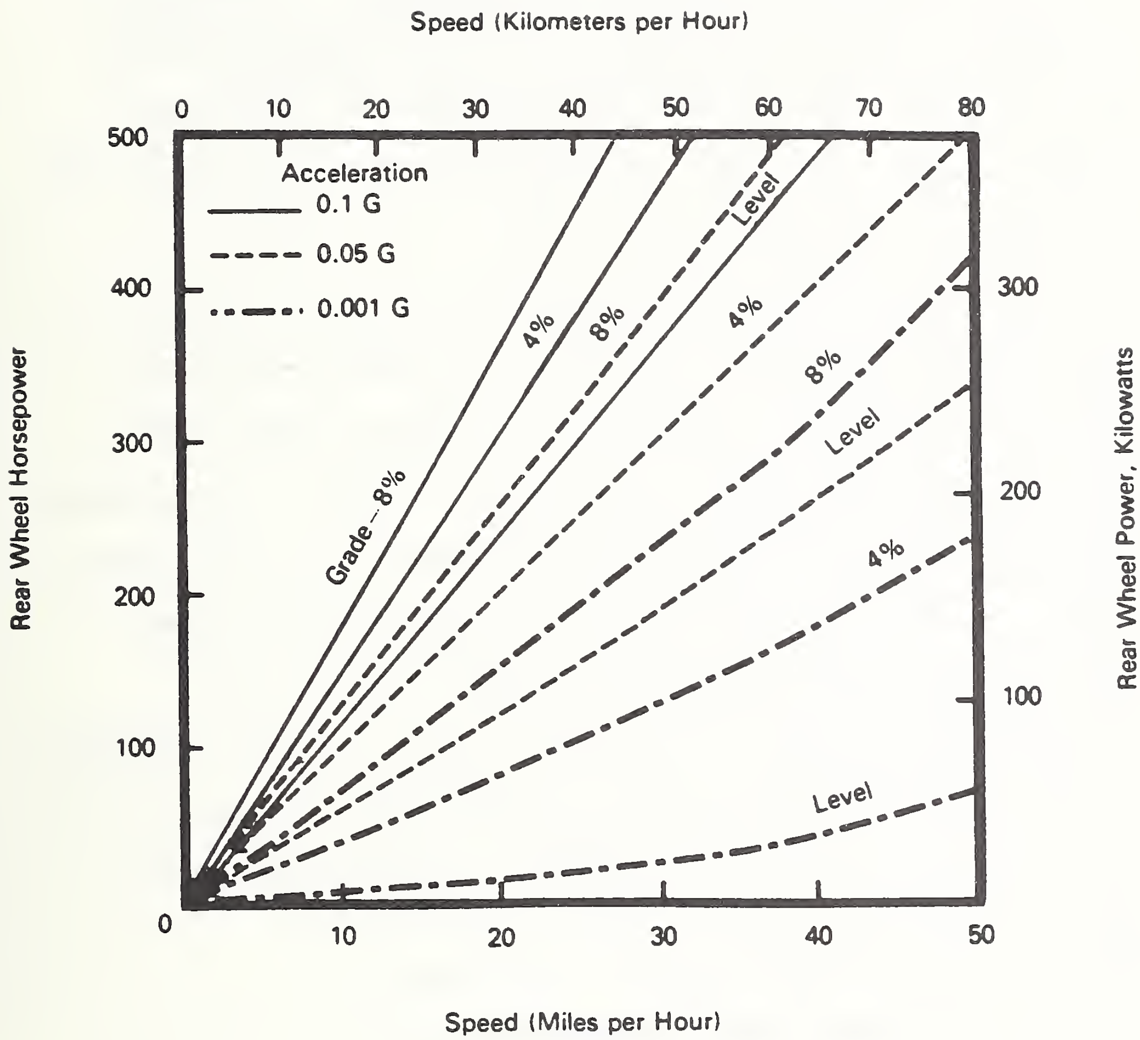
Figure 8. ADB duty cycle components

October 1981. The most recent procedure, SAE J1321, has been gaining wide acceptance within the industry as an accurate method of monitoring fuel use in trucks and buses, addressing consumption for both the entire vehicle and its components.

These SAE standards are testing procedures and depend on a realistic duty cycle selection. The specific duty cycle used to measure the fuel economy of a bus is very important since fuel economy measurements can vary by more than 100 percent, depending on the bus duty cycle.

2.2-2 Bus Energy Management and Performance Measures

The ADB cycle averages 3.6 stops per mile (1.6 km) compared with a little over 1 stop per mile (1.6 km) for the EPA automotive combined cycle. Thus, acceleration energy use is more critical in buses than in cars. In addition, since vehicle speeds are kept lower, aerodynamics are relatively less important with buses. In general, Equation 1, which pertains to energy balance for automobiles, applies to transit buses as well.
Figure 9 shows the bus power required for various grade and acceleration levels. At 30 mph (48km/h), a bus accelerating at 0.05 g will be using less than 40 hp to overcome rolling resistance and aerodynamic resistance (from the 0.001 g curve) and about 150 hp for acceleration.



Vehicle Weight = 32,000 lbs.

(Mass = 14,500 kg)

Figure 9. Effect of grade on required propulsive power for constant acceleration

One measure of performance for the transit bus is its ability to accelerate rapidly but smoothly. Gradeabilty, an additional performance measure, is the percentage of grade (feet of vehicle rise per 100 feet of horizontal distance) that a vehicle can negotiate at a sustained road speed from a running start.

The maximum engine power on a bus is generally 190 to 270 hp (142 to 201 kW). The power-to-weight ratio is in the range of 0.006 to 0.008 hp/lb (.009 to .013 kW/kg), about one-third of typical automotive values. Thus, buses have much less available power than cars, and performance measures such as acceleration and gradeability become critical in bus specification. Table 9 shows the acceleration rate for a V6 bus compared with an automobile. The bus is considerably slower past 10 mph (16km/h). The top speed of a bus on a 4.5 percent grade is typically about 25 mph (40km/h).

