U.S. Department
of Transportation

Urban Mass Transportation Administration

UMTA-MA-06-0120-84-2
DOT-TSC-UMTA-84-19

Transit Bus Fuel Economy and Performance Simulation

Russell Zub

Transportation Systems Center
Cambridge MA 02142

October 1984
Final Report

UMTA Technical Assistance Program

Technical Report Documentation Page

1. Report No. UMTA-MA-06-0120-84-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle TRANSIT BUS FUEL ECONOMY AND PERFORMANCE SIMULATION		5. Report Date October 1984
		6. Performing Organization Code DTS-63
7. Author(s) Russell Zub		8. Performing Organization Report No. DOT-TSC-UMTA-84-19
9. Performing Organization Name and Address U.S. Department of Transportation, Research and Special Programs Administration, Transportation Systems Center, Cambridge MA 02142		10. Work Unit No. (TRAIS) UM462/R4622
		11. Contract or Grant No. DTUM60-81-C-71103
12. Sponsoring Agency Name and Address U.S. Department of Transportation, Urban Mass Transportation Administration, Office of Technical Assistance, Washington DC 20590		13. Type of Report and Period Covered Final Report October 1982 - February 1984
		14. Sponsoring Agency Code URT-20
15. Supplementary Notes		

16. Abstract

This report presents the results of bus simulation studies which determined the effects of various design and operating parameters on bus fuel economy and performance. The bus components are first described in terms of how they are modeled. Then a variation of each component is performed and the resulting fuel economy and performance are presented as sensitivities and tradeoffs. Relative fuel consumption estimated by the HEVSIM Simulation Program and measured in track tests was shown to compare within ± 1 percent in six of nine cases. Explanations are offered in cases where the variation was slightly greater than the ± 1 percent band allowed by the SAE Type II J1321 test procedures.

17. Key Words Bus, Fuel Economy, Simulation, Performance, Testing	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 116	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This report presents the results of bus simulation studies to determine the effects of various design and operating parameters on bus fuel economy and performance. The bus components are first described in terms of how they are modeled. Then a variation of each component is performed, and the resulting fuel economy and performance are presented as sensitivities and tradeoffs.

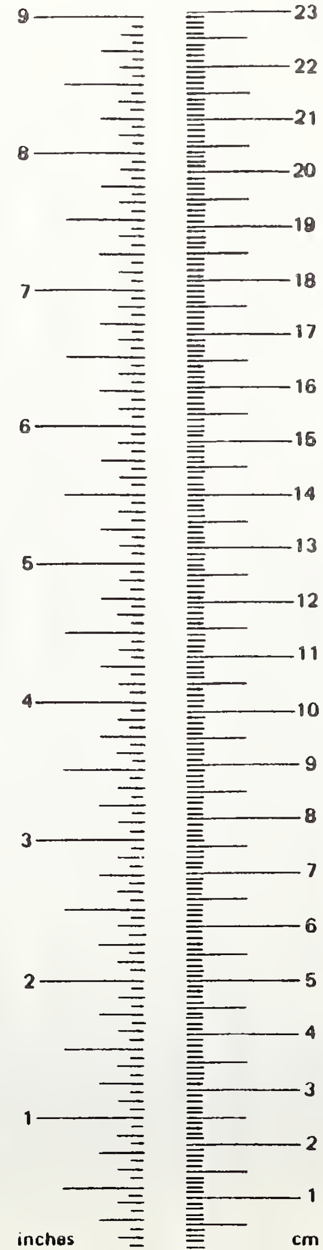
This report was sponsored by the U.S. Department of Transportation, Urban Mass Transportation Administration, Office of Technical Assistance. The author acknowledges the contributions of the following people: Richard Gundersen, Transportation Systems Center (TSC), for his helpful review and suggestions in translating technical results into understandable text; Jon Campbell and Sarah Madwed, TSC, for their proofreading of the document; Roger Flanders, Systems Development Corporation (SDC), for his data analysis and the running of the entire series of parametric runs; James Sterling, Laurie Wickham, and others of the Raytheon staff for their excellent job of preparing the document.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

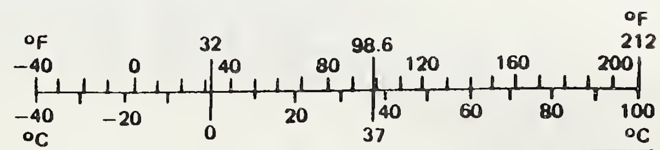
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight 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	36	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



CONTENTS

CONTENTS (CONTINUED)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

EXECUTIVE SUMMARY

There has been growing interest in the transit community concerning bus fuel economy and performance. A major reason for this interest was the requirement in the 1982 DOT Appropriations Act for use of life cycle cost as an evaluation criteria in bus procurements using Fiscal Year 1982 federal funding. In virtually all life cycle cost procurements since that mandate, fuel economy has been selected as one of the significant cost factors influencing the evaluations. Even with a softening of this mandate, subsequently contained in the Surface Transportation Assistance Act of 1982, interest in total bus costs and fuel economy, in particular, remains strong. To assist transit authorities in improving their understanding of the impacts on fuel economy and performance that result from changes in vehicle design, fuel type or operating environment, UMTA's Office of Bus Technology initiated a Bus Fuel Economy Technical Assistance Program. This program involves the development of fuel economy information from both track tests and computer simulation.

This paper addresses the simulation element of the UMTA Fuel Economy Program. More specifically, the paper addresses the development of fuel economy and performance sensitivity information on standard-size transit vehicles using the Heavy-Duty Vehicle Simulation (HEVSIM) Program. HEVSIM provides fuel consumption and performance estimates of a specified bus as it executes a given driving schedule. HEVISM was developed at the U.S. Department of Transportation, Transportation Systems Center. It was used extensively in automotive applications and subsequently enhanced to simulate heavy-duty vehicles. The data used in the HEVSIM Program was provided by six bus manufacturers and numerous component suppliers.

The analyses performed consist of what are commmonly known as sensitivity studies; that is, changing one variable while holding the others constant and measuring the resulting change in vehicle fuel economy and performance. The variables considered include: design components of the vehicle, especially the drivetrain and accessory loads; operating conditions, such as passenger loads; and drive cycle, such as speed variations and stops per mile. The parameters used to measure the effects of these changes are fuel economy (miles/gallon) and performance (gradeability, top speed and acceleration). Except where noted, all analyses are conducted using an Advanced Design Bus (ADB) drive schedule or cycle as defined in the Baseline Advanced Design Bus specifications.

Results

Based on the simulation of six representative standard-size buses, results are presented in Table ES-1. Individual ADB cycle changes (Commuter, Arterial, Central Business District cycles) and performance differences are discussed in the text. Additional findings, which are more difficult to quantify, are provided below.

Comparisons of driveline geometry (V-drive vs. in-line transmission) are difficult for a number of reasons. First, the two driveline geometries differ in more than one component. Generally, there is a difference in the number of gear speeds, shift logic, torque convertor and axle ratio. Second, comparisons in fuel economy should only be made with buses having equal perfomance. Third, buses with different equivalent performance levels may give opposite results. For example, the simulation of two buses of V-drive and in-line geometry with equivalent geared top speed of 50 miles per hour results in better fuel economy in the "V" configuration. Changing the top speed equivalent performance to 60 miles per hour results in the in-line demonstrating slightly better fuel economy.

TABLE ES-1. FUEL ECONOMY CHANGES

VARIABLE CHANGE	FUEL ECONOMY CHANGES
Drive cycle modifications	5 to 105%*
Weight decreased 10%	+6.0 to 6.5%
Gear efficiency decreased by 4.8%	-2.4%
Torque Converter (more efficient)	1%
Axle ratio (range variation)	up to 7%
Rolling resistance decreased 10%	+1.3%
Tire pressure decreased 10%	-0.5%
No. 2 fuel instead of No. 1	+2%
Fan duty cycle (on to off)	1 to 3%*
Alternator load decreased 43%	+1%
Power steering duty cycle (doubled)	less than 1%*
Air compressor duty cycle (doubled)	less than 1%*
Air conditioning (off to on)	-10.5%

*Depending upon particular drive schedule or duty cycle

The fuel economy change caused by changes in the shift schedule is largely dependent on the specified axle ratio. Therefore, as an example, sensitivities associated with electronic control shift logic changes should be compared at the same axle ratio.

Increasing injector size generally improves performance. The fuel economy difference among different size injectors is dependent upon the selection of an equivalent performance level.

In order to establish credibility in the HEVSIM results, a comparison of test track relative fuel consumption to HEVSIM relative fuel consumption was performed. The comparisons included relative fuel consumption changes due to changes in weight, axle ratio, shift schedule, tires (bias ply to radial) and the addition of an electric retarder. Six of the nine simulations agreed with the track results within the prescribed $\pm$ 1 percent band of the SAE Type II J1321 test procedure. Slightly larger differences between track test data and simulation results occurred in the following areas:

1) One weight change sensitivity (of the four compared) was within $\pm$ 2 percent of the test track results.
2) The comparison of the simulated and test track relative fuel consumption change for different shift schedules correlated within 1.2 percent in the Arterial and Commuter phases but differed by as much as 5.2 percent in the Central Business District phase. This difference must be considered with the fact that the test track retest showed a -3 percent change (non-repeatability) in the CBD cycle.
3) Both the simulation and test track results showed fuel savings going from bias to radial ply tires. The test track results estimated a 9.2 percent fuel savings, while the simulation showed a 3.4 to 4.4 percent improvement. Futher testing and analysis is required to evaluate these small discrepancies between test and simulated fuel economy impacts.

Considerations

Based on the analysis conducted, it can be concluded that variations in drive schedules have the single largest impact on fuel economy. In other words, changes in the speed/time profile of the bus have the potential to greatly overshadow the effects of other component changes. For this reason, fuel economy and performance impacts are provided not only for the combined ADB drive schedule, but for representative downtown service (Central Business District), suburban service (Arterial) and expressway service (Commuter). In this way a transit agency can better correlate its type of operations to obtain a more accurate estimate of fuel economy and performance impacts.

Changing individual powertrain components can affect the performance of other components. Because of this interaction the sensitivity values developed in this analysis are not necessarily additive. In addition, the analysis demonstrates that changing similar components on different buses can result in different sensitivity values. Therefore, the sensitivity values can vary slightly from manufacturer to manufacturer.

Although fuel economy improvements are the current focus of interest in transit today, it is important to understand the associated changes in vehicle performance, as well.

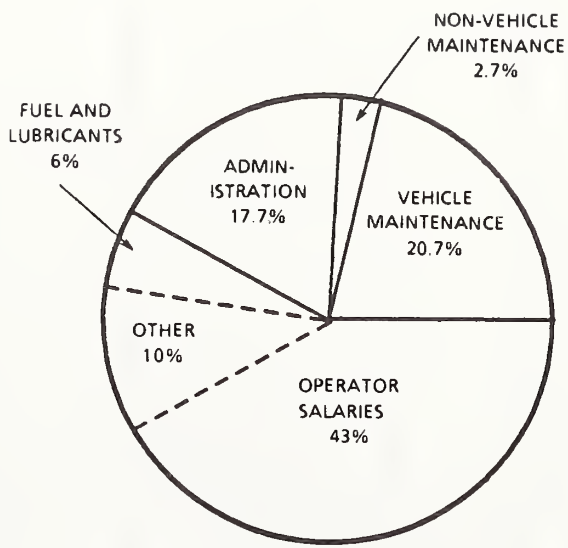
The results presented in this report are intended for relative comparisons only. The absolute numbers are listed solely as a reference to illustrate a relative change. The use of this model or other models for predicting absolute fuel economy or performance is not recommended unless the model has been validated for this purpose.

1. INTRODUCTION

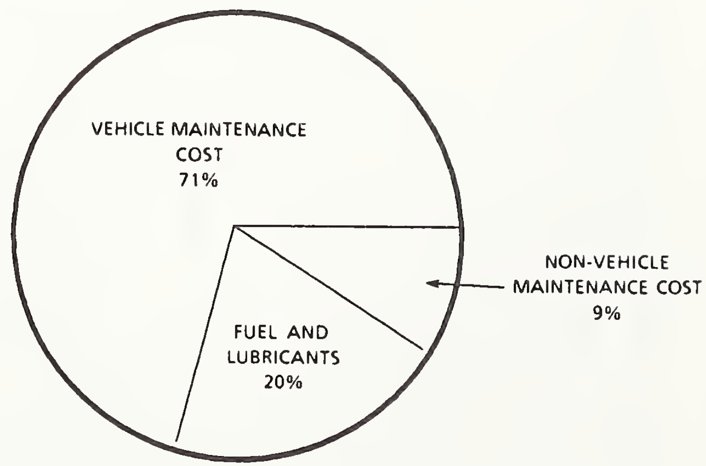
The domestic fleet of public transit buses currently uses more than 400 million gallons of diesel fuel per year. Although this may not compare to the magnitude of total fuel consumed by the private auto or other trucking industries, fuel costs represent a significant portion of the transit agency's operating budget. Fuel and lubricants on average account for about 5 cents of every dollar spent on operating and maintaining the bus fleet.(1)* A more meaningful breakdown is that fuel and lubricants represent about 20 percent of total, non-capital costs when drivers' salaries, administrative costs, and taxes and utilities are not considered, as shown in Figure 1-1. To quantify this further, a representative public agency operating about 750 buses, accumulating 21 million miles/year currently spends 7.1 million dollars per year for diesel fuel. Small percentage improvements in fuel economy could mean substantial savings to this public transit authority. The message is that fuel consumption is an important issue to public bus operators, especially in light of reduced Federal operating assistance, increasing labor costs and fare structures that are rising much slower that inflation.

Procurement of transit coaches by public agencies continues to be assisted by up to 80 percent subsidy from the Urban Mass Transportation Administration. It is of utmost concern both for the UMTA and the local authority that this significant investment in equipment be made wisely to maximize their respective returns and minimize recurring costs. With this goal in mind Congress passed

*Numbers in parentheses designate references at end of the report.



TOTAL O&M COST
BREAKDOWN FOR
DOMESTIC BUS FLEET



BUS TECHNOLOGY/FACILITY
RELATED COST BREAKDOWN
FOR DOMESTIC BUS FLEET

Source: Section 15 Info
Year 4

309 Transit Agencies
56,100 Buses

FIGURE 1-1. COST BREAKDOWN FOR DOMESTIC URBAN BUS FLEET legislation (DOT and Related Agencies Appropriations Act, Public Law 97-102) requiring evaluation of vehicle life cycle costs (LCC) as part of the grantee's procurement process. It was quickly realized by virtually all the grantees that fuel consumption was one of the most (if not the most) significant costs to be evaluated. However, since the process itself was new to the public transit community and since bus procurements are not frequent for most authorities (every 2-10 years), some confusion existed. Passage of the Surface Transportation Assistance Act of 1982 made LCC evaluations optional for procurements using FY'83 Federal assistance. Even with this change, interest in total bus costs and fuel economy, in particular, remains strong.

It was about this time that UMTA recognized a need to develop technical information that local agencies could use to assist them in their bus purchases. UMTA's Technical Assistance Program, sponsored by the Office of Bus and Paratransit Systems, has completed two interrelated elements of the Program, track tests of commercially-available, standard-size coaches, and parametric analyses using a computer simulation model called HEVSIM (Heavy-Duty Vehicle Fuel Economy and Performance Simulation). The track tests were initiated first in an attempt to answer the immediate concerns of the grantees using the LCC process. The second series of tests (2) have proved useful in substantiating the credibility of the HEVSIM results.

Simulation is a more cost-effective tool than track testing to provide technical information on fuel economy and performance trade-offs associated with changes in vehicle configuration (e.g., axle ratio, weight), new equipment (e.g., rotary screw compressors) or environment (e.g., grades, fuels, operating profiles). It is through this technical assistance process that the UMTA can improve the knowledge base of new equipment buyers and optimize their equipment investment decision for their environment.

2. GENERAL SIMULATION

2.1 GENERAL

Vehicle simulation programs are being used more frequently by manufacturers and occasionally by bus purchasers. These programs are used mainly for fuel economy and performance evaluations of present and proposed vehicle configurations. Advantages of simulation include:

1. Low cost compared to test track or laboratory measurements
2. Repeatability of results through elimination of random errors

Some of the vehicle simulation programs are listed below, along with their respective developers.

HEVSIM - U.S. Department of Transportation

VPER - General Motors Corporation Truck and Bus

VMS - Cummins Engine Company, Inc.

SCAAN - Detroit Diesel Allison

TCAPE - International Harvester

TOFEP - Ford Motor Co.

GPSIM - General Motors Engineering Center

An extensive analysis has never been performed to compare these programs, but a study of their outputs shows that they differ in flexibility and sophistication. Some do not have the capability of modeling automatic transmissions, although at least one can optimize the shift pattern for fuel economy. However, because the programs simulate actual operations, some comments regarding precision and accuracy are applicable to all of them.

Because of the elimination of random errors, the programs have a high degree of precision and are very useful for evaluating relative fuel economy and performance changes. In contrast, component test data used in conjunction with analytical equations introduces systematic errors that affect the degree of accuracy. For example, the engine test data used for simulating engine performance is usually within ± 5 percent of the values listed. This implies that if the vehicle being modeled by the program does not have the same engine represented by the test data, then the program accuracy will be compromised. Assumptions in the programs, such as the use of steady-state data and averaging some parasitic losses instead of accumulating real time losses, introduce more errors. The above factors must be realized if the models are used for predicting absolute levels of performance and fuel economy. Some manufacturers perform extensive vehicle and component testing to increase the accuracy of their programs. One bus manufacturer claims to be able to predict absolute bus fuel economy to within ±5 percent. The user of computer-generated bus fuel economy and performance data should be aware of the origin of the input data and accuracy of the output if the information is to be used on an absolute basis.

2.2 HEVSIM

The bus simulation program used for this study is the heavy vehicle simulation program HEVSIM, which is run at the U.S. Department of Transportation, Transportation Systems Center (TSC) in Cambridge, Massachusetts.* This program is based on an earlier vehicle simulation program, VEHSIM, that was also developed at TSC.

*HEVSIM documentation PB82164575, 583, 591 is available from NTIS, Springfield, Virginia 22161

The development of VEHSIM was initiated for automotive applications in studies requiring parametric investigation of automotive fuel economy, performance, and emissions. In the spring of 1976, the SAE Vehicle Correlation and Simulation Subcommittee was formed to direct the necessary revisions to make VEHSIM applicable to truck and bus simulation. Revisions included improved computational methods, detailed component data specifications, and essentially enhanced operational convenience through adaptation of remote terminal capability.

Because of the need to simulate heavy duty vehicles, primarily for the SAE/DOT truck and bus fuel economy program, VEHSIM was divided into two separate programs and data bases: VEHSIM for simulation of light duty trucks and automobiles, and HEVSIM for heavy duty vehicles. The input data required for HEVSIM simulation is illustrated in Figure 2-1.

The program in Cambridge operates on a DEC-System 10™ computer utilizing 42 Fortran-10 subroutines and 17 Macro-10 subroutines. The program is also in use at private companies and universities on other systems. The Fortran subroutines consist of 6,400 source code lines with 3,100 lines of comments. The Macro-10 subroutines include 700 lines of code plus 300 comment lines. Core size is 130K words (5 bytes per word). For a typical simulation of bus fuel economy and performance, the computer time is 84 CPU seconds when using a 0.05-second time step increment.

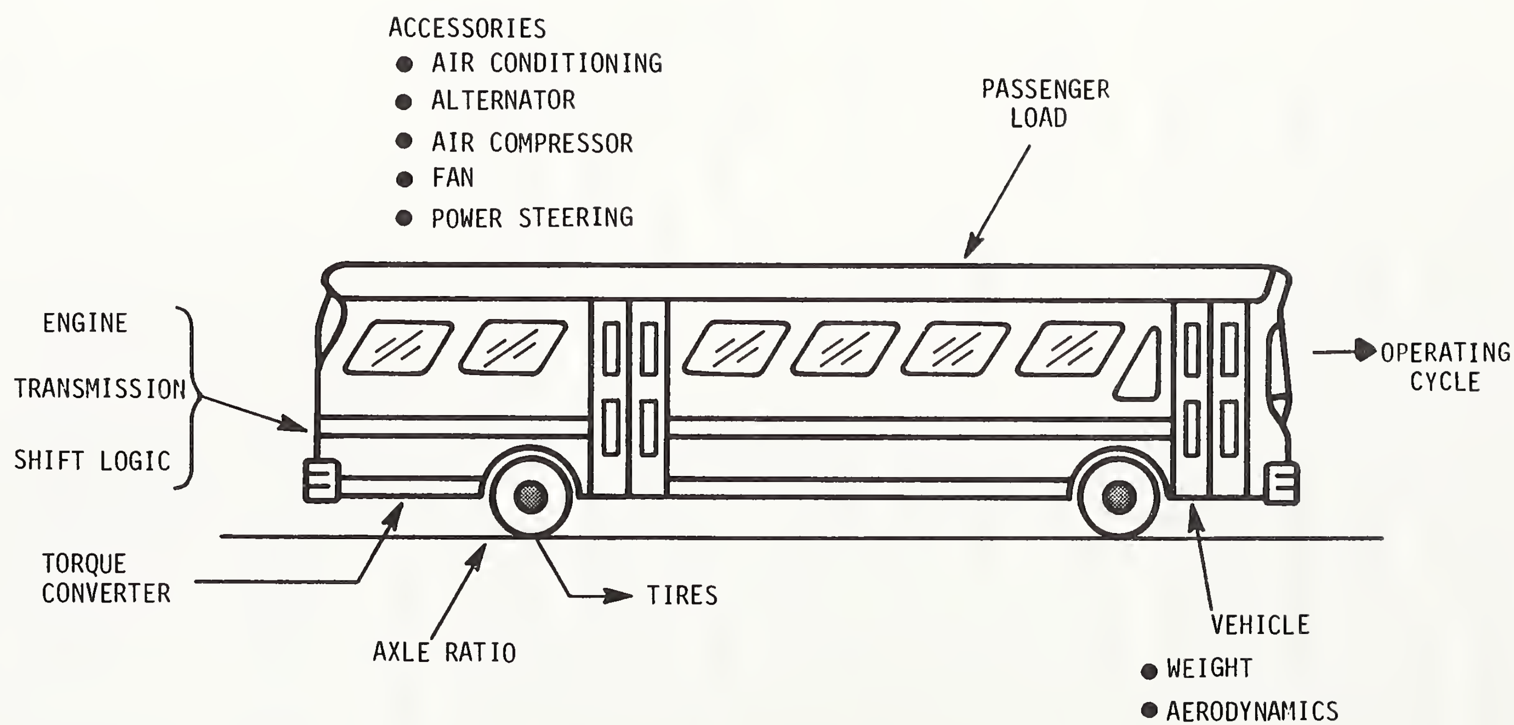


FIGURE 2-1. CALL-OUT OF HEVSIM INPUT DATA

3. VEHICLE SYSTEMS INTEGRATION

In order to simulate an entire vehicle system, it is necessary to select vehicle "parts" which combine to represent an actual vehicle. The vehicle parts are a combination of performance test data of a bus component and analytical equations that simulate the actual operation of a particular section or part of a vehicle. Combining all of the parts in a correct manner yields a simulated vehicle. This procedure, known as vehicle systems integration, involves scanning the parts file and matching the actual part to the simulated part. If the simulated part is not available, the user must either obtain more data to create a new part or apply engineering judgment in determining the part nearest to the actual vehicle system part. The user must then determine how this part integrates into the entire vehicle system. A description of each of the HEVSIM parts is provided in detail in Sections 3.1 to 3.9 to provide the reader with the background necessary to acquire a better understanding of the results of report. The precise format required for each part to be entered into the data base is described in the HEVSIM documentation.

3.1 ENGINE

The engine, for simulation purposes, is represented by a compilation of steady state engine test data, commonly termed an "engine map." These engine maps are obtained from engine dynamometer tests and usually consist of 20 load points for each of 10 to 15 speed points. The load points can be torque and manifold vacuum (if applicable), and the throttle angle may also be included to accommodate certain shift logics based on engine throttle angle. To produce an engine map, processing and display programs are usually required because of the voluminous data involved.

Engine maps differing in format may also be provided by the engine manufacturers. These maps usually are provided in graphic form, showing fuel rates or brake specific fuel consumption as shown in Figure 3-1. For proper simulation it is extremely important that all the data are consistent. For example, a negative torque should occur at a closed throttle angle, and torques should uniformly increase for increasing throttle angle. In some engine tests, wide open throttle (WOT) cannot always be achieved at idle or low rpm conditions. Therefore, the WOT load point at idle should be extrapolated from the WOT torque curve. Alternatively, the vehicle acceleration is restricted initially to a rate that is equivalent to vehicles accelerating at WOT in actual operations. Also, when receiving maps in this format, the user should be aware of the associated test parameters such as specific gravity, intake restrictions and accessory loading, since variations in these parameters may sometimes produce different fuel rates for identical engines.

3.2 TRANSMISSION/AXLE

The transmission is simulated as a combination of gear ratios and the axle as a single gear ratio. The ratios for each gear and axle must be specified. Gear efficiency may be assumed constant, although the losses in the gears are attributed to a combination of a viscous portion that is speed dependent and to the effect of the power transmitted that varies with both speed and load.

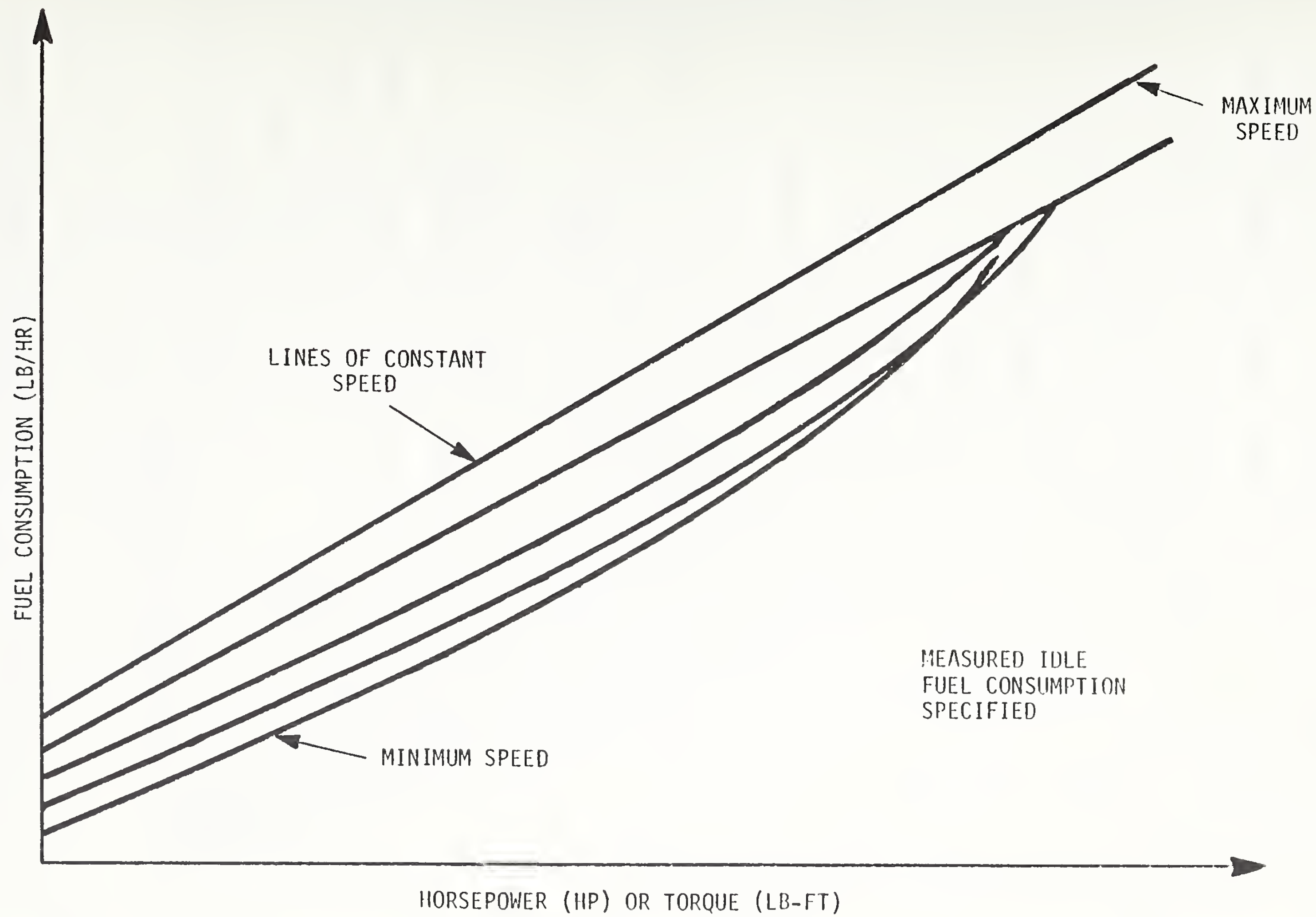


FIGURE 3-1. SAMPLE ENGINE FUEL MAP FOR SPECIFIED INJECTORS AND FUEL

3.3 TORQUE CONVERTER

When simulating automatic transmissions, a torque converter must be considered. The purpose of the torque converter is to increase the engine torque at low vehicle speeds and ultimately limit torque increases to zero at higher vehicle speeds. The performance representation of the converter is similar to that of the engine, the converter also being depicted as a map, as shown in Figure 3-2. From this map it can be seen that the output torque and speed are dependent upon both the input load and speed. The characteristic curves are determined by the "K" factor, which is equal to the speed divided by the square root of the torque. For simulation purposes, the converter is divided into two modes of operation: drive and coast. The drive mode is used when the engine is propelling the vehicle and the coast mode is used in the opposite situation. Although the torque converter data provided by the manufacturer is represented in many different ways, the program will always reference the "K" curves when calculating the output speed and torque.

The selection of a torque converter is determined in conjunction with other drivetrain components. Usually no single torque converter is appropriate for all applications. The efficiency of a converter is the product of the speed ratio and torque ratio and will be different for each converter at different operating speeds. Efficiency is increased at higher speeds through the use of lockup clutches, which eliminate slip. Torque converter pumping losses, which are dependent upon speed, are subtracted from the engine output as are other parasitic losses.

3.4 SHIFT LOGIC

The shift logic is the operating control strategy for determining when the transmission changes gears based on engine load and vehicle speed. The actual hydraulic or electronic controls for shifting are represented, for

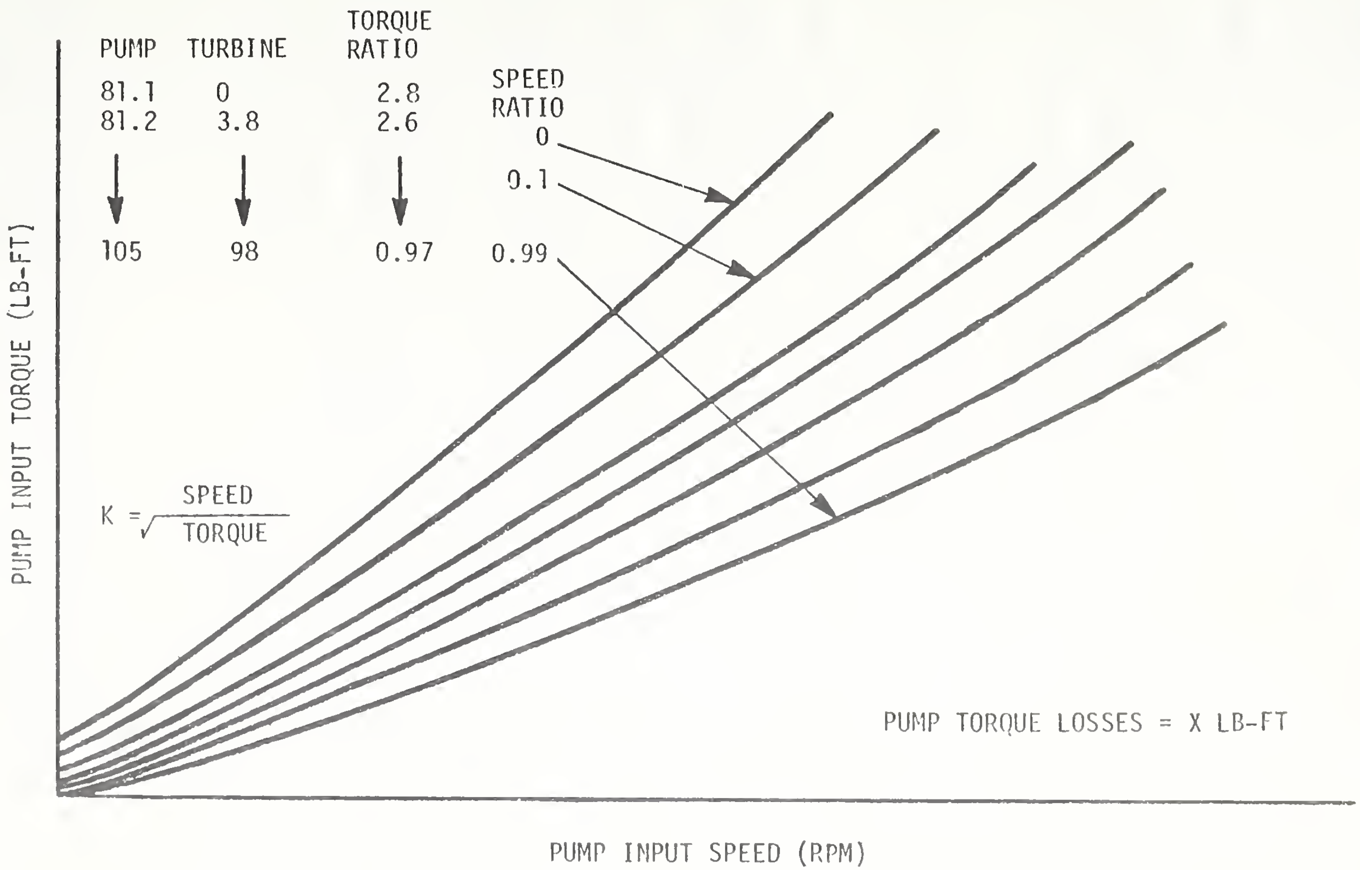


FIGURE 3-2. SAMPLE PRESENTATION OF TORQUE CONVERTER PUMP CHARACTERISTICS

simulation purposes, by a series of lines called shift lines. Each shift logic is usually tailored for a specific vehicle-drivetrain combination and is presented in terms of these shift lines for a given load and speed (vehicle, engine, or propshaft), as shown in Figure 3-3. Generally, the manufacturer will recommend a particular shift schedule for given requirements. It is important to note that simulating, a shift logic not designated for a particular vehicle or modifying shift-dependent parameters (axle ratio) may produce erroneous results.

3.5 TIRES

Tires used on buses are characterized for simulation purposes by their rolling radius, rolling resistance, and inertia. The rolling radius is assumed to be the average between the static and dynamic values. The rolling resistance is primarily a function of the product of vehicle weight and the tire rolling resistance coefficient. This coefficient is usually measured on a laboratory dynamometer and then corrected for road and environmental conditions. The resulting coefficient, which can change with tire pressure, tire wear and slip angle, is usually considered an average value. The inertia, which includes the tire, wheels, and driveshaft, is provided by the particular bus or tire manufacturer.

3.6 VEHICLE

Certain basic characteristics describe the vehicle, such as weight, frontal area and aerodynamic drag. The weight of the simulated vehicle should be selected according to the drive schedule to reflect some operating condition. Examples of common weights used in simulation analysis of transit buses are curb weight (no passengers) and seated load weight (curb plus 150 lb per passenger).

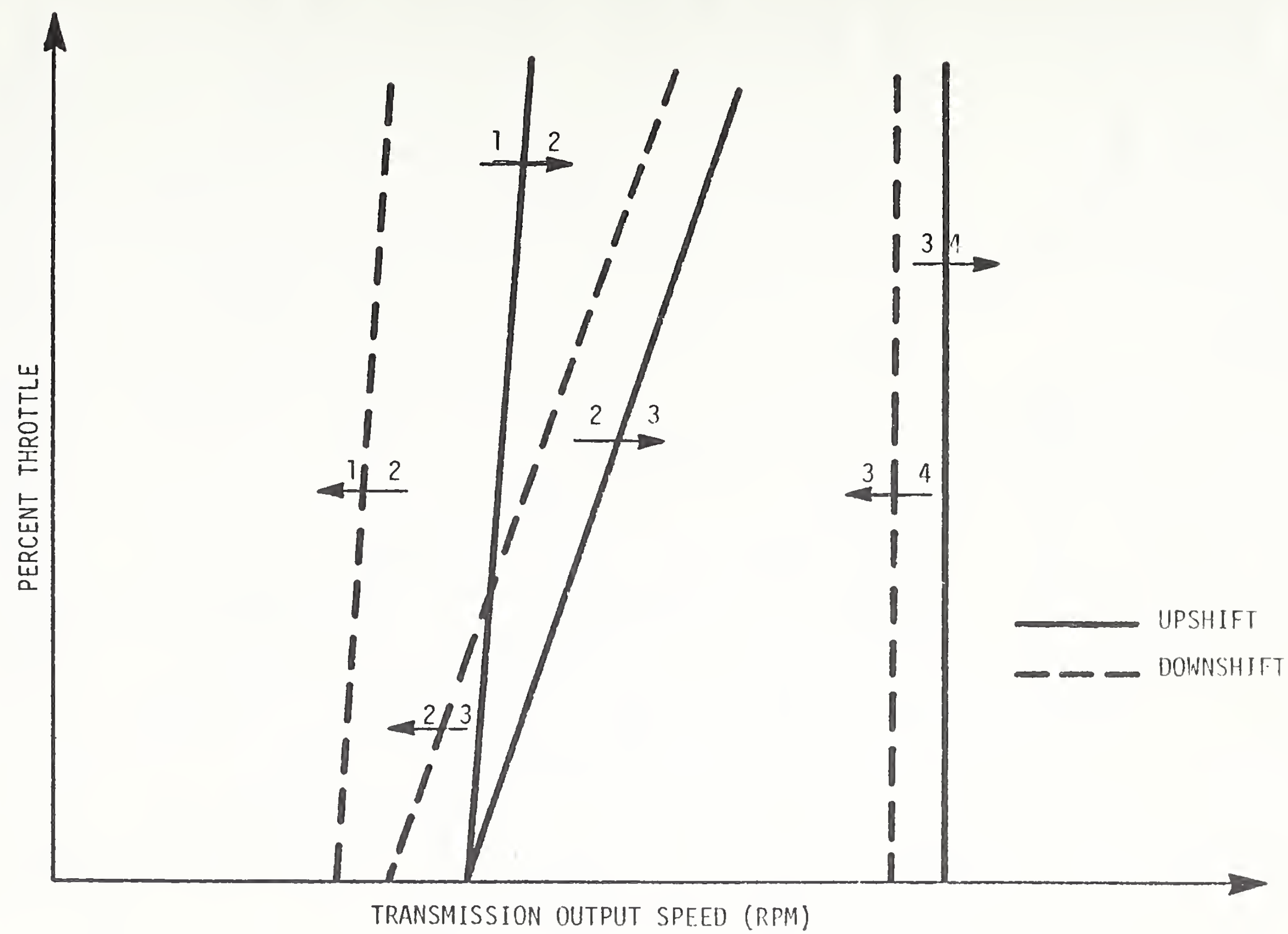


FIGURE 3-3. SAMPLE AUTOMATIC TRANSMISSION SHIFT LOGIC

The aerodynamic drag coefficient is usually obtained from wind tunnel tests or coast-down measurements. This coefficient, which basically characterizes the aerodynamic efficiency of the vehicle, can be changed by additions such as roof-top air conditioners or side mirrors. The projected frontal area is the product of the width and height of the vehicle, minus the ground clearance area. This would be equivalent to the area that could be measured by a planimeter using a frontal picture.

3.7 DRIVE SCHEDULE

Driving schedules can be divided into two categories: performance and fuel economy. Performance schedules usually include acceleration time and maximum gradeability at a specified speed. With the exception of passing schedules, all performance schedules can be consolidated into one top speed schedule. The current standard schedule for transit buses is the Advanced Design Bus (ADB) schedule. All of the above schedules consist of accelerations, cruises, decelerations and stops. Program input for drive schedules is flexible to allow the user a choice of constant acceleration, constant throttle, or constant speed for relative or absolute time or distance. Any variation of grades or wind may also be input to the program. Essentially any speed, time, or grade profile approximating an existing bus route can be reduced to a table of data and input to the model.