2.2-3 Chassis and Body Characteristics

Buses have both larger frontal areas and larger drag coefficients than automobiles and thus, for equivalent speeds, bus aerodynamic drag can be substantially larger than that for passenger cars. Table 10 shows aerodynamic drag coefficients for a number of vehicles.

Table 9. Acceleration from stop for a car and a V6 bus on level ground

Vehicle Speed (mph)	Passenger Car (g)	V6 Bus (g)
0	--	0.138
10	0.079	0.082
20	0.072	0.059
30	0.066	0.023
40	0.046	0.017

Source: John S. Ludwick, Jr., and George F. Swetnam, Jr., "A Preliminary Review of Propulsion Requirements for an Urban Transit Bus," MTR 6688, June 1974

Note: 1 mph = 1.62 kph

Table 10. Air resistance drag coefficient of several representative types of vehicles

Vehicle Type	C_D (Dimensionless)
Racing car	0.25-0.3
Passenger car	0.40-0.55
Intercity bus	0.65-0.75
Urban transit bus	0.55-0.80
Truck	0.80-1.60
Tractor-trailer truck	1.30-2.00
Geometrical Bodies:	
Streamlined body	0.13
Sphere	0.47
Square (flat) plate	1.2

Recent work on bus aerodynamics has focused on the use of add-on devices for bus bodies to reduce drag. One study has shown that drag can be reduced as much as 27 percent by modifying body shape and improving overall aerodynamic characteristics. This can reduce fuel consumption on the ADB cycle by 2 percent.

As with cars, vehicle weight affects rolling resistance, acceleration, and grade power requirements. Figure 10 shows the effect of bus weight on fuel economy over the ADB cycle.

Bus tire rolling resistance coefficients at various speeds are shown in Figure 11. Although this coefficient behaves the same as that for automotive tires, its magnitude may be 30 percent less because of the higher bus tire pressure. Most buses also use bias rather than radial tires for improved durability.

2.2-4 Power Train Characteristics

The predominant engine used in transit buses is the 8V-71 Detroit Diesel Allison 8-cylinder, 2-cycle diesel engine. The diesel engine has been the main power source for transit buses since the 1950s. The 2-cycle diesels are characterized by high low-speed torque and high power-to-weight ratio. The diesels also substantially improve bus fuel economy compared to gasoline engines.