3.8 ACCESSORIES

Bus accessory loads are basically parasitic losses that reduce the available power output of the engine. As input to the simulation program, they are loads for a given range of speeds and may look similar to those shown in Figure 3-4. Bus component suppliers usually provide its customers with performance curves for each of the bus accessories. These performance curves

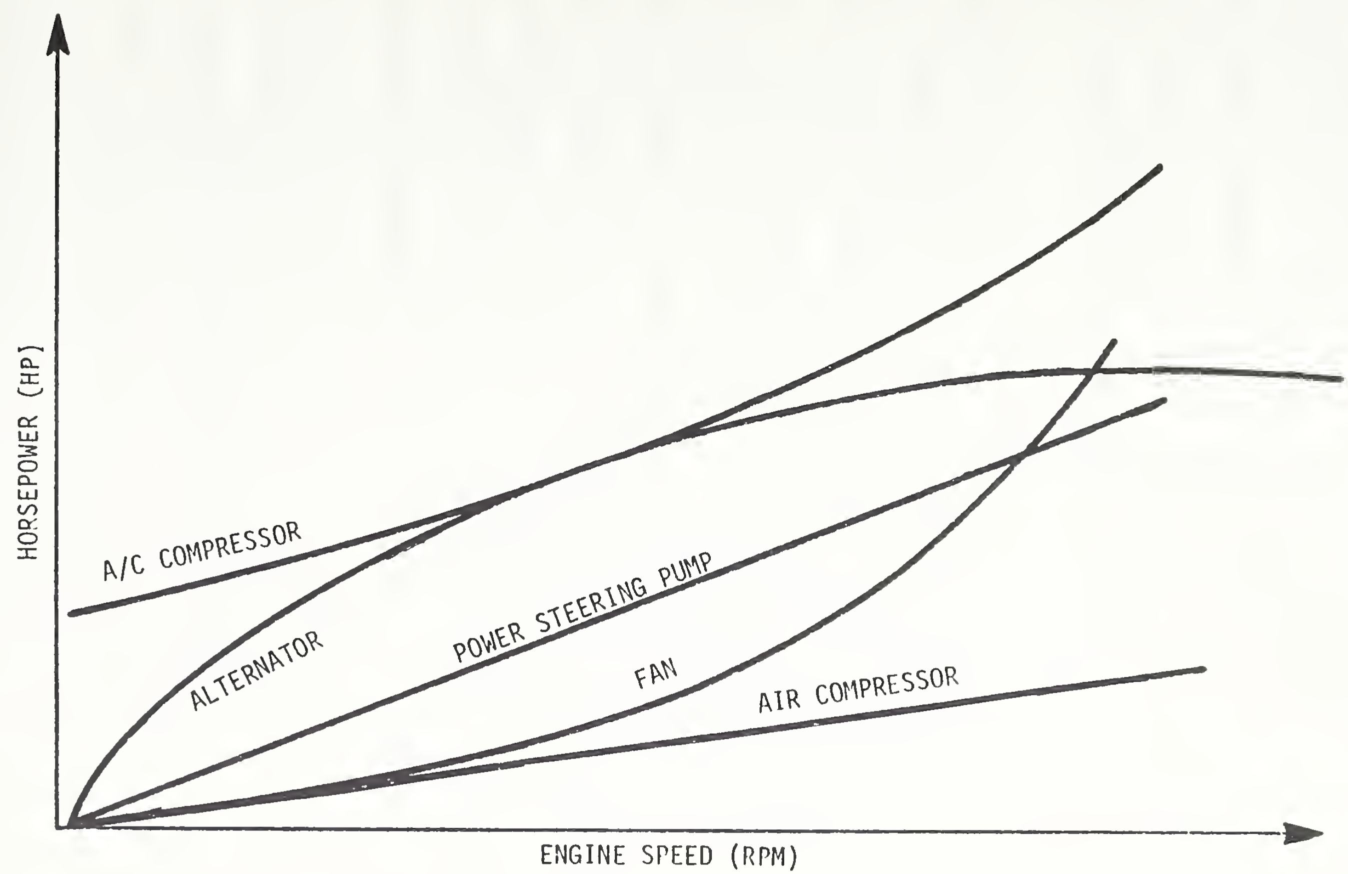
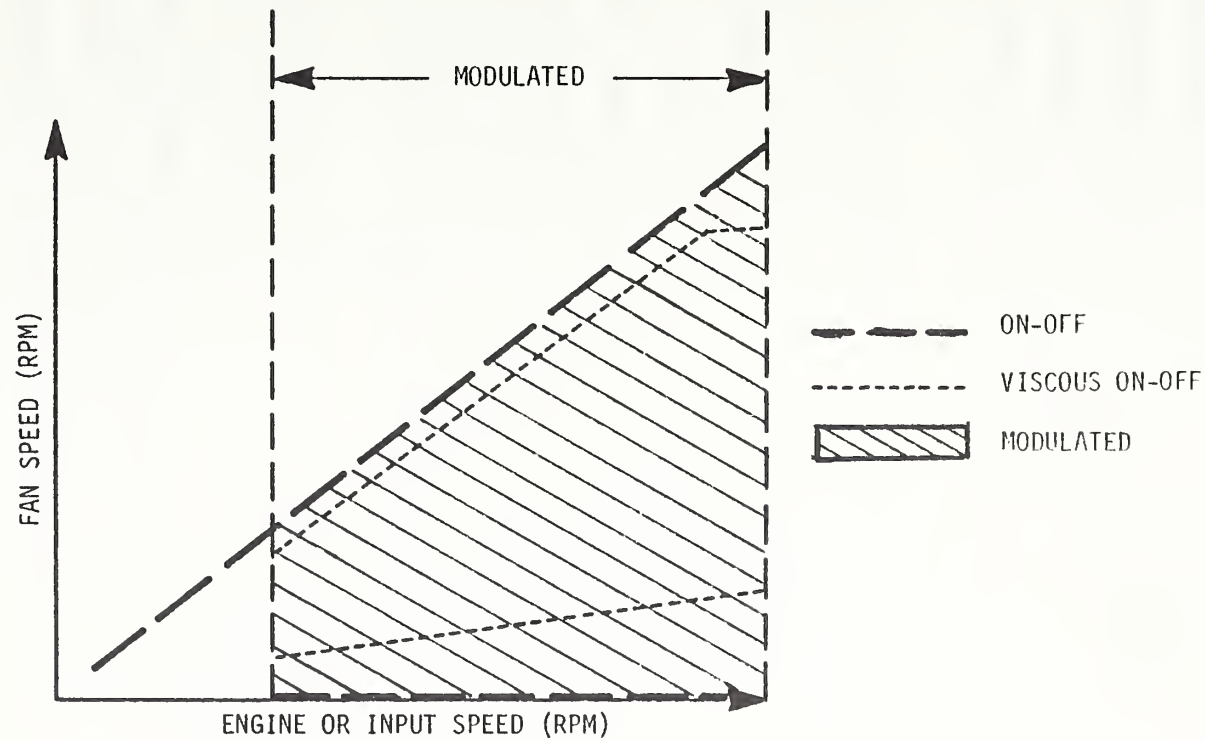


FIGURE 3-4. SAMPLE MAXIMUM ACCESSORY LOAD FOR GIVEN VEHICLE ENGINE

are used as a basis for the input to the simulation program. Since most accessories are belt or gear driven, the speed ratio (accessory rpm/engine rpm) must be known in order to deduct power relative to engine speed. The duty cycle must also be specified. Duty cycle is defined as the percentage of time that an accessory is operating in a given mode, divided by the maximum time it could be operating in that mode. The term "mode" is usually fully loaded, unloaded or partially loaded. The following accessories are generally required for simulation purposes.

The engine fan or engine compartment fan and fan drive are modeled as separate components for simulation purposes. Fan power consumption over a range of speeds is provided by the manufacturer. Variables such as number of blades, diameter, and pitch are included in this performance curve. The mechanism driving the fan is designated as the fan drive system. This system, which relates engine speed to fan speed, is represented by either a fixed-ratio on-off, speed-modulating, or viscous on-off system as shown in Figure 3-5. The fixed ratio on-off system operates on either of the dashed lines. The viscous system operates on either of the dotted lines, and the modulated system operates anywhere within the shaded area. Just where the fan operates and how much time it spends at each line or point is modeled by the duty cycle, which is an average value of the real-time, on-off operation of the system. The duty cycle is dependent upon system orientation and engine cooling requirements. Although the duty cycle can be estimated, actual measured values should be used if available.

The power steering load, like these of other accessories, is considered a parasitic loss. Although there are numerous pump types, displacements, and flow rates, the pump for simulation purposes is characterized by a load and



SOURCE: SAE J1342

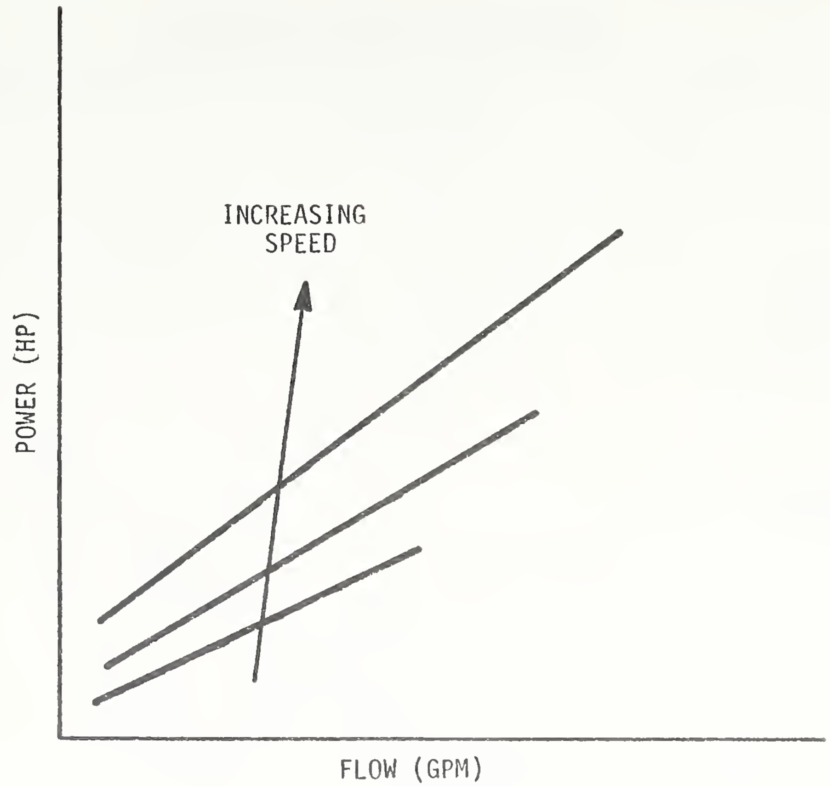
FIGURE 3-5. FAN DRIVE SYSTEMS

speed profile. The pump speed/engine speed ratio is determined by the pulley or gear diameters if applicable. The manufacturer-supplied pump characteristics may reflect those shown in Figure 3-6. From this curve and the known route of the designated cycle, a duty cycle must be determined. A route requiring numerous turns requires a higher flow rate or higher head than a straight route. Again, actual test data is preferred if the specific test operating conditions are known.

The generator or alternator, which converts mechanical energy to electrical power, has a performance curve for a given voltage as shown in Figure 3-7. Speed ratio relates the engine speed to generator (alternator) speed. The input to the program is the load curve, but the load on the generator (alternator), which is dependent upon the current demand, must be known. If test data is not available, the load can be estimated and the duty cycle can be determined. The load estimate is determined by summing the average wattage of all the electrical components over the cycle to be simulated.

The air compressor simulation curve, like the power steering curve, depicts a pump operating under varying conditions. Unless there is a leak in the air system or there is an unusually high load demand, average constant loaded and unloaded operating curves can be assumed, as shown in Figure 3-8. The pressure head against which the compressor is pumping can be determined from the manufacturer.

Simulation of the air conditioning system is so complex that a separate subroutine is used in conjunction with the HEVSIM program. This additional subroutine accounts for passenger load, ventilation requirements, door openings, infiltration, and heat transmission through the bus body. After an inside temperature set point and ambient conditions are selected, the program



SOURCE: SAE J1341

FIGURE 3-6. SAMPLE POWER-STEERING PUMP CHARACTERISTICS

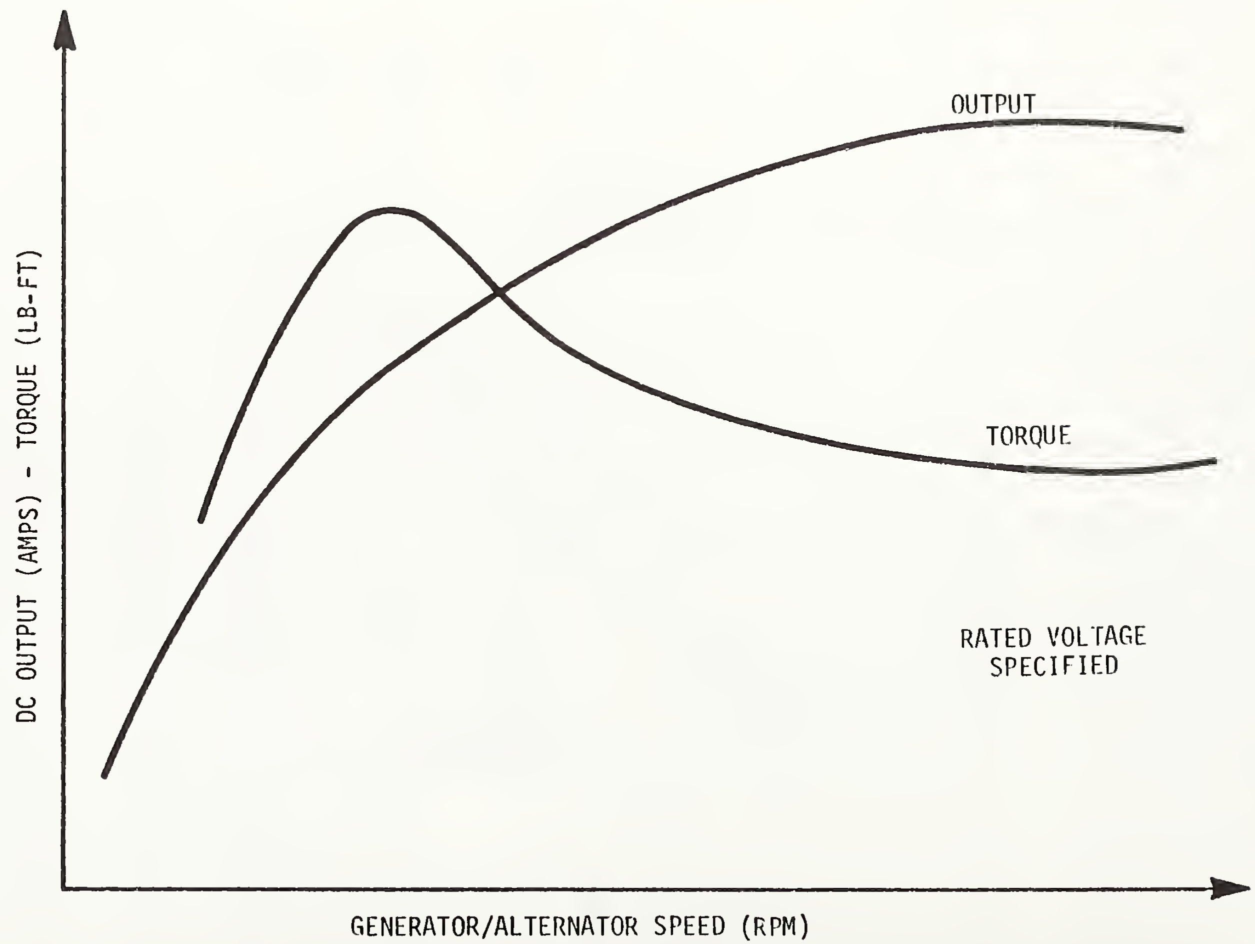


FIGURE 3-7. SAMPLE GENERATOR/ALTERNATOR NOMINAL PERFORMANCE

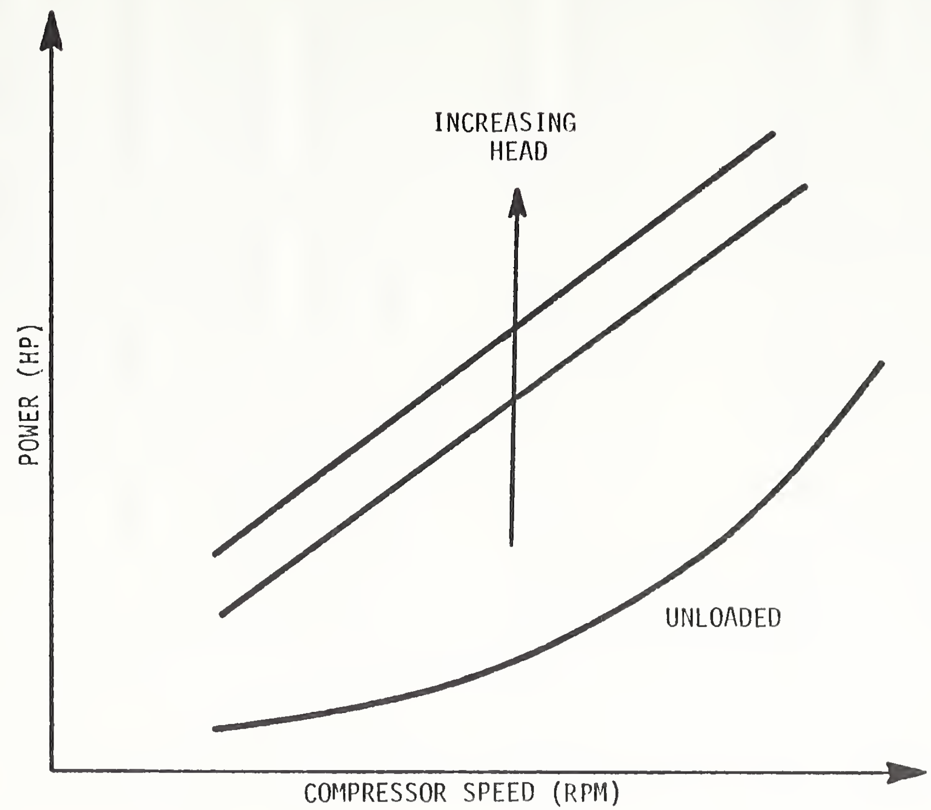


FIGURE 3-8. SAMPLE AIR COMPRESSOR OPERATING CURVES

calculates the sensible and latent loads for the specified conditions. These conditions are then used to determine the compressor load, which is based on compressor operating points as determined by the particular drive schedule. The gearing of the bus determines the operating points of the engine, which consequently affects the compressor through the compressor speed ratio. The compressor load is weighted based on regional weather data. This yields a time-weighted average load which, as with other accessories, is considered a parasitic loss for the engine. Losses due to the use of electric evaporator and condenser fans is simulated by increasing the alternator duty cycle.

3.9 BASELINE CONFIGURATIONS

Six, forty-foot transit buses manufactured by six different companies were selected for simulation analysis in this study. They represent a variety of different drivetrains accessories, body designs, and weights as shown in Table 3-1.

The buses are characterized by parts or components as described previously. The data for each manufacturer's parts, which represent actual hardware, was supplied by the manufacturer or component supplier. To ensure accurate representation of these commercial vehicles, each manufacturer was asked to certify descriptions of make and model of each component modeled. Because of the competitive nature of bus procurements, the data is proprietary and therefore parts will not be described by a particular manufacturer's name.

Since an enormous amount of data would be generated if the sensitivity of of every component of each bus were evaluated, only two or three components of each bus are studied in this report. As each component is investigated, differences among the six buses that could impact the evaluation criteria are delineated. Evaluation or reference criteria used in this study are fuel economy and performance, which will be described in Section 4.

TABLE 3-1. BASELINE CONFIGURATIONS

BUS	ENGINE	FUEL INJECTOR	TRANSMISSION	TORQUE CONVERTER	AXLE RATIO	SEATED LOAD WEIGHT (lb)
A	6V92TA	7G65	V-730	TC-470	5.125	30,780
B	6V92TA	7G65	V-730	TC-470	5.375	31,860
C	6V92TA	7G75	HT-747	TC-495	4.625	32,890
D	6V92TA	7G70	HT-740	TC-495	4.11	33,320
E	6V92TA	7G75	V-730	TC-490	5.375	32,830
F	6V92TA	7G70	V-730	TC-470	5.125	33,340

3.10 FUEL ECONOMY SIMULATION

The calculation of simulated fuel economy is performed on an incremental basis and can be divided into two parts to facilitate the comprehension of the process. First, for a given time increment, the road-load forces, driveline losses, transmission losses, and accessory loads are calculated to yield a torque and speed (power) output required by the engine. The second part occurs when this requirement is transferred to the engine "map," where an incremental fuel rate is calculated. This incremental fuel rate is then stored and the process is repeated until the drive schedule is completed. Then, the total distance is divided by the total amount of fuel.

The first part of the calculation involves the amount of engine energy output required to propel the bus over the drive schedule. The output of the engine during a time increment can be thought of as energy required by all the vehicle components. The contribution of each component will vary depending upon the drive schedule. Typical allocation of energy is shown in Table 3-2.

The second part of the calculation is the process of converting fuel into work or energy. The efficiency of this process is measured by the brake-specific fuel consumption (BSFC). The lines of constant BSFC and the ADB phase engine operating points are plotted on the engine map, as shown in Figure 3-9, in one-second intervals with the constant speed portion of all three phases indicated. The cluster of points at the maximum power is a result of wide-open-throttle accelerations. There are no BSFC lines in the motoring region because the engine is not propelling the vehicle during this mode.

From this brief analysis it can be seen that the fuel economy can be improved by reducing the load on the engine and/or by having the engine operate in more efficient regions. The latter can be accomplished by changing the drivetrain (e.g., axle ratio).

TABLE 3-2. PERCENT ENGINE ENERGY FOR BUS B OVER ADB DRIVE SCHEDULES

Component	Percent Engine Energy (hp-hr)		
	CBD	ART	COM
Transmission and driveline	7	9	13
Torque converter	12	5	1
Aerodynamics	2	8	25
Rolling resistance	14	16	23
Accessories	22	19	25
Brakes (mass)	43	43	13

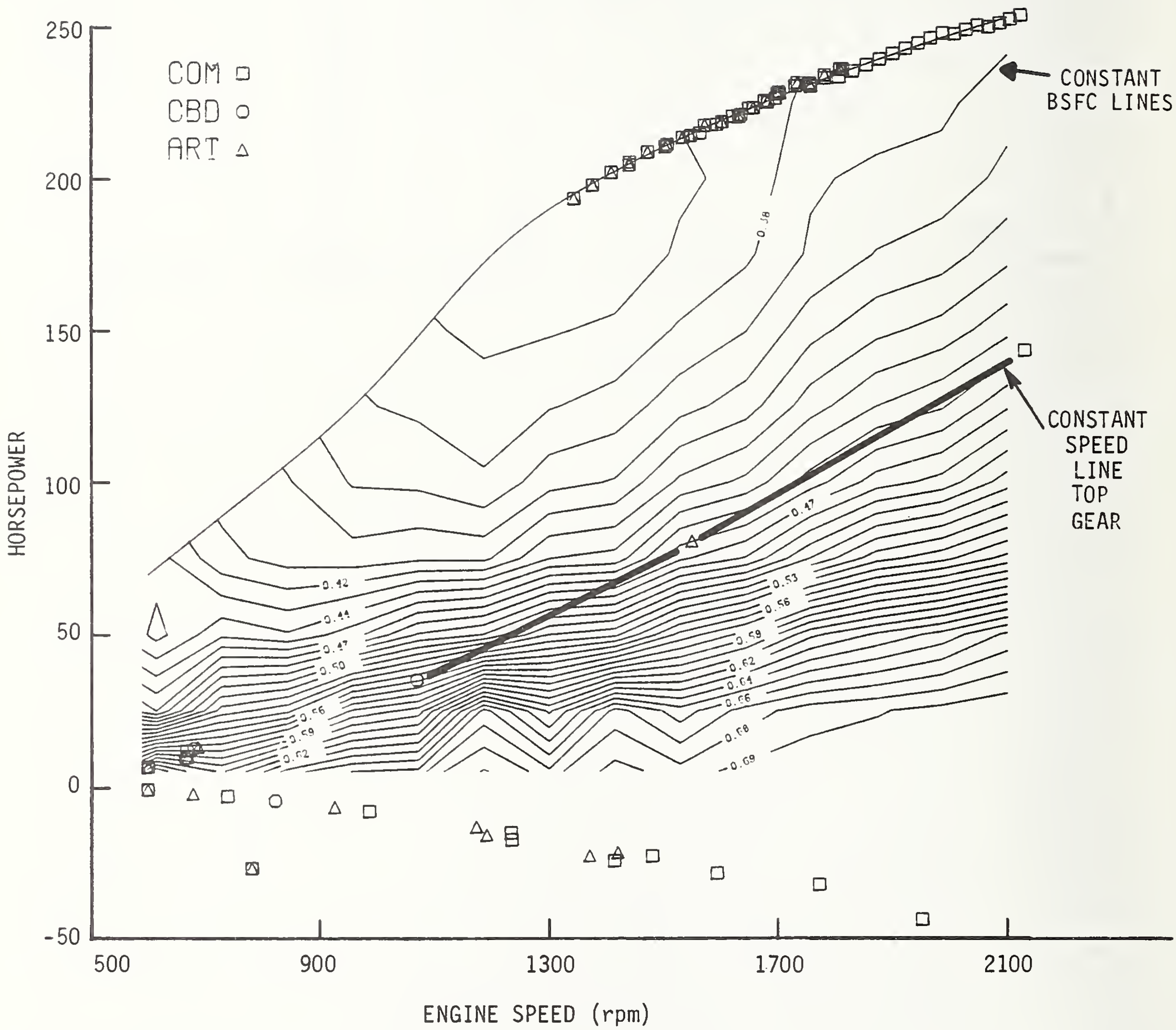


FIGURE 3-9. ENGINE OPERATING POINTS FOR ADB CYCLE - BUS B

4. SENSITIVITY CRITERIA

4.1 GENERAL

In order to determine the effect of changes in transit bus variables on fuel economy and performance, evaluation criteria must be established. Fuel economy is determined by simulating the bus over a reference test or drive cycle.

The drive cycle used in this study is the Advanced Design Bus (ADB) operating profile, which consists of simulated transit-type service. The cycle, shown in Figure 4-1, consists of three phases to be repeated in sequence: a central business district (CBD) phase of two miles with seven stops per mile and a top speed of 20 mph; an arterial route phase (ART) of two miles with two stops per mile and a top speed of 40 mph, and a commuter phase (COM) of four miles with one stop and a maximum speed of 55 mph.

The composite ADB cycle is composed of six miles of CBD phase, four miles of COM phase, four miles of ART phase and an idle phase of five minutes. The resulting ADB fuel economy without idle can be approximated by:

$$ADB_{fe} = \frac{1}{\frac{.286}{COM_{fe}} + \frac{.286}{ART_{fe}} + \frac{.428}{CBD_{fe}}}$$

where ADB_{fe} = Advanced Design Bus Cycle fuel economy

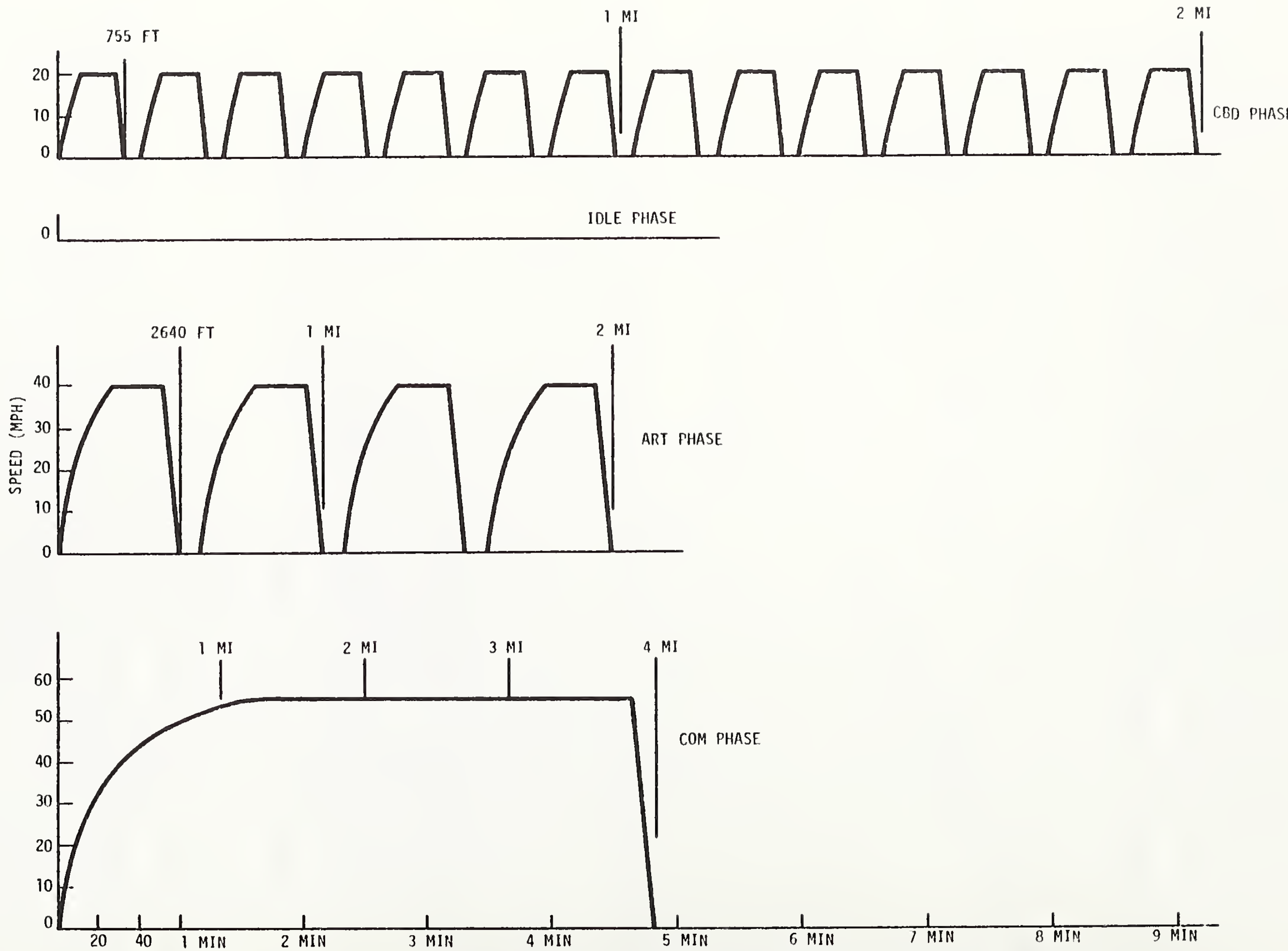
COM_{fe} = Commuter phase fuel economy

ART_{fe} = Arterial phase fuel economy

CBD_{fe} = Central Business District phase fuel economy

In all cases the acceleration occurred with a 100 percent wide-open-throttle.

The evaluation used for performance is acceleration, gradeability, and top speed. The acceleration is portrayed by the amount of time to accelerate to a given speed at wide open throttle. ADB maximum acceleration times are shown in Table 4-1.



SOURCE: BASELINE ADVANCED DESIGN TRANSIT COACH SPECIFICATIONS, UMTA

FIGURE 4-1. TRANSIT COACH OPERATING PROFILE DUTY CYCLE

TABLE 4-1. MAXIMUM TIME FOR ACCELERATION

Speed (MPH)	Standard Powerplant (SEC)	Low Power Alternative (SEC)
10	5.6	6.0
20	10.1	12.0
30	19.0	24.0
40	34.0	45.0
50	60.0	-
60	-	-

Gradeability is defined as the maximum grade a vehicle can negotiate at a given speed. Fundamentally, gradeability is the difference between the rear wheel power and the road load power. The minimum gradeability requirements for ADB specifications are that a bus at seated load weight should be able to travel on a roadway with a 16 percent grade at 7 mph and 2.5 percent grade at 44 mph.

Theoretical top speed of the bus can be calculated using the drivetrain ratios and the governed engine speed. However, attaining that calculated top speed depends upon the available engine power. Therefore, gearing and engine power must be considered when evaluating top speed. All calculations of performance and fuel economy are at the seated load weight (SLW) of the bus.

4.2 SENSITIVITY ANALYSIS

The purpose of this section is to systematically evaluate changes in fuel economy and performance with respect to vehicle design or component changes. The approach taken is to first identify the vehicle and the component or variable to be changed, then change one vehicle variable at a time and calculate the resulting performance and fuel economy. This procedure is repeated for each of the variables. With data on six different transit coaches and numerous design variables it is possible to develop an extensive amount of data. However, judgements were made to limit sensitivity data to areas where, although trends were commonly known, quantification was absent. It is important to realize that these sensitivities are accurate only for the configuration and route profile modeled. They are considered to be representative, however, of the direction and magnitude that could be anticipated in other standard-size coaches commercially available today. All sensitivity data provided in this report are segregated by driving cycle phase,central business district (CBD), arterial (ART), and commuter (COM), as well as the combined ADB values. This permits some tailoring of the results to specific route structures. Section 5 of this report provides guidelines (along with caveats and qualifications) on how to use this data in specifying some bus options for particular operating environments.

The results are presented in terms of performance graphs and fuel economy sensitivities. Fuel economy sensitivity, a dimensionless number, is defined as the percent change in fuel economy divided by the percent change in the variable being evaluated. The percent change occurs from a specified reference point. Each resulting sensitivity relationship will be accompanied by a discussion to explain the direction and magnitude of change.

4.2.1 Weight

The seated load weight of the six baseline buses varied from 30,780 to 33,340 lbs. Bus F was used for the weight variation runs. The weight of the bus affects both the inertia and the rolling resistance, and, therefore, it is apparent that reducing weight will increase fuel economy and reduce acceleration time. The weight variation has a nearly linear effect on the fuel economy of the three phases and the ADB cycle, as shown in Figure 4-2. However, the slope of the CBD cycle, for example, is greater than that of the commuter cycle,

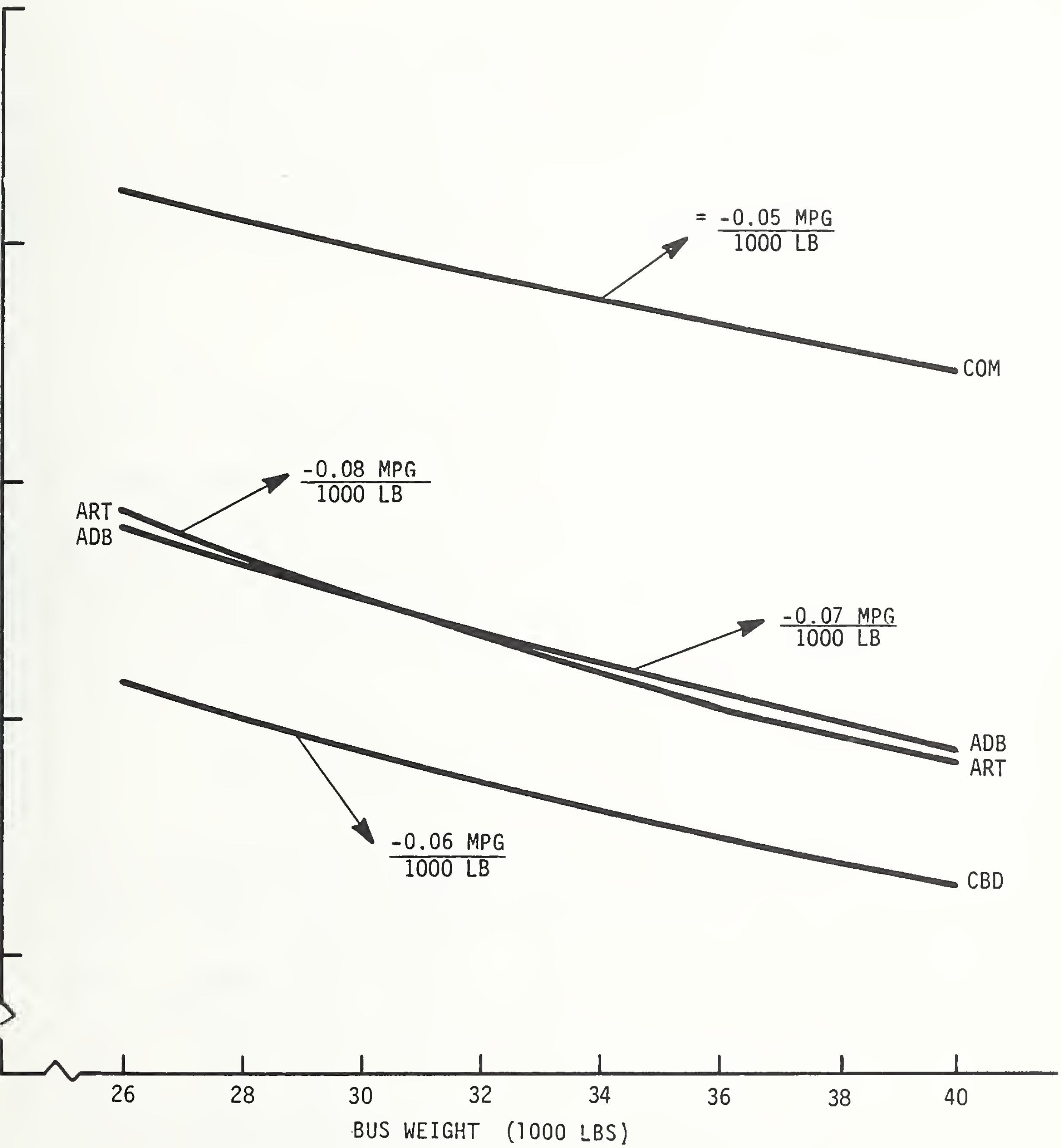


FIGURE 4-2. FUEL ECONOMY FOR WEIGHT CHANGE OF BUS F

indicating the greater effect of weight in the CBD cycle. Decreasing the weight in the baseline bus by 10 percent results in a fuel savings of 6.5 percent in the CBD phase; 6.9 percent in the ART phase; 3.5 percent in the COM phase and 6.0 percent in the ADB cycle.

Reduction in weight will cause a reduction in road load power and acceleration energy, thereby increasing gradeability and reducing acceleration times as shown in Figure 4-3. Top speed remains unchanged, although previous results indicate that, as weight is reduced, the time needed to obtain top speed is also reduced.

4.2.2 Transmission

The two types of transmissions considered in this study are V-drive and in-line transmissions. The V-drive has an 0.875 bevel gear ratio between the torque converter and transmission, while the in-line is a straight-through design without a bevel gear. The transmission gear ratios, shown in Table 4-2, are identical except for the extra first gear ratio of the in-line.

TABLE 4-2. TRANSMISSION GEAR RATIOS

Gear ratio	V-drive	In-line
1	2.02	3.69
2	1.38	2.02
3	1.00	1.38
4	-	1.00

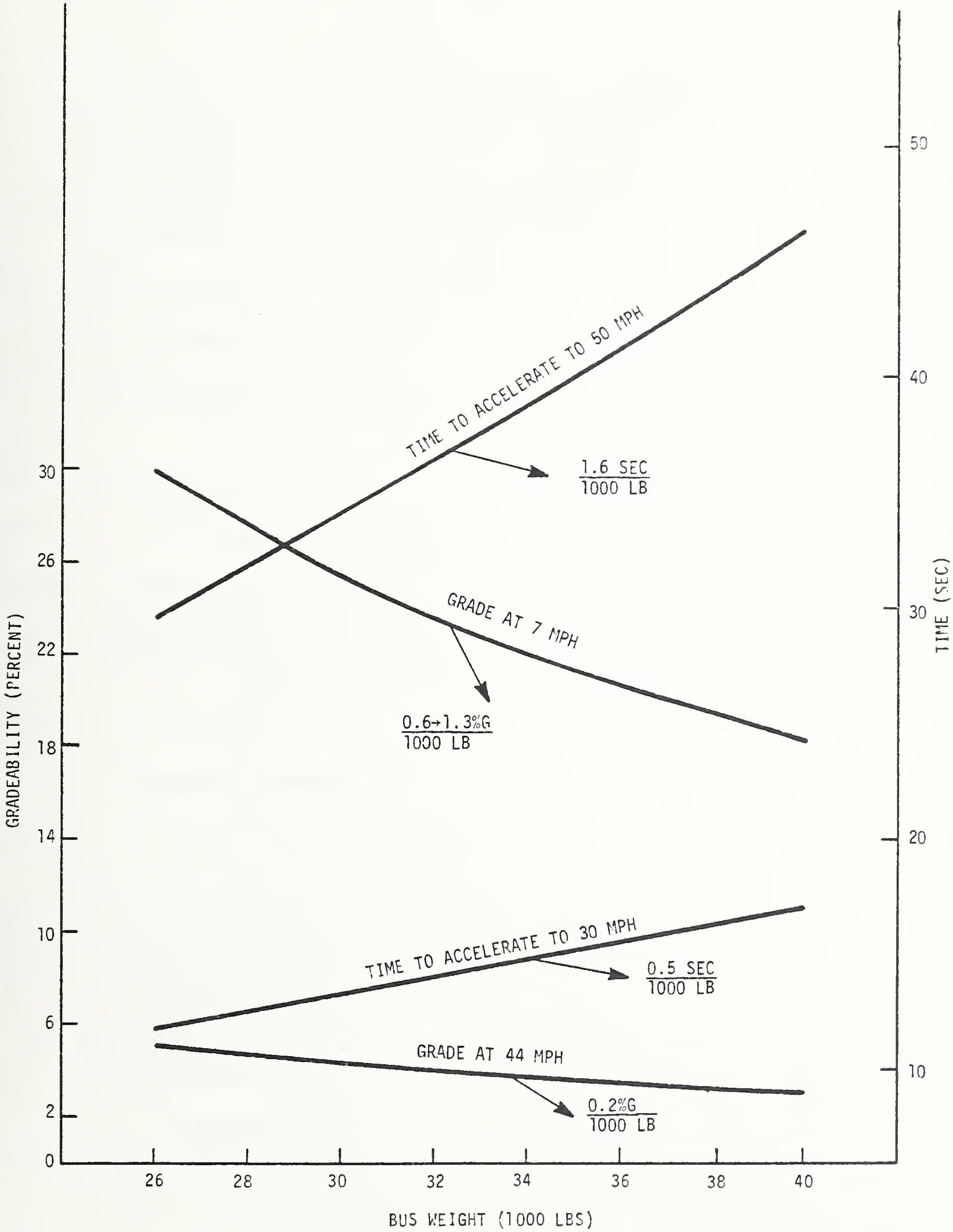


FIGURE 4-3. PERFORMANCE VS. WEIGHT CHANGE FOR BUS F

A fuel economy comparison between the two transmissions was made by simulating Bus C with different N/V ratios (engine rpm/vehicle mph) to obtain a range of performance. The transmission, shift logic, pumping losses, and torque converter were then modified to those of Bus E. This second configuration represents a bus equipped with a V-drive transmission and identical in other components (except shift logic, converter, and axle ratio) to Bus C, which has an in-line transmission. The N/V ratio was varied in this configuration to obtain different levels of performance.