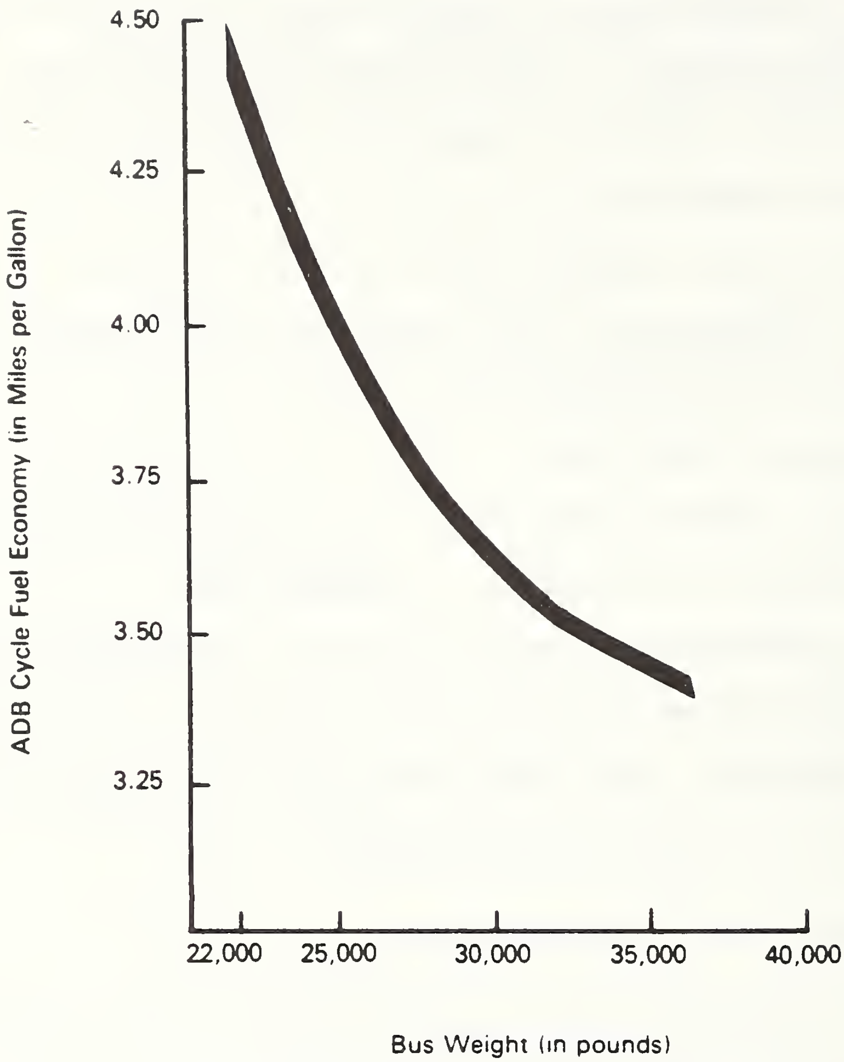


Figure 10. Fuel economy versus bus weight

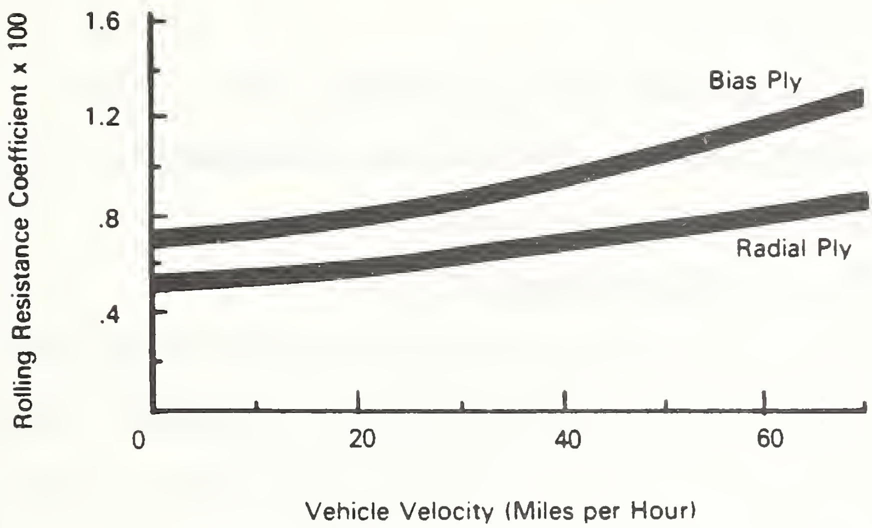


Figure 11. Rolling resistance coefficients

Source: Kevin A. Copeland, "Fuel Economy on Automatic Equipped Transit Buses," General Motors Institute, April 1980.

However, the 2-stroke diesel cycle is generally not as efficient as the 4-stroke diesel cycle primarily because of the volumetric inefficiency in the intake system and mechanical losses in the blower system.

Other engines in bus use include the DDA 6V-92TA, which is a turbocharged and aftercooled 6-cylinder, 2-cycle engine. The "aftercooling" refers to a cooling of the intake air after turbocharge compression. This further increases the air density and thus the power potential of the engine. The Cummins VTB-903 is a turbocharged, 8-cylinder, 4-cycle diesel engine. All three of these engines have maximum power around 270 hp (201 kW). The DDA 6V-71 is a naturally aspirated 6-cylinder diesel with maximum power around 190 hp.

Table 11 compares the fuel efficiency of several of these engines with other standard features on a bus, such as a 3-speed transmission with a torque converter, a rear-wheel axle ratio of approximately 5.13, and a weight of 34,000 pounds (15,400 kg). The turbocharged 6V-92TA shows improved fuel economy because of its improved efficiency at high loads. The VTB-903's improved fuel economy is due to the inherently greater efficiency of a 4-cycle engine.

Table 11. Fuel efficiency of different engines

Configuration	Engine	Fuel Economy (mpg) CBD	ART	COM	ADB	0-15 mph Performance (sec)
A	8V-71	3.23	3.37	4.97	3.70	5.9
B	6V-92TA	3.59	3.66	5.05	3.98	6.5
A	VTB-903	3.45	3.64	5.30	3.95	6.8

Configuration = Bus Type/Transmission/Torque Converter/Rear Axle Ratio/Weight

A = RTS-II/V-730/TSC-490/5.29/31,498 lb

B = RTS-II/V-730/TC-470/5.857/31,498 lb

Note: 1 mpg = .425 km/l

1 mph = 1.62 kph

Most buses use lock-up torque converters for fuel efficiency. The effect on fuel economy of transmission gearing for buses depends heavily on the driving cycle. A transmission with advantageous gearing in low-speed driving will yield better fuel economy on an urban-type cycle than will a transmission optimized for higher speeds.

One of the major users of energy on a bus is the air-conditioning system. Such systems can degrade fuel economy by 8 to 20 percent. They also extract a performance penalty, increasing 0- to 30-mph (0- to 48-kph) acceleration times by 18 percent.

2.2-5 Other Recent Developments

Alternate fuels can be used to reduce petroleum fuel dependency. Candidates for diesel engines in buses include methanol, ethanol, methane, propane, ammonia, and hydrogen. None of these fuels can be used directly in existing engines since their octane numbers in all cases are too low to cause self-ignition on the diesel cycle. Table 12 shows five types of internal-combustion engines that can be developed by modifying existing engines. The gasoline engine (Otto cycle) appears to be the most suitable power plant across existing alternative fuel types with potential use for all but diesel fuel. Methanol, ethanol, and gasoline could potentially be used in three of the engine

Table 12. Types of internal-combustion engines developed by modifying existing engines

	Characteristic		
Engine Type	Method of Fuel Delivery	Method of Fuel Ignition	Compression Ratio
Diesel	High-pressure injection	Compression	17-20
Gasoline	Carburetion, low-pressure injection	Spark	8-11 (depending on fuel)
Stratified Charge	High-pressure injection	Spark	10-16 (depending on fuel)
Fumigated Diesel	Carburetation, high-pressure injection	Compression	17-20
Dual Injection	High-pressure injection	Compression	17-20

types--gasoline, spark-assisted stratified charge, and dual fuel injection.

Energy storage devices offer another possible area of bus fuel conservation. Research is being conducted on hydraulic retarders that are capable of storing braking energy. These retarders use a single or dual hydraulic motor and pump arrangement to compress air in hydraulic accumulator storage vessels. The stored energy is then used to propel the vehicle forward during acceleration. When used in stop-and-go driving, this type of retarder can greatly improve the fuel efficiency of a bus. A 30 percent fuel consumption reduction (50 percent fuel economy improvement) in transit buses has been achieved using these systems.

2.3 URBAN RAIL TRANSIT SYSTEMS

The two principal submodes of urban rail transit are heavy and light rail; automated guideway transit (AGT) is a third submode. Heavy rail transit is provided by trains of electrically self-propelled railcars, 50 to 80 feet (15 to 24 m) long, operating on tracks using an exclusive, separated right-of-way. The New York, Chicago, and San Francisco systems are examples. Light rail urban transit is provided by lighter electrically self-propelled railcars operating individually or in trains on tracks using city streets or on semi-exclusive or exclusive rights-of-way. Examples of light rail systems can be found in Pittsburgh, San Francisco, and San Diego. AGT systems are small, electrically self-propelled, automatic, driverless vehicles or trains that operate on exclusive, separated guideways. Examples of AGT systems are those at the Atlanta and Houston airports and the public system in Morgantown, West Virginia.