The fuel economy comparison was made at the equivalent geared top speed performance, as shown in Table 4-3. At 20 mph in the CBD phase, V-drive fuel economy was 12 percent better than in-line fuel economy. This difference comes mainly from the relatively high first-gear ratio of the in-line transmission in addition to the differences in shift logic and converters.

TABLE 4-3. RELATIVE PERFORMANCE AND FUEL ECONOMY COMPARISON OF V-DRIVE AND IN-LINE TRANSMISSION

Transmission[1]	Fuel Economy (mpg)				Performance			
					Gradeability(%)		Acceleration time(sec)	
	CBD	ART	COM	ADB	7 mph	44 mph	0-30 mph	0-50 mph
In-line	← Baseline →				← Baseline →			
V-drive	+12%	-1%	-1%	+6%	-30%	-20%	+10%	+2%

[1]Geared top speed is 60 mph

In the ART phase, the fuel economy of each transmission is nearly identical at the 60 mph geared top speed. Because the OPT shift schedule is used for the V-drive, both vehicles are in top gear at 40 mph. In the COM phase, both vehicles are again in top gear at the 55-mph cruise speed, resulting in nearly identical fuel economies. The resulting ADB fuel economy is 6 percent better for the V-drive than the in-line for the vehicle configurations studied. The first gear ratio of the in-line, which causes poor fuel economy in the CBD phase, contributes to higher performance at low speeds. At 60 mph geared top speed, the 7 mph gradeability and 0 to 30 mph time of the V-drive are different than the corresponding in-line figures by 30 percent and 10 percent, respectively.

The 20 percent gradeability difference at 44 mph is caused mainly by the shift logic, which allows the in-line to remain in third gear while the V-drive is in top gear. The 0 to 50 mph time is 2 percent greater for the V-drive than the in-line.

Comparison of fuel economy and performance at a geared top speed other than 60 mph will yield results different from those for 60 mph. This is because of the interaction of the N/V ratio and shift logic, as previously described. Furthermore, it is apparent that if another performance criteria such as 0-30 mph time was chosen, the fuel economy changes between the two transmissions would again be different.

One feature of the in-line is an option to have a second gear start. Simulating this feature increased the ADB fuel economy by less than 1 percent.

Another input to the transmission file is the driveline efficiency of the gears, which is based on test data. If the load dependent efficiency of a gear was decreased by 4.8 percent (from 98 to 94), the ADB fuel economy would decrease by 2.4 percent.

4.2.3 Torque Converter

Of the six baseline buses, the in-line configuration buses used a TC-495 converter and the V-drive buses used either a TC-470 or a TC-490 converter. Selection of a converter is based on matching the engine to the converter without exceeding the design torque capacity, as shown in Table 4-4. The stall torque ratio is the torque multiplication provided by the converter at stall speed.

TABLE 4-4. TORQUE CONVERTER CHARACTERISTICS

Converter	Torque Capacity (lb-ft)	Stall Torque Ratio
TC-470	800	3.25
TC-490	850	2.51
TC-495	930	2.21

Because the in-line transmission has a 3.692 first gear ratio, as opposed to a 2.021 first gear ratio for the V-drive, the torque multiplication required, assuming identical engine output, is less for the in-line. Therefore, a TC-495 converter would be a reasonable selection for the in-line transmission. Since the V-drive buses used either a TC-470 or TC-490 converter, a simulation using Bus Configuration F was run to ascertain fuel economy and performance differences. The ADB fuel economy of the TC-490 was approximately 1 percent better than that of the TC-470 because the TC-490 has a greater efficiency than the TC-470 at corresponding vehicle speeds.

The fuel economy improvement of a more efficient converter appears to be minimal in this comparison, since the lockup eliminates converter slip and the bus is in second gear lockup at a 20 mph cruise. Another configuration or drive schedule utilizing more converter operation would obviously magnify the fuel economy effect.

Performance differences will be greater at low speeds since both converters lock in second gear. Gradeability at 7 mph decreases by 5 percent and the 0 to 30 mph acceleration time increases by 2 percent when changing from the TC-490 to the TC-470 converter. Gradeability at 44 mph, acceleration time to 50 mph, and top speed remain relatively constant with either converter.

4.2.4 Shift Logic

Shift logic incorporated in the automatic transmission is based on engine load and propshaft speed. There can be more than one shift logic designed for a given transmission, the difference being contingent on the speed of the vehicle. Selection of a shift logic by a manufacturer will depend on a transit agency's operational requirements.

The six baseline buses examined have a total of four different shift schedules: three for the V-drive and one for the in-line transmission. A comparison among the V-drive transmissions will be made using Bus Configuration B.

Differences among the Standard (STD), Alternate (ALT), and Optional (OPT) shift schedules can be seen by plotting all the upshift lines on a common graph, as shown in Figure 4-4. The ALT 1-2, and lockup 2 lines occur earlier than the comparable STD lines. The 2-3 lines are equivalent. The OPT 1-2, lockup 2, and 2-3 lines occur earlier than those of the ALT.

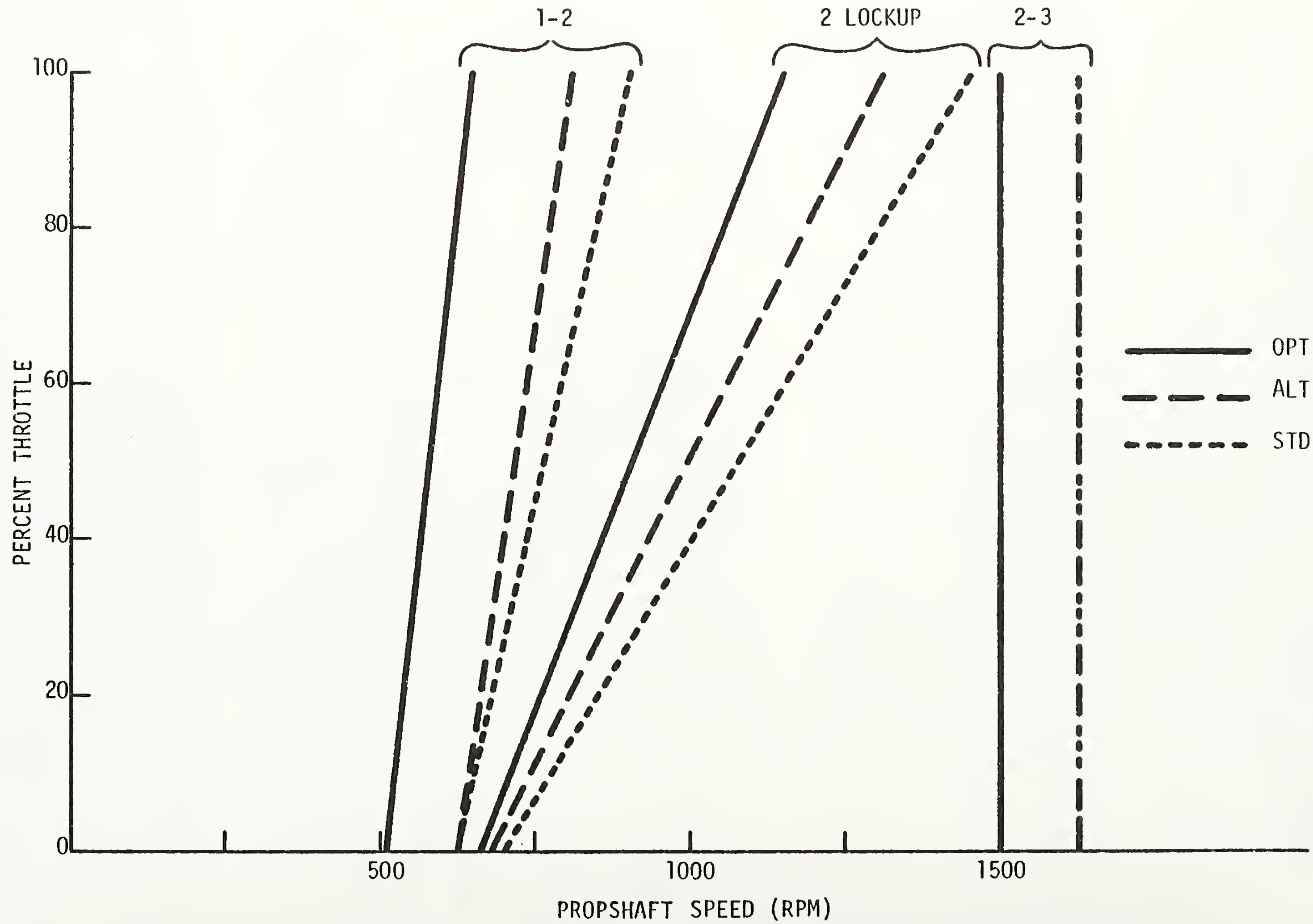


FIGURE 4-4. SHIFT SCHEDULE FOR V-DRIVE TRANSMISSIONS

Earlier upshift in any gear will generally result in better fuel economy since the vehicle will reach cruise earlier. Fuel savings depend on how early the upshift occurs and the particular drive schedule. The simulation results indicate that there is virtually no difference in the COM phase fuel economy using each of the three different shift schedules. This is because the engine speed for cruising at 55 mph is always the same.

The ART phase fuel economy improved by 2 percent using the ALT schedule and by 4 percent for the OPT schedule due to the earlier upshift speeds. The bus cruised at 40 mph in third gear for all three-shift schedules. However, these values can be misleading because the 2-3 upshift lines are very near the 40 mph cruise condition. For example, there could be a condition in which Bus B had an axle ratio of less than 4.92 and would therefore cruise in second gear at 40 mph for the STD shift schedule. Consequently the ALT and OPT shift schedule would show much more than a 2 and 4 percent improvement. To illustrate this point, Bus B was simulated with an axle ratio of 4.625. The results shown in Table 4-5 are a good example of the interaction of axle ratio and shift logic influencing fuel economy.

TABLE 4-5. ARTERIAL PHASE FUEL ECONOMY

Case	Axle Ratio	Shift Logic	Arterial (%ΔMPG)
1	4.625	ALT	BASE
2	5.125	STD	+2.0
3	5.125	ALT	+3.9
4	5.125	OPT	+6.4
5	4.625	OPT	+7.6

The CBD phase should show little fuel economy changes with the three-shift schedules because of the slight variations in the 1-2 lines. All three would be in second gear at the 20 mph cruise. The simulation results show that the ALT and OPT shift schedules achieve less fuel economy than the STD shift schedule. The STD 1-2 shift occurs at closed throttle conditions and the OPT and ALT 1-2 shift at wide open throttle. The amount of fuel used during cruise and deceleration is nearly identical.

Differences in fuel economy occur only when the vehicles operate in different gears due to the shift schedules. All three shift schedules do not shift before 15 mph in first gear and are all in third gear at 44 mph. Therefore, there will be no gradeability differences at these speeds. The change in acceleration times is less than 1 percent and the top speed remains constant.

4.2.5 Axle Ratio

Although it is common to think in terms of axle ratio when investigating driveline reduction, a more complete description that relates engine speed to vehicle velocity is shown below:

$$N/V = \frac{14.0 \times GR \times AR \times TR \times BVG}{RR}$$

where

N/V = Engine rpm/vehicle mph

GR = Gear ratio

AR = Axle ratio

RR = Tire rolling radius (ft)

TR = Converter torque ratio

BVG = Bevel gear ratio (V-Drive)

The above equation is used in top gear because the torque ratio of the converter is usually unity in top gear. One obvious benefit of discussing N/V ratio instead of axle ratio is that a comparison of two buses with different tire diameters is possible. Although the buses may have identical axle ratios, differences in tire sizes have the effect of reducing or increasing the axle ratio of one bus, depending upon the circumstances.

The N/V ratio of the six baseline buses ranges from 33.8 to 38.8, which corresponds to axle ratios of 4.11 to 5.375. Bus E, which has an axle ratio of 5.375, OPT shift logic, and TC-490 torque converter, was used to simulate N/V changes.

The fuel economy sensitivity resulting from an N/V change is not evident until it is understood that the shift logic is dependent on the N/V ratio. Inflections in the CBD and ART fuel economy lines, shown in Figure 4-5, are caused by the transmission changing gears because of the N/V change.

CBD inflection occurs at approximately N/V equals 30 when, for this particular throttle opening, a shift from first to second gear occurs. The engine operates more slowly and in a more efficient region.

ART inflection exists at approximately N/V equal to 35, when a shift from second to third gear occurs, with the higher gear resulting in better fuel economy. Because the first to second gear shift line is modulated, the inflection point will not occur at the same point for different bus loads. Therefore, these particular results are valid only for this bus with this OPT shift logic. However, although there are inflections, the overall ADB fuel economy changes by as much as 7 percent in the range studied. Reducing the baseline bus N/V by 10 percent from 38.7 to 34.8 resulted in an ADB fuel economy improvement of 1 percent.

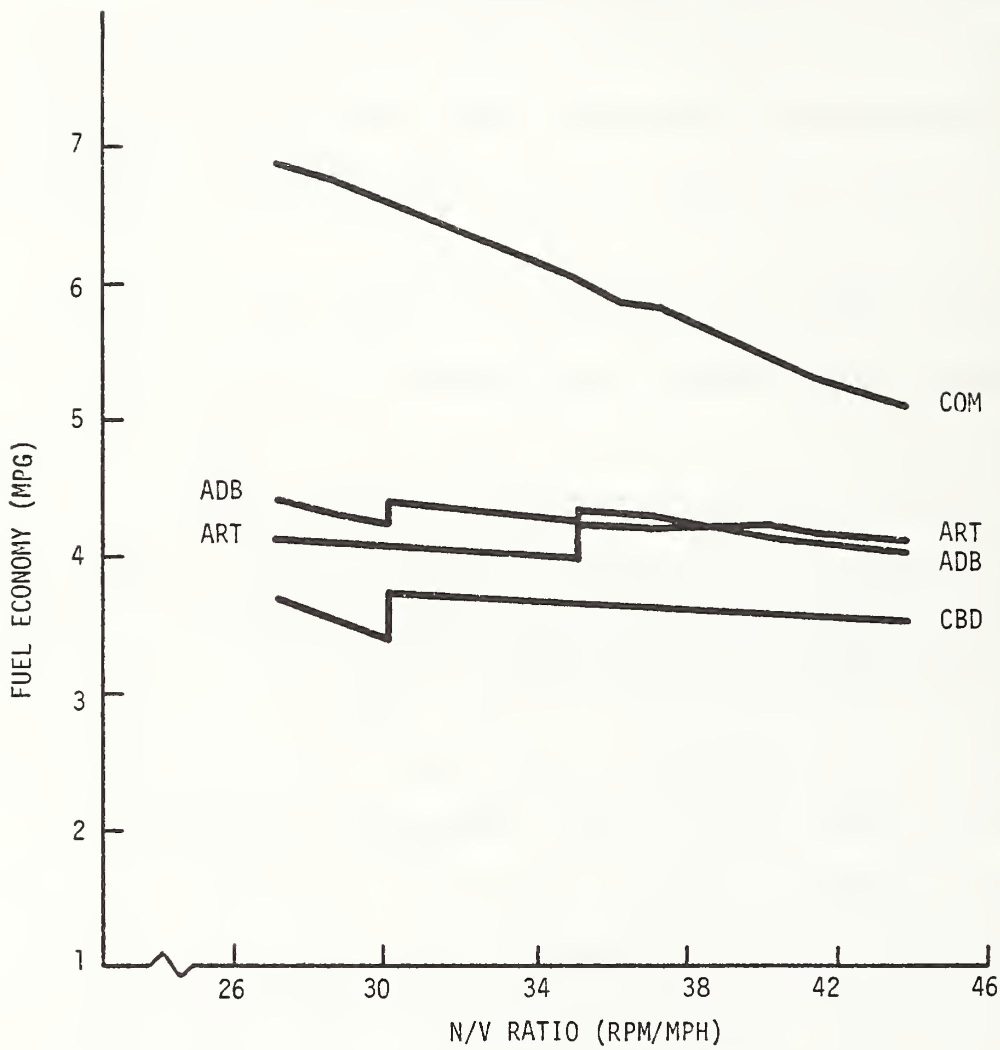


FIGURE 4-5. FUEL ECONOMY VS. N/V RATIO FOR BUS E

As N/V increases, so will gradeability because torque at the rear wheels will be increased. One exception is when a shift to a higher gear occurs, such as at 44 mph gradeability as shown in Figure 4-6. This numerically lower gear ratio reduces the torque multiplication to the rear wheels. Acceleration times generally decrease with a numerical increase in N/V ratio.

Factors such as time spent in each gear, shift time, and engine torque curve can all contribute to non-linear results as shown at the lower range of the 0-to-50 mph time. For the baseline bus, a 10 percent decrease in N/V ratio increased 0-to-50 mph time by less than 1 percent; increased the 0 to 30 mph time by 3 percent; decreased gradeability at 7 mph by 6 percent and gradeability at 44 mph by 7 percent.

The geared top speed of the base vehicle is 54 mph at 2100 rpm. Changing the N/V ratio directly affects the speed as shown in Figure 4-7. Decreasing the N/V ratio by 10 percent in the baseline bus results in a top speed increase of 10 percent to 60 mph.

An analysis similar to the above was performed for Bus Configuration C, which has an in-line transmission and different shift logic. Reducing the N/V ratio by 10 percent from the baseline improved the ADB fuel economy by 6.6 percent, increased the 0-to-50 mph acceleration time by 1.3 percent and increased the top speed by 10 percent.

4.2.6 Tire Rolling Resistance

Because all the baseline vehicles have identical tires, the rolling resistance coefficients are identical under similar operating conditions. Factors such as slip angle, road surface, or even different types of tires can change the tire rolling resistance.

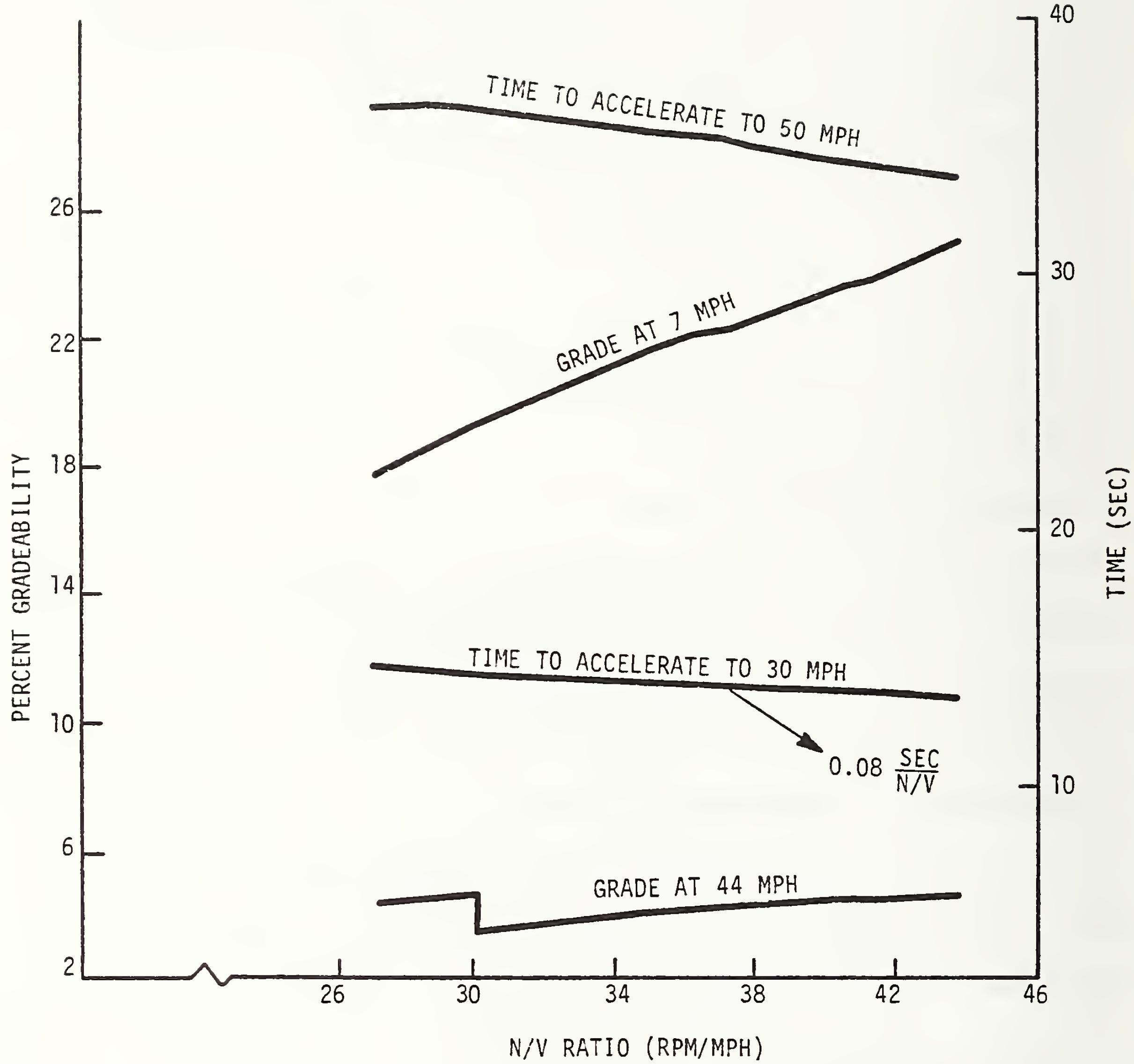


FIGURE 4-6. PERFORMANCE VS. N/V RATIO FOR BUS E

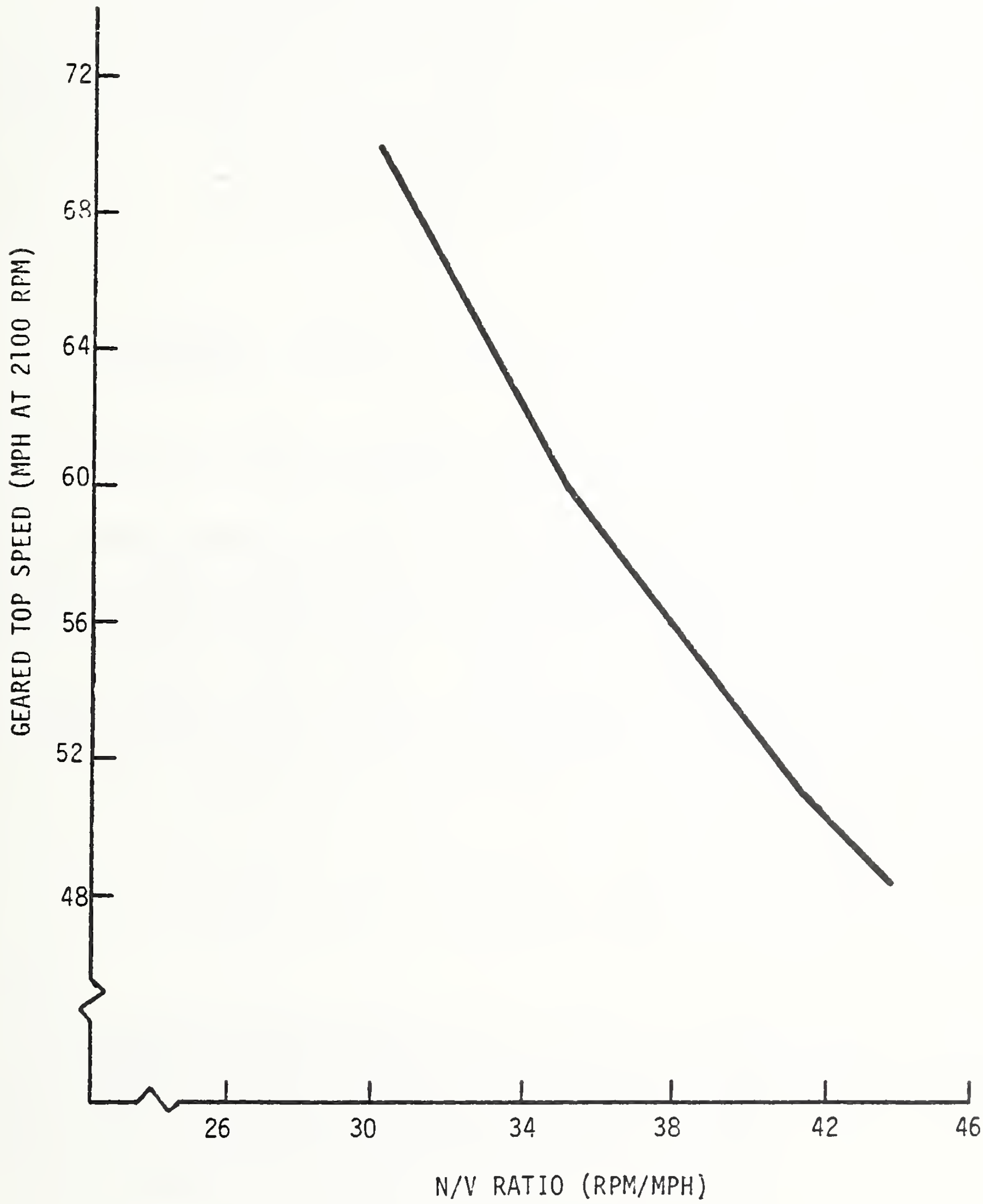


FIGURE 4-7. TOP SPEED AS A FUNCTION OF N/V RATIO FOR BUS E

The effect of tire rolling resistance on ADB fuel economy was determined by simulating baseline Bus D with different rolling resistances, as shown in Table 4-6. Running with under-inflated tires can also increase rolling resistance. This effect was determined by using an SAE 5-point matrix with a regression formula (SAE J1379). The fuel economy penalties for tire pressure decreases of 10 percent and 20 percent are shown in Table 4-7.

TABLE 4-6. SENSITIVITY OF FUEL ECONOMY TO ROLLING RESISTANCE

Rolling Resistance Change	Fuel Economy Change			
	CBD	ART	COM	ADB
-10%	1.1%	1.5%	2.1%	1.3%
+10%	-1.0%	-1.4%	-2.0%	-1.2%

TABLE 4-7. SENSITIVITY OF FUEL ECONOMY TO TIRE PRESSURE FOR BUS D

Pressure Decrease	Fuel Economy Decrease			
	CBD	ART	COM	ADB
10%	0.4%	0.6%	0.8%	0.5%
20%	1.0%	1.3%	1.9%	1.2%

4.2.7 Aerodynamic Drag

The wind average aerodynamic drag coefficients (C_D) supplied by the manufacturers for the six baseline buses range from 0.55 to 0.57, while frontal areas average from 70.0 ft^2 to 76.9 ft^2. Bus C was used to simulate aerodynamic drag coefficient changes.

The change in fuel economy for an increase to 0.8 or decrease to 0.5 in the aerodynamic drag coefficient is linear, ranging from 1.9 mpg/1.0 C_D for the COM phase to 1.75 mpg/1.0 C_D for the ADB cycle. The CBD phase showed virtually no change in fuel economy. Since the power required due to overcome aerodynamic drag increases as the cube of speed, the only significant performance change occurs in the 0-to-50 mph time, equal to 5 sec/1.0 C_D.

When analyzing drag coefficients independent of shift schedules, it should be remembered that aerodynamic load is based on the product of the drag coefficient and the frontal area. Therefore, the results could also be used to analyze changes in frontal area, provided the drag coefficient remained constant. A drag coefficient of 0.5 for the baseline bus would be equivalent to a frontal area of 66.8 ft^2, and a drag coefficient of 0.8 equivalent to an area of 107 ft^2.

4.2.8 Fuel

Diesel fuel for buses is generally derived from middle petroleum distillates, which can have different properties depending upon refinery techniques and the nature of the crude oils. The standard which classifies fuels is the American Society for Testing and Materials (ASTM) D-975 Standard Specification for Diesel Fuel Oils, which sets standards for 1-D and 2-D fuel grades. The standard essentially provides boundaries for fuel properties such as heating value, volatility- and cetane number.

Diesel fuel 1-D has approximately 1.5 percent more Btu/lb than 2-D fuel. However, 1-D fuel has a lower specific gravity and has about 2 percent fewer Btu/gal than 2-D fuel. Because diesel fuel injectors operate on a volumetric basis, a diesel engine converted from 1-D to 2-D fuel would experience an increase in power and fuel economy. The results depend on where the fuel properties are located in the ASTM boundaries.

A comparison of 1-D and 2-D fuels is made by simulating Bus B with each fuel. The simulation involves creating another engine map that represents the use of 2-D fuel and substituting this for the original 1-D engine fuel map.

The results yield a 2 percent increase in ADB fuel economy, and performance increases of 5 and 6 percent for the 0 to 30 mph and 0 to 50 mph times, respectively. Gradeability performance increases 5 percent at 7 mph and 9 percent at 44 mph. The baseline engine has 65 mm injectors. However, simulations using 70 mm and 75 mm injectors showed that fuel economy was also increased by 2 percent when 2-D fuel was used instead of 1-D fuel. Performance parameters also increased, although not to the extent that they had increased with the 65 mm injectors.

Because acceleration in the ADB schedule is at wide open throttle, the fuel economy comparisons are not at constant performance. A constant performance comparison between 2-D and 1-D fuel would result in a higher fuel economy increase than indicated above, although constant performance would be an unrealistic assumption. The effects of smoke, emissions, cold start, and noise level are not considered in this analysis.

4.2.9 Injectors

Although the six baseline buses have identical engines, there are a variety of injector sizes. The injectors, which can be 65, 70 or 75 mm, essentially increase the maximum output of the engine, as shown in Table 4-8. For simulation purposes, this means extending the power and fuel curves of a 65 mm engine map to 70 or 75 mm.

TABLE 4-8. MAXIMUM ENGINE POWER WITH DIFFERENT INJECTORS

Speed	Injectors		
(rpm)	65 mm	70 mm	75 mm
1200	175	186	198
1400	201	215	230
1600	219	236	252
1800	234	254	270
1950	244	266	282
2100	253	277	294

No. 2 Diesel Fuel

1.470 Timing

TV7101 Turbocharger

Bus B, which has 65 mm injectors, was simulated with 70 and 75 mm injectors to evaluate their effect on fuel economy and performance. The performance improves, as shown in Figure 4-8, with the percent differences indicated at the baseline N/V ratio of 38.7. Geared top speed at 2100 rpm remains constant.

The ADB fuel economy resulting from an injector increase of 65 mm to 70 mm decreases by less than 1 percent; a change from 70 mm to 75 mm also causes

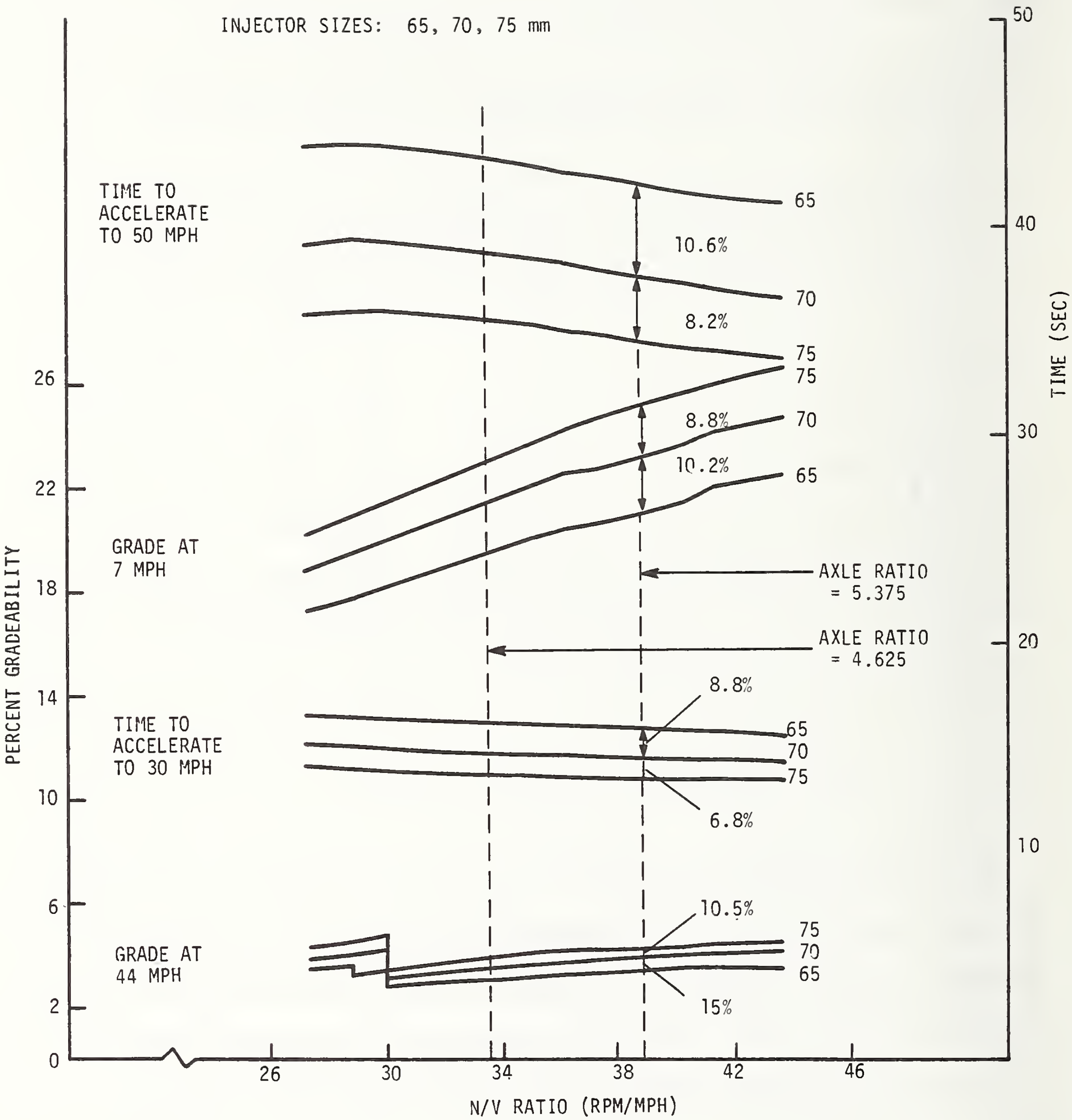


FIGURE 4-8. PERFORMANCE DIFFERENCES WITH THREE INJECTOR SIZES - BUS B

a decrease of less than 1 percent. However, this change occurs at various performance levels, as previously discussed. Therefore, a fuel economy comparison at equivalent performance levels would be more equitable.

As shown in Figure 4-9, this comparison can be accomplished by varying the N/V ratio and calculating the fuel economy difference at a line of constant performance. This difference is 6 percent between 65 mm and 70 mm injectors and about 1 percent between 70 mm and 75 mm injectors at the selected performance level.

In the comparison of the 0 to 30 mph time, the difference among the injectors is so great that there is no line of equal performance, as shown in Figure 4-10. The dashed lines indicate regions of fuel economy inflections due to shift points. From these figures, it can be seen that the selection of desired performance levels may not result in a consistent selection of injector sizes. Consequently, a priority of performance indicators may be required.

4.2.10 Engine Fan

Although their engines are identical, the six baseline buses have different cooling requirements, as indicated by their various fans and fan drives. Fan blade diameters range from 26 to 32 inches, some have different blade angles, and all but one have a viscous drive.

If all six fans operated at an engine speed of 2000 rpm, the fan horsepower requirements would vary from 7 to 24 hp. This large difference can be explained numerically by using the fan laws. However, the reasons for different cooling requirements would have to be examined with respect to the entire cooling system and options such as air conditioning. Therefore, it should not be assumed that the six fan-power requirements are identical.