2.3-1 Energy Use and Load Factors

Urban rail transit accounts for only about 0.04 percent of U.S. transportation energy consumption, virtually all of which is delivered as electric power. While efficiency of rail transit equipment is intrinsically high, it is strongly dependent on commuter traffic patterns. A crush-loaded transit car has a passenger transit efficiency of more than 30 times that of an average car. When passenger loadings drop to one-tenth of crush capacity or below, the energy efficiency of urban rail transit is heavily eroded.

Table 13 gives key indicators of performance and energy use for selected U.S. fixed guideway systems. There is a remarkable variation in equipment efficiency, as shown by the range of kWh per car-mile--between 4.98 and 131.5. This variation is further amplified by the distribution of

Table 13. Key performance indicators and energy use of U.S. fixed guideway systems

City	Route Miles	Station Spacing	Passengers: Capacity Total	Passengers: Capacity Seated	Passengers: Average Use	Vehicle Miles (million/year)	Energy Consumed kwh/ car-mile	Energy Consumed kwh/ pass.-mile
Heavy rail								
Boston	34.2	0.68	239	64	NA	11.10	5.95	--
Chicago	89.0	0.62	150	49	15.9	49.65	4.98	0.31
Cleveland	19.0	1.11	140	80	NA	5.50	8.80	--
New York (NYCTA)	230.6	0.50	350	76	38.3	248.50	5.84	0.15
Philadelphia (SEPTA)	24.4	0.50	250	67	25.7	13.10	9.31	0.36
Light rail								
Shaker Heights	13.1	NA	NA	82	29.0	1.25	4.30	--
Philadelphia	20.8	NA	NA	68	18.2	2.85	6.06	--
Newark	4.3	NA	NA	73	10.2	0.55	5.70	--

Table 13 (continued)

AGT								
Tampa	0.7	0.09	100	--	6.0	0.41	57.6	9.6
Dallas/Ft. Worth	12.8	0.09	40	--	--	0.00	81.5	--
Morgantown	2.1	0.7	21	--	5.3	0.58	131.5	24.8
Houston	1.5	0.16	36	18	12.2	0.22	1.0	0.09

Note: NA = Not Available

1 mi = 1.609344 km

Sources: APTA Transit Fact Book, APTA, 1981. "The World in Transit," Railway Age, September 28, 1981. Light Rail Transit, U.S. Department of Transportation, Spring 1976. Pushkarev, Urban Rail in America, Indiana University Press, 1982. Turner and Wolf, Houston Airport Peoplemover, IEEE Vehicular Technology Conference, May 1982.

passenger use of trains, yielding transport efficiencies in the range of 0.15 to 24.8 kWh per passenger-mile. Some systems shut down during off-peak periods, while others continue operating. Systems like the New York subway are characterized by wide ranges in load factor--crush loads during travel peaks and very light loads during most off-peak hours. Patterns of passenger use and operating service characteristics act on absolute vehicle efficiency to generate the wide range of efficiencies observed.

2.3-2 Rail Transit Energy Budget

Figure 12 is an energy reconciliation for electric power distributed to the San Francisco BART system. BART's use of electric power (kWh per car-mile) is typical of new high-performance heavy rail transit systems. In the figure, the energy use percentages are related to the original value of the energy used at the source. Thus, the input is the input to the power plant, where a 62 percent loss is associated with the conversion of petroleum or coal to electricity.

In a typical transit cycle, a train dwells at a station using energy only for auxiliaries, accelerates out of the station to line speed, cruises at that speed while overcoming friction and windage, and decelerates into the