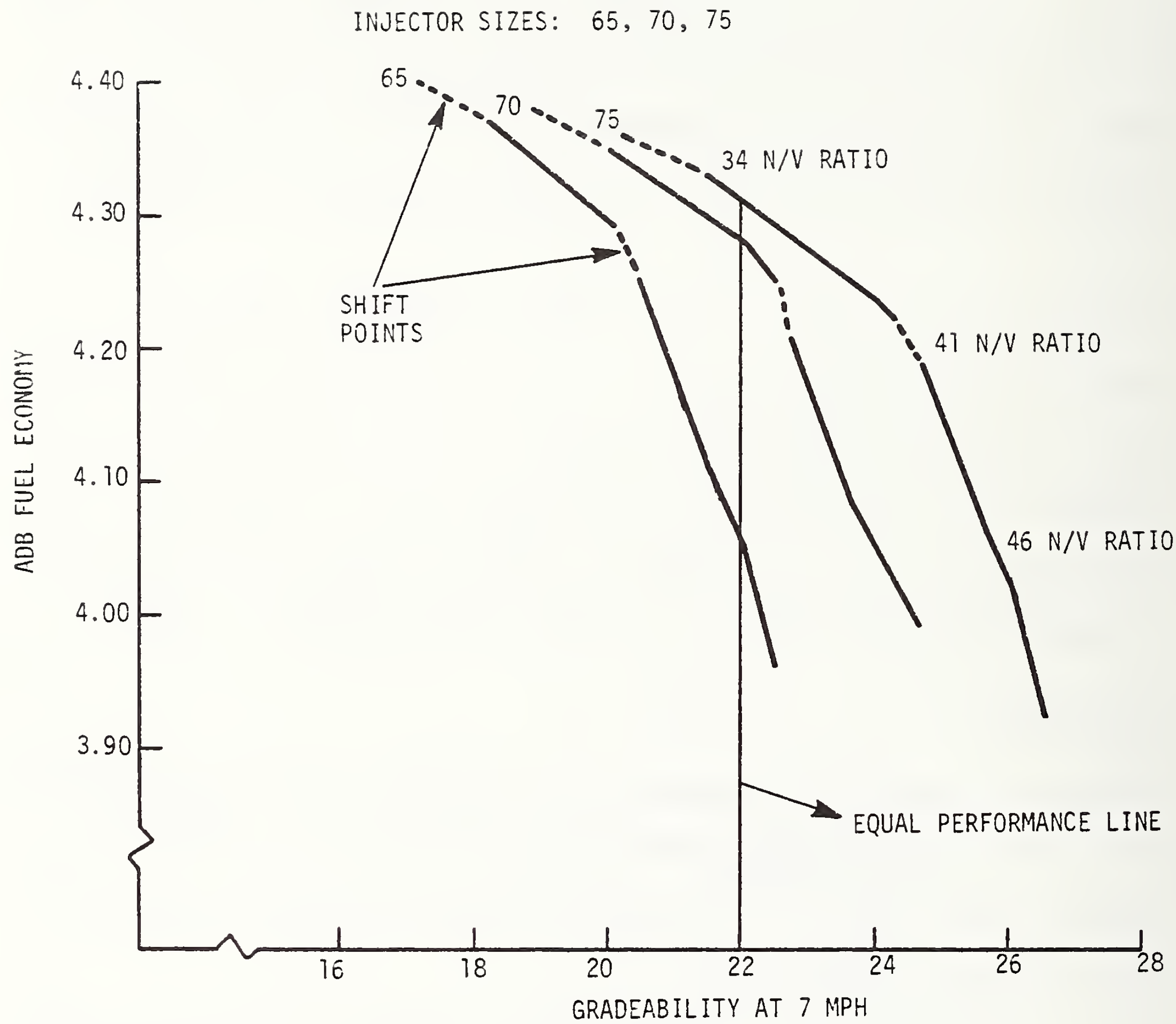


FIGURE 4-9. GRADEABILITY VS. ADB FUEL ECONOMY FOR THREE INJECTORS

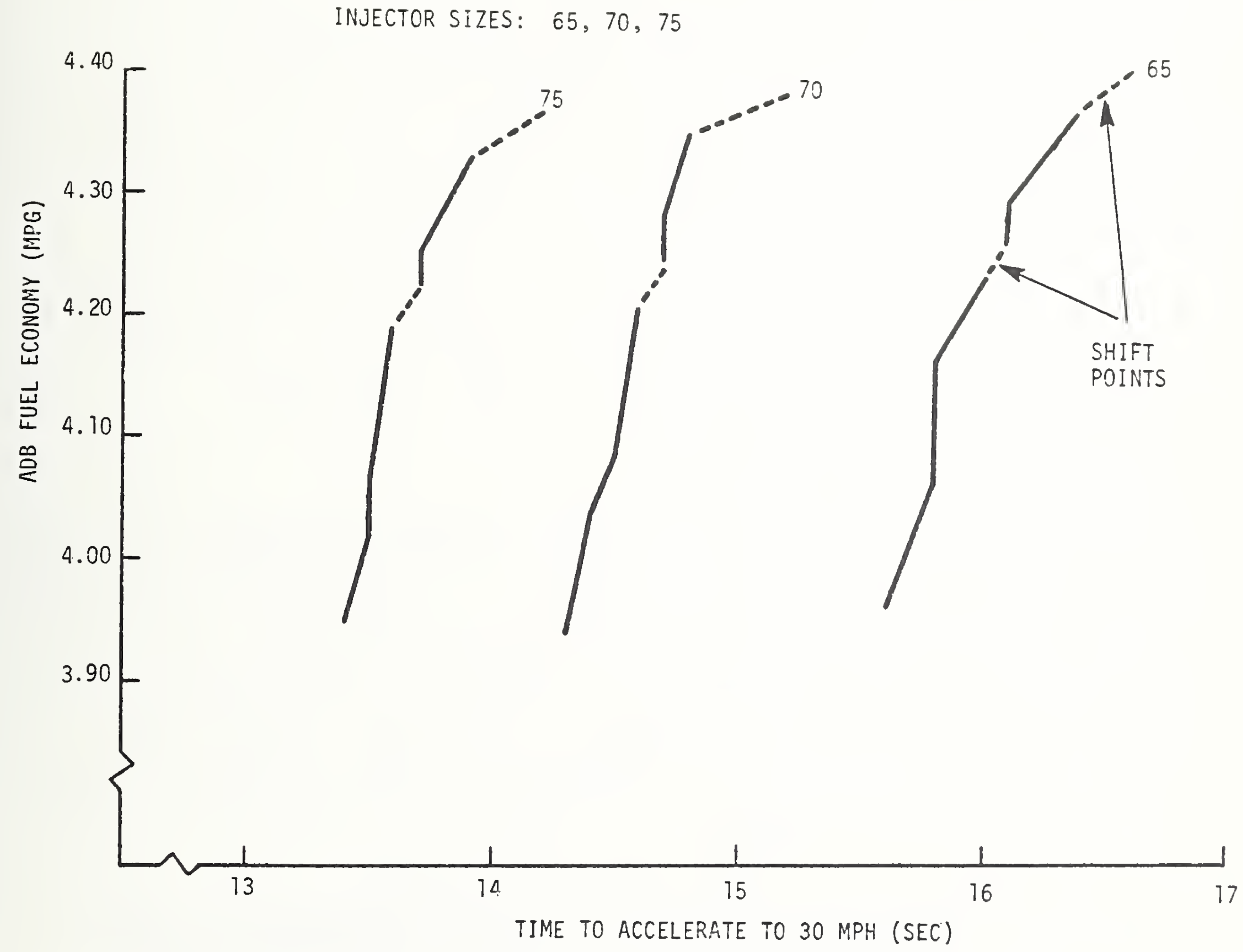


FIGURE 4-10. ACCELERATION VS. ADB FUEL ECONOMY FOR THREE INJECTORS

One factor that is related to all six buses and suited for simulation is the duty cycle of the fan. Depending on a number of factors such as driving conditions, this number could range from 0 to 1.0. The effect of the fan duty cycle on fuel economy and performance was simulated using baseline Bus Configuration C. There is an ADB fuel economy and performance change of less than 1 percent when the fan goes from off to its fastest operating mode.

Because of the differences in power requirements of the different fans, another simulation was run, varying the fan duty cycle on Bus Configuration B, as shown in Figure 4-11. Higher fan power requirements cause the ADB fuel economy to decrease by 3.7 percent and 0-30 mph time to increased by 3.2 percent when the fan is switched from off to its fastest operating mode. The separate fuel economy phases and the ADB fuel economy are shown in Figure 4-12.

4.2.11 Alternator

Alternator curves supplied by manufacturers represent the maximum electrical power output for a corresponding mechanical power input. The actual electrical load imposed on the alternator is dependent upon the electrical demand of the bus, which is in part contingent on the driver. Typical power requirements, which can be obtained from maintenance manuals, are shown in Table 4-9.

Because of the complexity of modeling the actual battery, it is assumed to be fully charged and never discharging. Therefore, the duty cycle can be approximated as the actual output divided by the maximum possible output for a given configuration and drive schedule. This essentially means that as the electrical load is increased, the duty cycle increases linearly.

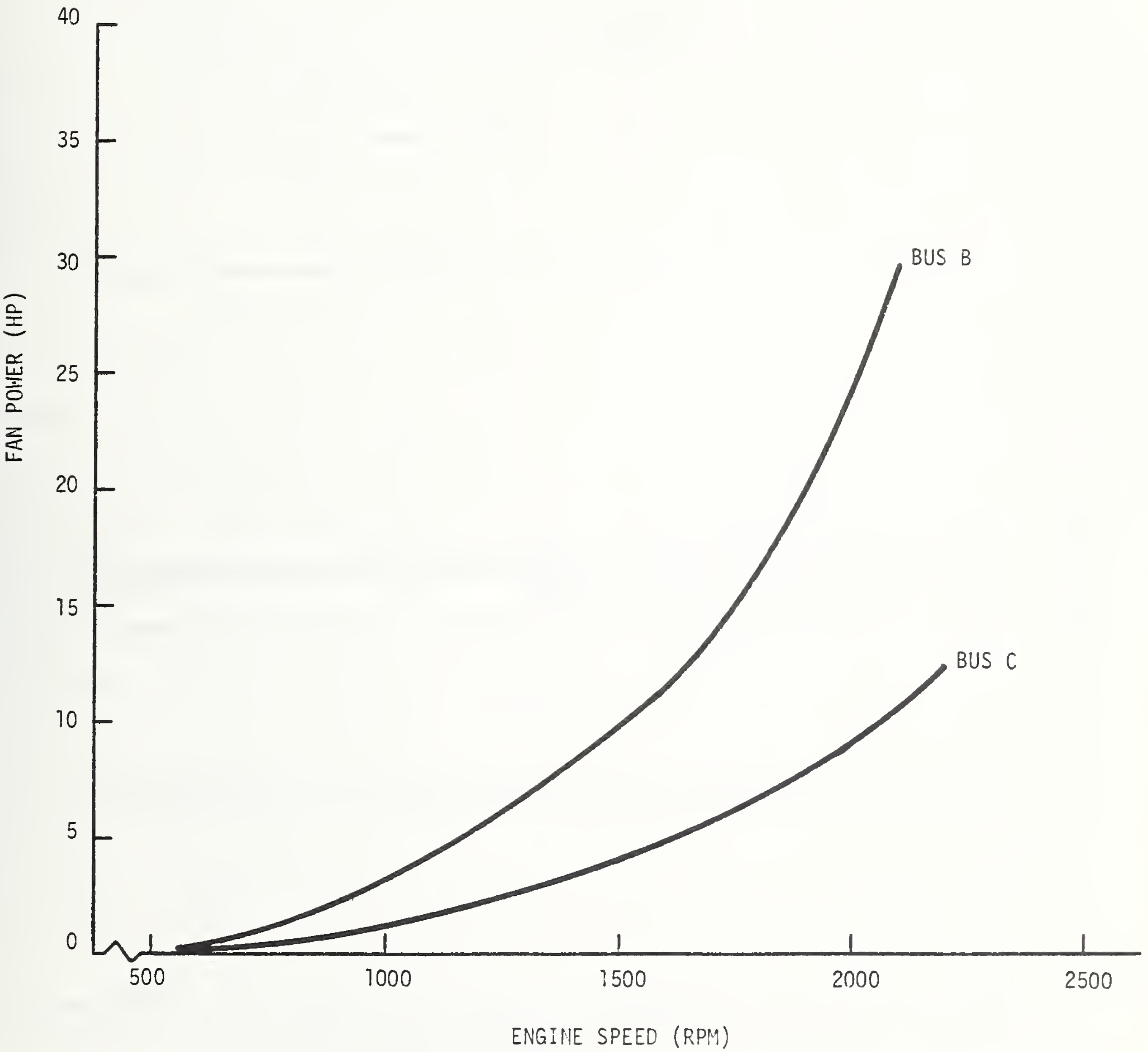


FIGURE 4-11. FAN POWER REQUIREMENTS

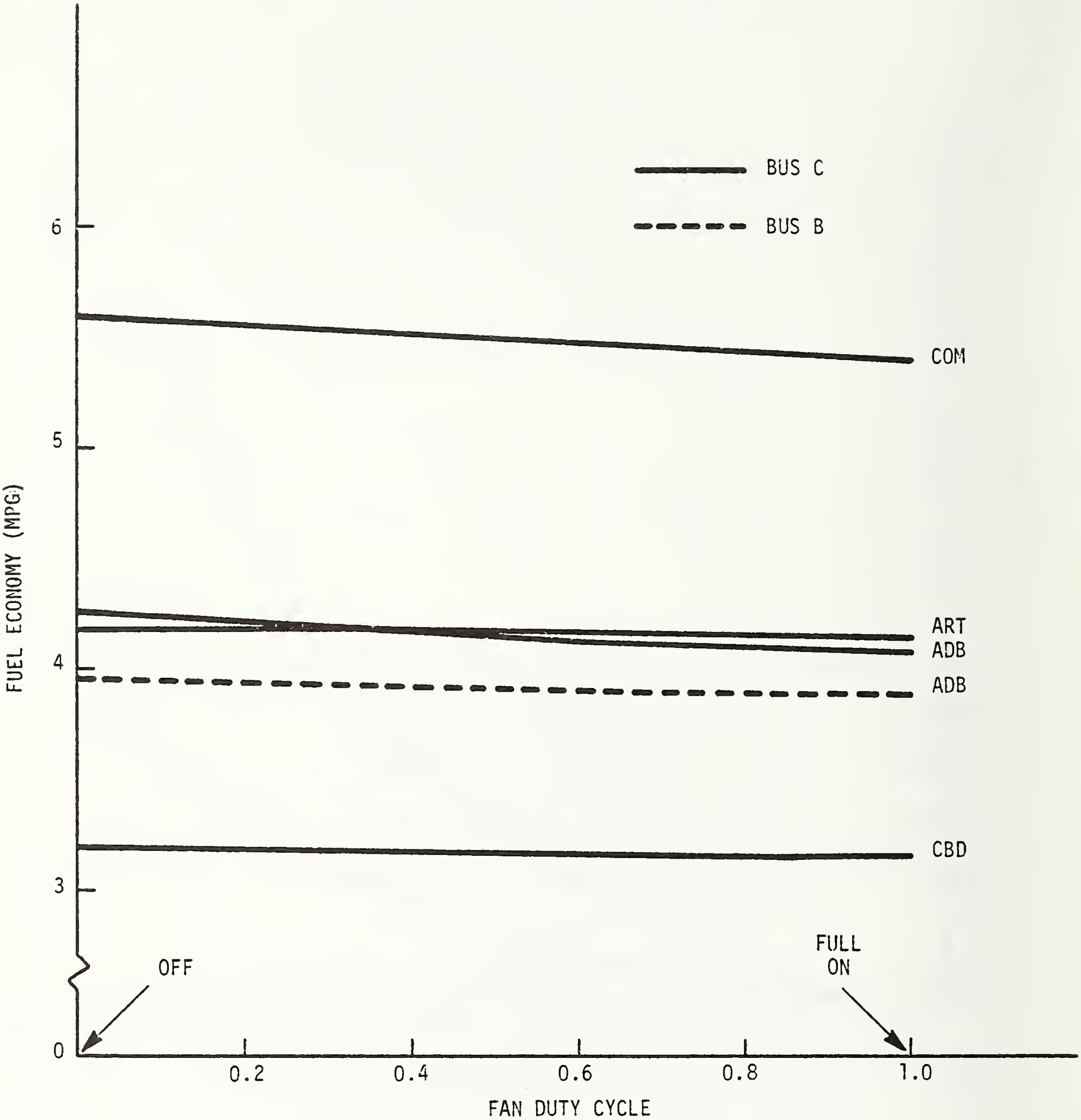


FIGURE 4-12. FUEL ECONOMY FOR BUS FAN DUTY CYCLE

TABLE 4-9. TYPICAL POWER REQUIREMENTS FOR BUS SYSTEMS

Component	Power (watts)
Headlights (2)	100
Interior lights	300
Defroster blower	40-100
Destination sign	40-100
Ventilation Motors (2)	1300-1400

To determine the effect of electrical load and duty cycle on ADB fuel economy, Bus D was simulated with a range of electrical loads. Bus D has a 24-volt, 275-amp-maximum alternator that has a baseline assumed constant load of 2000 watts. This is equivalent to high beams, ventilation motors and other small miscellaneous marker lights. Reducing the load by 43 percent, to 1150 watts, increases ADB fuel economy by 1 percent, as shown in Table 4-10. The 0-to-50 mph time is decreased by 1 percent due to the reduced load.

4.2.12 Power Steering/Air Compressor - The power steering and air compressor are grouped together because both use a relatively small amount of engine power as compared to other accessories. Five of the six buses use one manufacturer's power steering pump, although there was a range of displacements among those five.

Based on the manufacturer's recommendation, a typical load was assumed for all six buses. Doubling this load, or increasing the duty cycle by a factor of two, resulted in the ADB fuel economy decreasing by 1 percent for Bus A. Fuel economy is also influenced by power steering, which is dependent upon the route. More turns will require more use of the power steering.

TABLE 4-10. ELECTRICAL LOAD AND ADB FUEL ECONOMY

Electrical Load (watts)	ADB Alternator Duty Cycle	ADB Fuel Economy Change
0	off	+ 4.0
1150	0.20	+ 1.0
2000	0.35	base
3450	0.60	- 3.1
4550	0.80	- 5.0
5750	1.00	- 7.4

The air compressor used was identical in five of the six buses. The sixth bus used another manufacturer's product, but the performance curves, which are based on 100 psi delivery pressure, were nearly identical. The air compressor duty cycle depends upon the integrity of the system, (e.g., no leaks) and the driving schedule. The sensitivity of air compressor duty cycle to fuel economy was simulated by assuming Bus E had a baseline duty cycle of 0.5. Increasing this to 1.0 resulted in an ADB fuel economy decrease of less than 1 percent.

4.2.13 Air Conditioning

In order to simulate the effect of air conditioning the following additional baseline conditions for bus F were established:

Passenger seats: 48

Front door area: 20 ft^2

Infiltration: 500 cfm

Solar load: 11,500 Btu/hr

Fresh Air: 20%

Temperature set point: 72°F

The ambient conditions used for simulation are based on the weather conditions previously recorded (3). Since it is impossible to predict the passenger load and solar load which affect the total load on the air conditioning system, a composite bus load was established as shown in Table 4-11.

TABLE 4-11. COMPOSITE BUS LOAD

Weighted Load	Passengers	Solar (Btu/hr)
25%	12	2,300
50%	48	5,750
25%	72	11,500

The composite load is simulated for each outdoor temperature bin. To illustrate the effect of bus air conditioning on fuel economy, Bus F was simulated with air conditioning for three geographic locations, as shown in Table 4-12. When the bus is simulated without air conditioning, the ventilation fan is assumed to be operating. From the results, it can be seen that for these three cities, under the above conditions, the average fuel economy becomes poorer due to air conditioning is 10.5 percent.

TABLE 4-12. ADB FUEL ECONOMY CHANGE DUE TO AIR CONDITIONING

LOCATION	FUEL ECONOMY CHANGE WITH AC (%) 72°F Set Point
San Antonio, Texas	10.9%
Albany, N.Y.	9.9%
Tampa, Fla.	10.8%

4.2.14 Engine

From previous results, it can be seen that modifying vehicle parameters usually affects the engine operating points, which subsequently alter fuel economy. Because questions may arise on the applicability of the reported sensitivities to other engines, a few parameter variations were simulated with a different engine of a power equivalent to the engines in Buses F and D.

The fuel economy sensitivity to weight of the alternate engine is superimposed on Figure 4-2, as shown in Figure 4-13. The fuel economy of the alternate engine is better and more sensitive to weight reduction than the base engine. A similar analysis was completed for Bus D, using a rolling resistance coefficient variation. The ADB fuel economy results are summarized in Table 4-13.

TABLE 4-13. FUEL ECONOMY SENSITIVITY FOR BASE AND ALTERNATE ENGINE

Variable	Base Engine	Alternate Engine
Weight Reduction For 1000 lb	.07 mpg	~.10 mpg
For 10% Reduction	6.0%	6.5%
Rolling Resistance Reduction For 1 lb/1000 lb Coefficient	.07 mpg	.09 mpg
For 10% Reduction	1.7%	1.9%

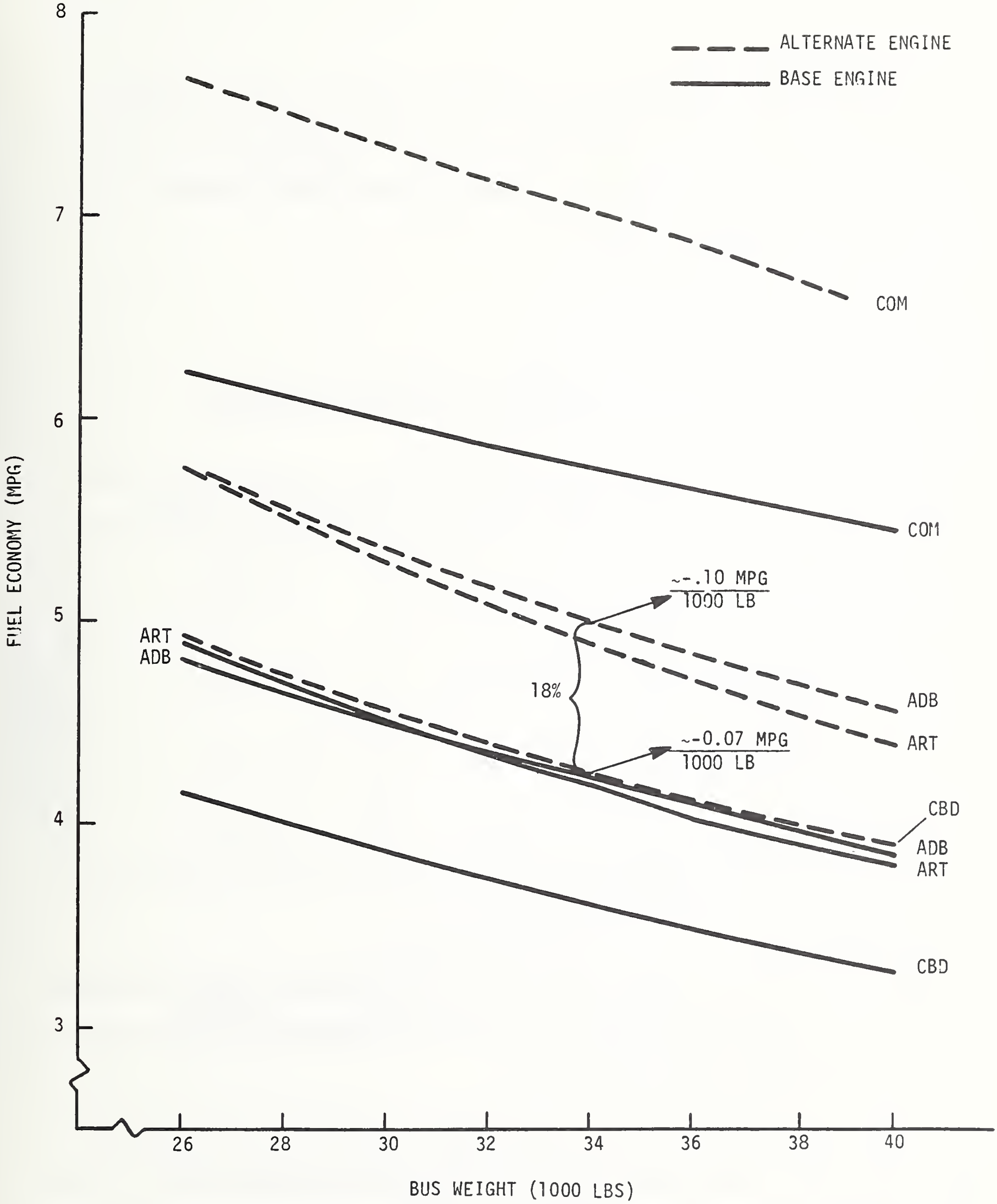


FIGURE 4-13. FUEL ECONOMY SENSITIVITIES TO WEIGHT FOR BASE AND ALTERNATE ENGINES

The bus performance when equipped with the alternate engine is shown in Figure 4-14 and the relative differences summarized in Table 4-14. Although the rated peak horsepowers are similar, the differences in absolute numbers can be traced to the engine torque curves.