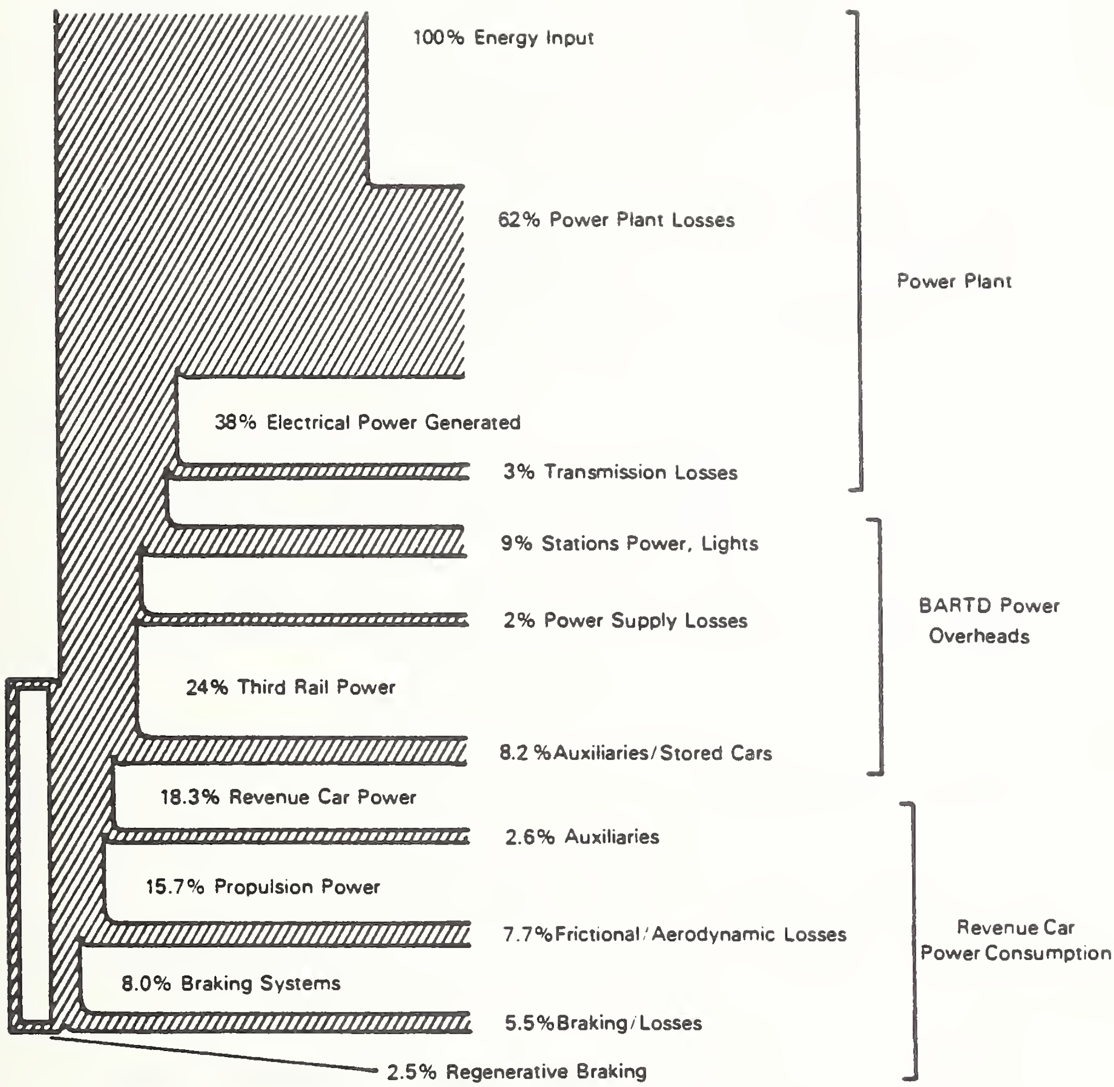


Figure 12. BARTD energy utilization

Source: Bolger, et al., "Application of Energy Storage Power Systems to Non-Highway Transportation," Lawrence Livermore Laboratory, May 1977.

next station. The energy uses associated with this cycle are shown in Figure 13 for a typical case.

As the train accelerates, electric power is stored in the train as kinetic energy. When the train decelerates at the next station, that energy must either be dissipated as heat by friction or dynamic brakes, be regenerated back into a receptive load on the power distribution system by chopper, or be stored aboard the vehicle. In the example in Figure 14, the stored energy of motion at the moment deceleration begins is 83 percent of the energy used on the 1-mile (1.6-km) run. Techniques for energy management in rail transit address both reduction of this energy requirement and provision for reuse of the energy of motion.

2.3-3 Energy Reduction

The energy needed to move rail transit cars may be reduced absolutely by reducing the mass or maximum velocity of the train. Energy may also be reduced relative to the amount of work done by lengthening the distance between stations. Figure 14 shows the relationship between transit system energy consumption and station spacing for several weights of vehicles. The heaviest vehicle's variation in transit efficiency is 2.15:1 for the typical range of heavy rail station spacing.

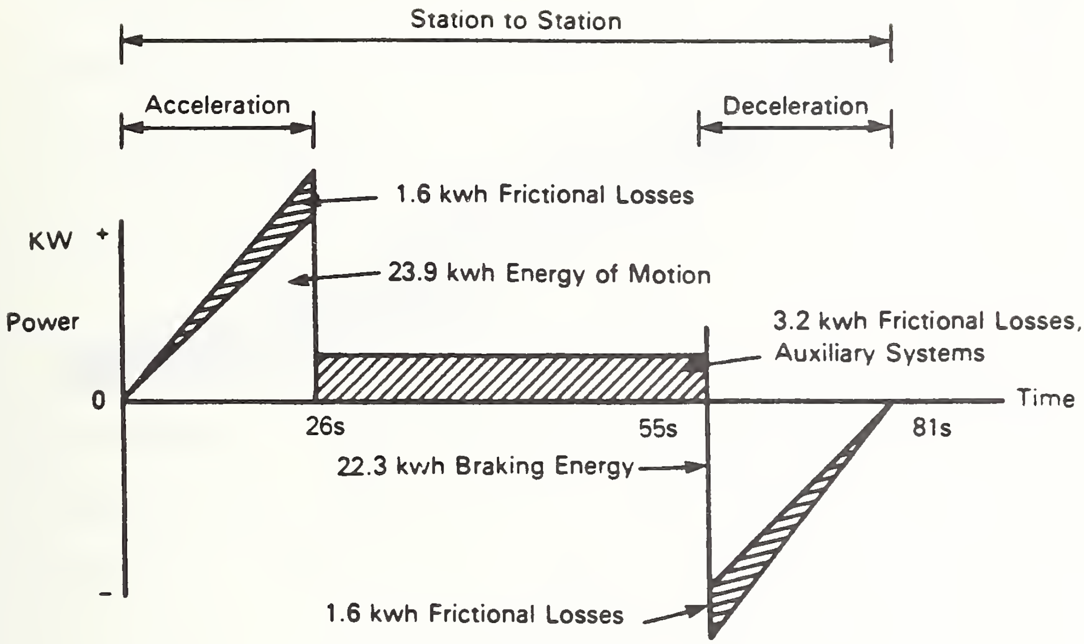


Figure 13. Typical energy requirement for 6-car 225-ton train over 1-mile run

Source: R. A. Uher, "Energy Management for Electric Rail System," Carnegie-Mellon University.

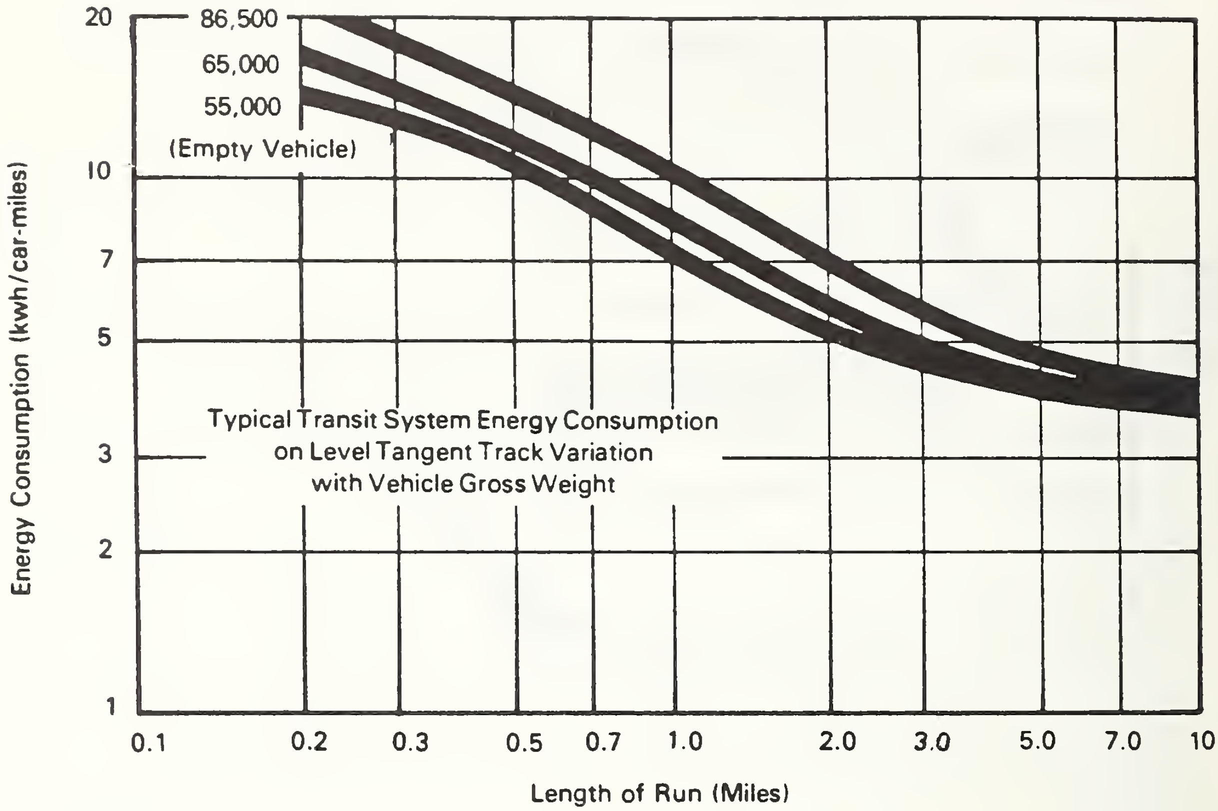


Figure 14. Relationship between transit system efficiency station spacing and vehicle weight

Source: R. A. Uher, "Energy Management for Electric Rail Systems," Carnegie-Mellon University.

An operating policy that matches train length or number of cars (and therefore total weight) and schedule to passenger demand is necessary to control energy costs. A consequence of such a policy is the need for trains that can be lengthened or shortened quickly, without multiple train crews.

Another technique for reducing energy consumption is in reducing top operating speed--that is, degrading the performance of the system by increasing schedule times. Further energy savings can be achieved from coasting, if schedule times can be increased. Under a coasting strategy, a train is accelerated to its top speed as rapidly as possible, within the constraints of the performance limits and the electric utility demand charge. From that point, the vehicle is allowed to coast to some lower speed. Figure 15 shows the potential improvements in transit car efficiency that can be attained by decreasing top speeds and by adopting a suitable top speed and coast operating strategy. In both cases, schedule times must increase.

Control of DC traction motors for rail transit has historically been accomplished by switching resistors in series with the motor, by changing field and armature connections, and by field weakening. This technique, known as cam control, is inherently dissipative of energy during

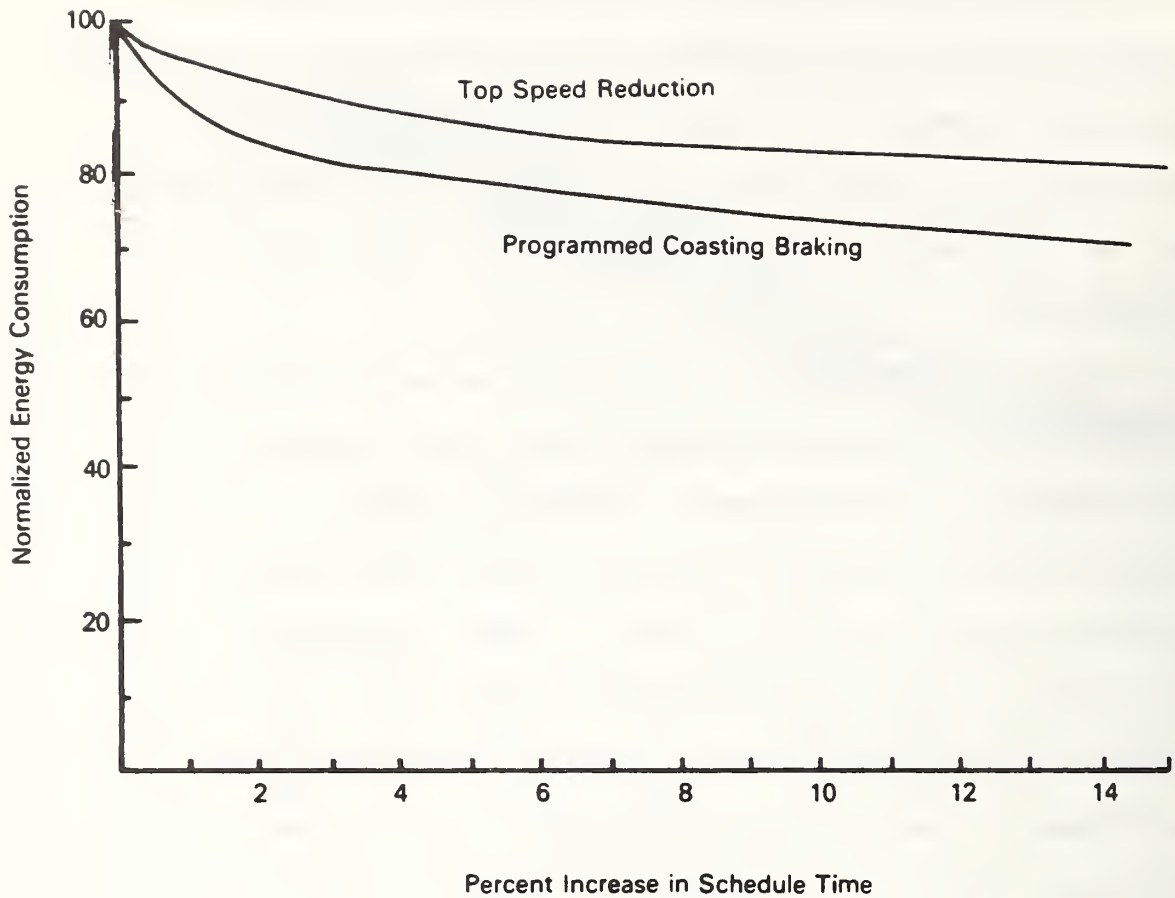


Figure 15. Comparison of top speed reduction

Source: R. A. Uher, "Energy Management for Electric Rail System," Carnegie-Mellon University.

acceleration. The advent of thyristor chopper motor controls provided the capability to control the DC motor starting torque without dissipative current limiting. For a station spacing of 0.6 mile (1 km), the transit power requirement (kwh per car-mile) decreases by 15 to 40 percent with chopper controls. However, for station spacing on the order of 2 miles (3.2 km) or greater, the influence of this loss is negligible.

The thyristor chopper brings another substantial advantage to rail transit--the ability to regenerate the energy of motion into DC power, which can then be recoupled to the DC power distribution system (third rail). If a suitable load is attached to the line, some of the kinetic energy can be reused.

2.3-4 Energy Storage

A perfect system could recover about 50 percent of the third-rail energy. As shown in Figure 12, the contribution of regeneration in the BART system is 10 percent of the third-rail energy use. Energy recovery is strongly influenced by system design, which must provide loads on the third rail to make it receptive to regenerated energy of motion. The receptivity of the line can be increased by running trains close together, which increases the probability that a nearby train will be accelerating when another is decelerating. Energy transfer between trains is increased by raising the maximum permissible regeneration voltage with respect to the open circuit substation voltage, by decreasing the power rail impedances, and by placing substations far from decelerating trains. Figure 16 shows the calculated values of recovered energy for a range of headways for three voltage differences between substation and regeneration voltage.

The receptivity of the system to regeneration can also be assured by providing storage for the energy on the vehicle or along the wayside, most likely by using flywheels. Studies and tests suggest that energy savings in the range of 25 to 35 percent are feasible. The receptivity of the system can also be increased by making the substations convert power bidirectionally. Regenerated power would then be transferred back into the utility supply. However, this approach does not appear to be cost-effective except on sustained downhill runs.

Energy can also be reused by providing a vertical profile track, where acceleration out of the station is aided by a downgrade and deceleration into a station is aided by an upgrade. The kinetic energy is partially recovered as gravitational potential energy. Figure 17 shows a gravity profile energy map of the 1-mile (1.6-km)

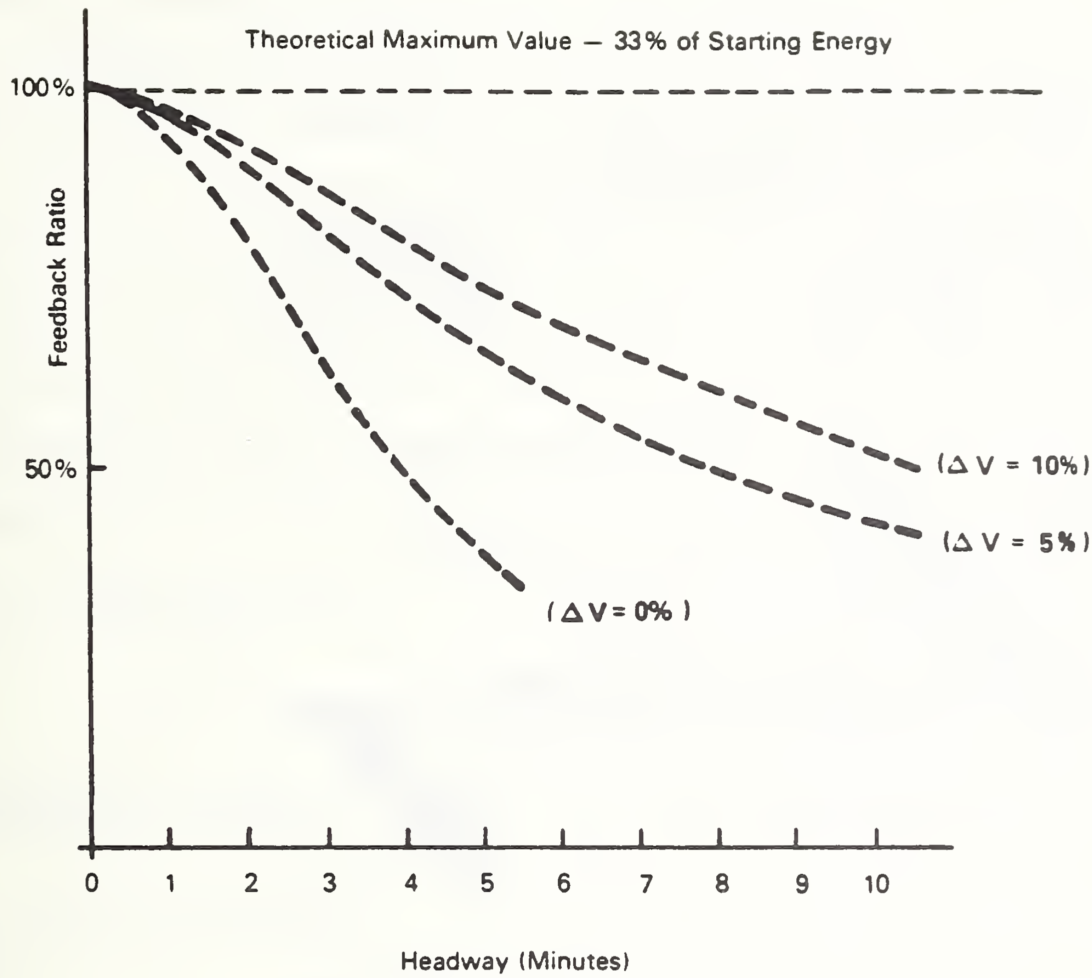
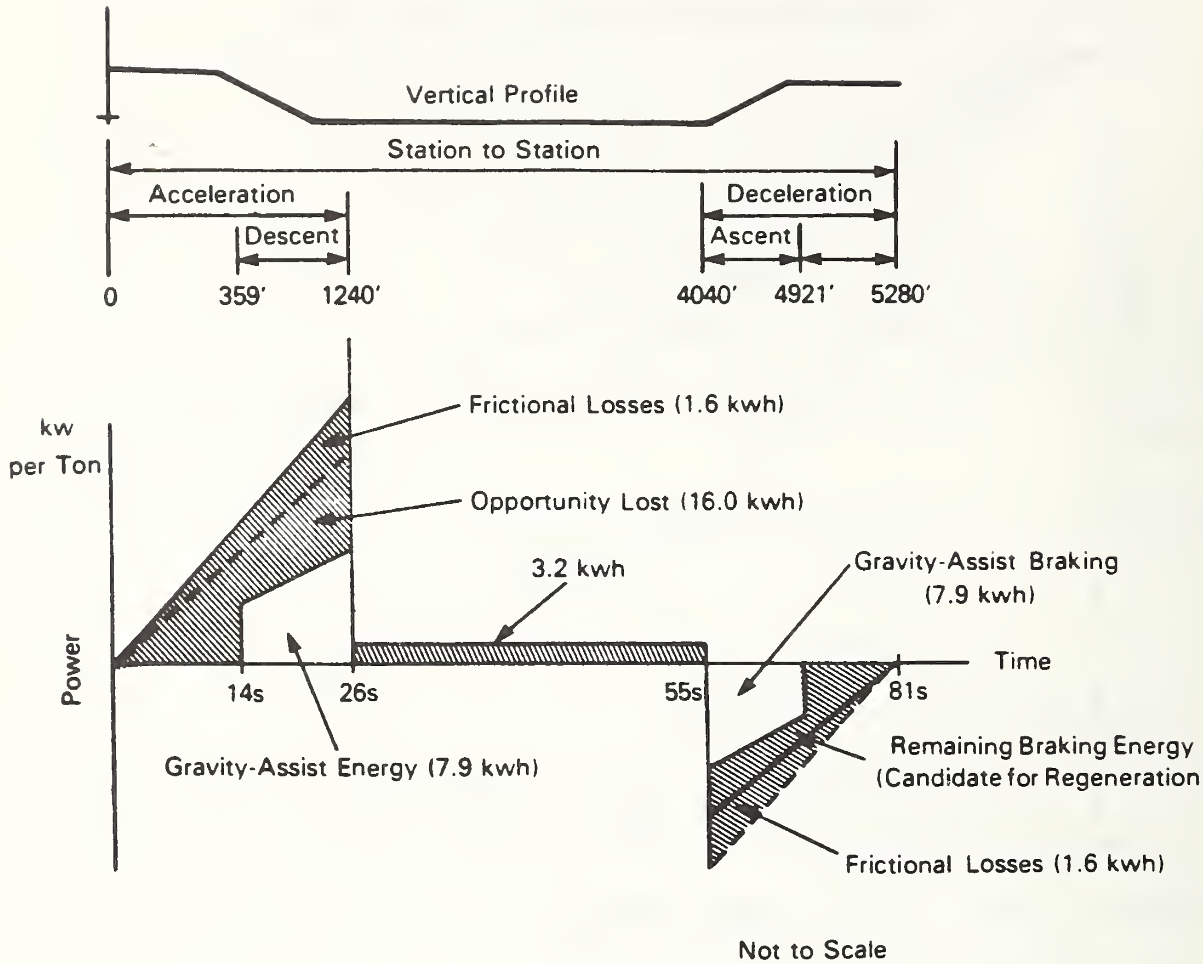


Figure 16. Energy feedback ratio relative to headways

Source: J. Amler, "The Effects of DC-Chopper Technology in Public Rapid Transit Passenger Transport," Federal German Ministry for Research and Technology, January 1978.



*Energy for 6-car train with car weight of 75,000 pounds

Figure 17. Energy map for vertical profile system

Source: Booz, Allen & Hamilton. "Study of Energy Management Alternatives for SCRTD," April 1982.

station run shown in Figure 13. In this example, 31 percent of the accelerating energy is provided by the gravity profile. Further, even without regeneration, 35 percent of the energy of motion is recovered; additional gains can be achieved with a coasting strategy. However, special civil work and propulsion and train controls must be provided that recognize and integrate the gravity energy contribution; the cost of such civil work and additional control systems often outweigh the energy savings potential.

APPENDIX A

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APPENDIX B

REPORT OF NEW TECHNOLOGY

The work described in this report on energy use in transportation did not result in any new or unique devices.

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