TABLE 4-14. PERFORMANCE SENSITIVITY FOR BASE AND ALTERNATE ENGINES WITH 1000-LB WEIGHT REDUCTION

Variable	Base Engine	Alternate Engine
Δ Time to Accelerate to 50 mph	1.6 Sec	1.1 Sec
Δ Time to Accelerate to 30 mph	0.5 Sec	0.4 Sec
Δ Gradeability at 7 mph	0.6-1.3% G	0.7-1.1% G
Δ Gradeability at 44 mph	0.2% G	0.2% G

4.2.15 Drive Cycle

Within the ADB drive cycle, the COM phase will generally yield the highest fuel economy and the CBD the lowest. The variation among drive cycles using the CBD as a baseline is shown in Table 4-15.

As another measure of comparison, the Environmental Protection Agency (EPA), urban (FTP), and highway (HWFET) velocity time profiles shown in Figure 4-15 were also simulated. These profiles are not intended to represent actual

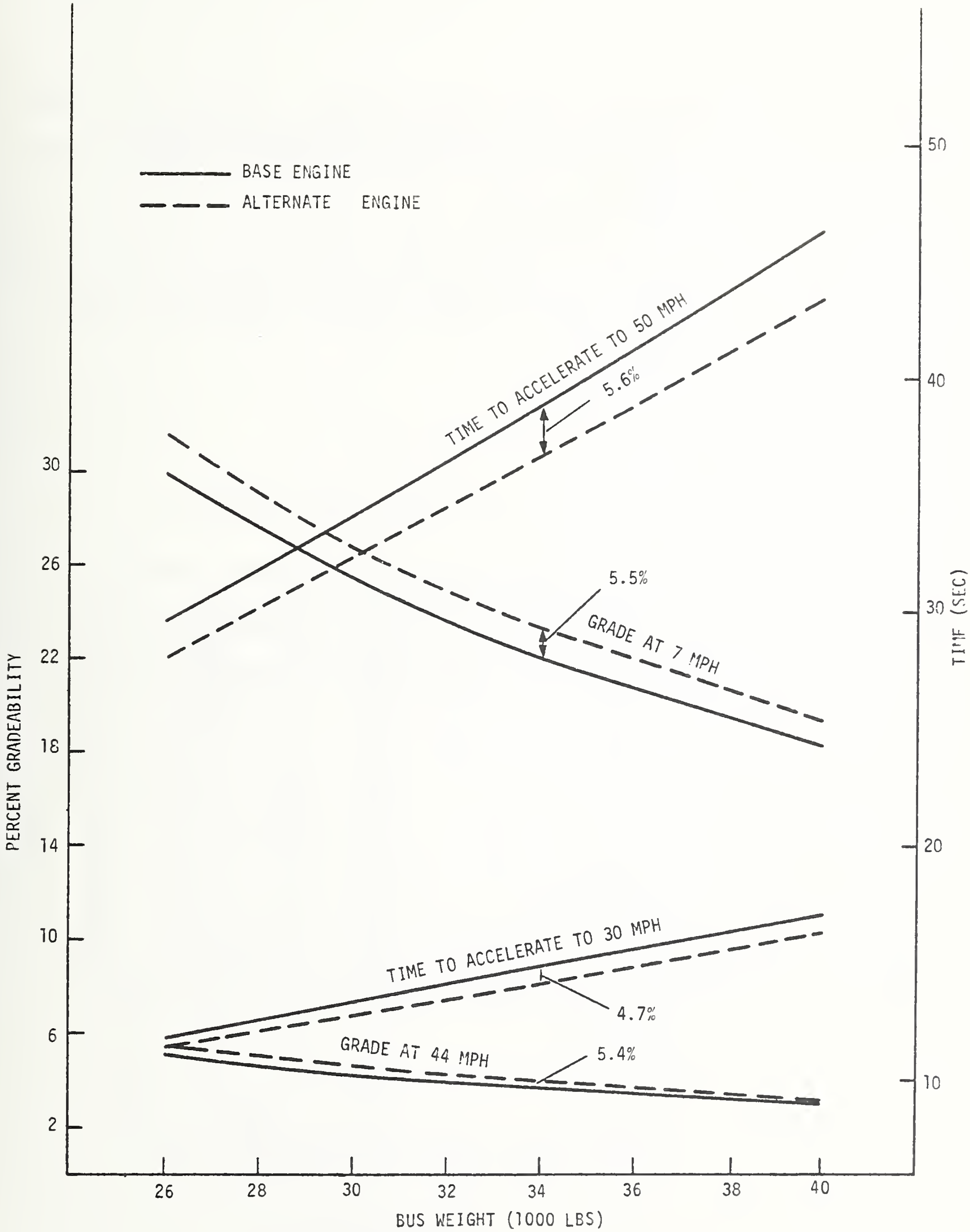


FIGURE 4-14. PERFORMANCE COMPARISONS OF BASE AND ALTERNATE ENGINES

bus routes, but to illustrate the effect of drive cycles on fuel economy. The correlation of ADB fuel economy to actual in-service values is a separate topic and deserves attention at some other time.

The magnitude of the simulated results is not unrealistic and substantiates previous results in which drive cycle was found the most significant variable when determining fuel economy.

TABLE 4-15. COMPARISON TO CBD PHASE FUEL ECONOMY (%)

	Drive Schedule			
Bus	ART	COM	FTP	HWY
A	5%	44%	19%	59%
B	15%	48%	28%	63%
C	31%	74%	46%	94%
D	30%	85%	43%	105%
E	17%	55%	30%	72%
F	16%	59%	31%	76%

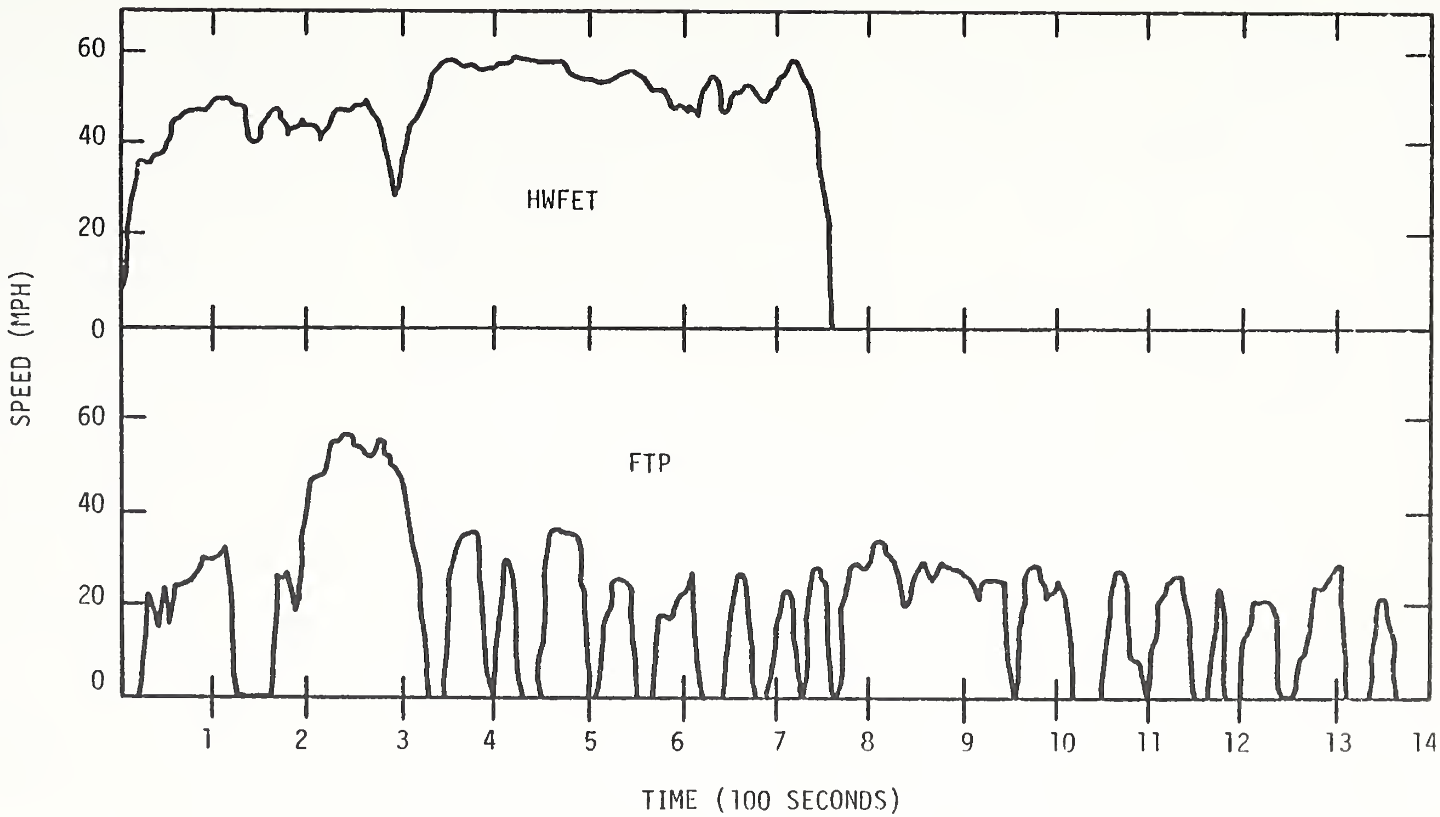


FIGURE 4-15. SPEED VS TIME TRACES OF FTP AND HWFET DRIVING CYCLES

5. SENSITIVITY APPLICATION

5.1 GENERAL

Qualitatively, the sensitivity values are useful because they provide a relative ranking of the importance of vehicle components to fuel economy and performance. Quantitatively, they can be valuable in calculating fuel savings if certain limitations are observed. The procedure for using sensitivities is to first define a baseline configuration and the associated fuel economy and performance values. Then, the percent change in fuel economy for the desired vehicle change can be estimated by using the sensitivity values.

There are a number of constraints, the first being that the baseline vehicle must be similar to the vehicle being analyzed. This has been illustrated in the section on engines in which it was noted that identical component changes can cause different fuel economy changes.

Another caveat is that the individual fuel economy sensitivities are not necessarily additive. For example, individual changes were made to Bus Configuration B, as shown in Table 5-1. In Case A, the individual effects did match the combined numerical effect. In Case B, however, they were different by 9 percent. This 9 percent difference can be explained by the non-linear brake specific fuel consumption (BSFC) lines and the effect of load on the shift logic.

Finally, the sensitivity range should not extend beyond those studied. In the section on weight (4.2.1), it was shown that fuel economy response to a weight decrease is nearly linear, but is most likely not linear outside of that range. Because of these sensitivity limitations or the need to evaluate new components modifying the entire vehicle system, a more comprehensive analysis is desirable. This analysis, which follows, evaluates the vehicle system first on the basis of energy then on performance in order to have a more complete picture of the operation of the vehicle.

TABLE 5-1. COMPARISON OF INDIVIDUAL AND COMBINED FUEL ECONOMY SENSITIVITIES USING BUS B

	Modification	Fuel Economy Change	Individual/Combined
CASE A		MPG	Comparison
	Individual Δ's		
	1	0.20	
	2	0.02	
	3	0.07	
		= 0.29	
			0%
	Combined Δ's		
	1, 2, 3	0.29	
CASE B			
	Individual Δ's		
	1	0.20	
	2	0.02	
	3	0.07	
	4	0.14	
		= 0.43	
			9%
	Combined Δ's		
	1, 2, 3, 4	0.47	

Δ = Change

1 = 10% Weight Reduction

2 = 10% C_D Reduction

3 = 10% C_1 Reduction

4 = 10% Axle Ratio Increase

5.2 FUEL ECONOMY

The actual fuel economy calculation for ADB purposes is 14 miles divided by the total gallons of fuel for 6 miles of CBD, 4 miles of ART, 4 miles of COM and 5 minutes of idle. This composite fuel economy is frequently approximated by the equation in Section 4 for simplicity, and because some component changes do not affect the idle fuel rate.

Because of the above factors, efficiency in ADB fuel economy for identical-phase improvements will be influenced most by first improving the CBD phase fuel economy, and then that of either the ART or COM phases.

The task of improving fuel economy would initially appear straightforward. A decision is first made concerning a representative drive schedule. Then, by using a table similar to Table 3-2, a component or system which will potentially offer the best return in terms of fuel economy is selected.

For example, weight reduction might be selected in the CBD or ART phase and aerodynamic improvements might be considered in the COM phase. After the losses are considered, the powertrain that will utilize the most efficient points of the engine should be considered. However, this task is very difficult because of the interrelation of powertrain components and the requirement of obtaining acceptable levels of performance, which is discussed next.

5.3 PERFORMANCE

The criteria used for bus performance are acceleration time, gradeability, and top speed. Acceleration time is inversely proportional to acceleration, which is similar to gradeability, as shown in Figure 5-1. Fundamentally, gradeability and acceleration are identical measures of the net available engine torque used to either accelerate or climb grades. The reason bus component

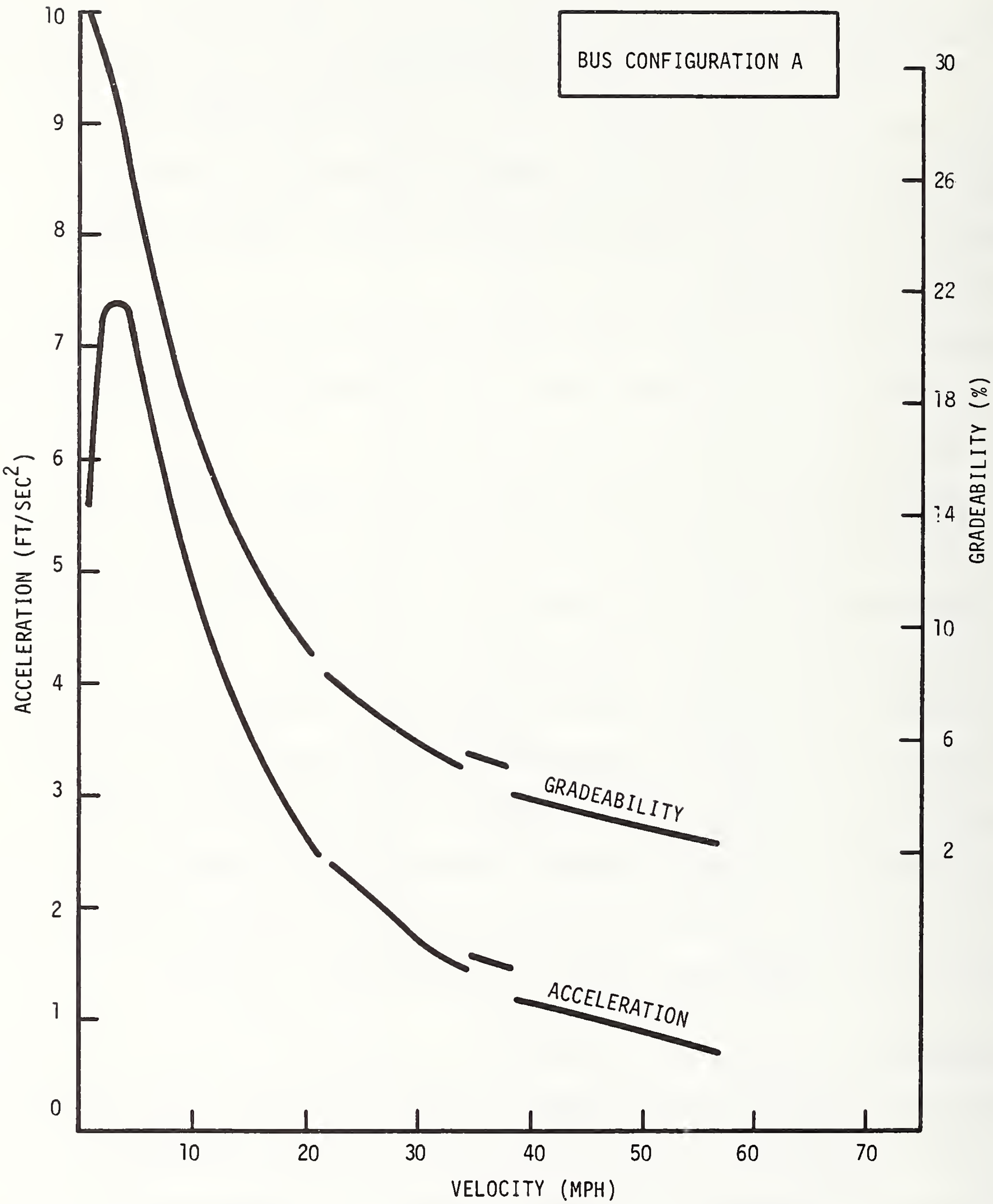


FIGURE 5-1. ACCELERATION AND GRADEABILITY AS A FUNCTION OF BUS SPEED

changes do not affect gradeability and acceleration times proportionally is that gradeability is a single steady state calculation at one speed whereas the calculation of acceleration times includes inertia effects which increase the kinetic energy of the tires, powertrain and other rotating components. These reasons explain why a change in the 2-3 shift line may affect the 44 mph gradeability to a greater extent than the 0-to-50 mph acceleration time. These reasons also explain why a torque converter change would affect the 0-to-30 mph time but leave the 44 mph gradeability unchanged, assuming all other components remain the same (lockup at 44 mph).

Top speed is, as mentioned earlier, limited by available engine power or powertrain gearing. The gearing is the deciding factor in the six baseline buses, which have top speeds (at 2100 engine rpm) of 54 to 62 mph. Any change in the N/V ratio will affect the top speed, as shown in Figure 4-5.

To determine the selection of components that yields the best performance, a representative drive schedule or performance schedule must be selected. If a low speed route is required, the 7 mph gradeability and 0-to-30 mph times would be relevant as performance criteria. If the ADB performance specifications are used, the bus must meet standards through its entire operating range, including top speed.

A reduction in load on the engine will generally allow the engine to use the resulting increase in power to enhance its performance. This load reduction may be accomplished by weight reductions, aerodynamic improvements, rolling resistance decrease, and more efficient use of accessories. Modification of the powertrain, presents the interrelationship of fuel economy and performance tradeoff alluded to earlier. Increasing the N/V ratio may improve fuel economy, acceleration performance, and gradeability; decreasing the N/V ratio may also improve fuel economy but decrease acceleration performance and gradeability.

5.4 COMPROMISE

The strategy for optimizing fuel economy first calls for reducing the load on the engine, as shown in Table 5-2. These reductions should not compromise the minimum subsystem performance level. Selection of such performance levels, however, is beyond the scope of this paper.

TABLE 5-2. FUEL ECONOMY AND PERFORMANCE COMPROMISE

Reducing Engine Power Requirements • Weight • Aerodynamics • Rolling resistance
Powertrain Components • Engine • Injectors • Converter • Shift logic • Transmission • Axle (N/V) ratio

For example, although the six baseline buses have similar engines, their fan system power requirements are quite different. The reason is attributed to the different cooling requirements of each bus. The next step is to select a minimum acceptable vehicle performance level and by varying available powertrain components determine the resulting fuel economy (ADB, if suitable).

This procedure may require a number of iterations due to the interaction of the subsystems and the entire vehicle. If, for example, the air conditioning system were modified to require less power to operate, the engine injectors could perhaps be reduced to maintain the earlier performance level. This could also affect other powertrain components. Hence, iterations must be performed.

This task is an appropriate application for the computer simulation model, since it can easily handle numerous repetitions. A test track plan would require significantly more time and capital. The task, however, requires an understanding of the integration of vehicle components since the user selects the input parameters. Once appropriate inputs are selected, the results could parallel an example similar to that of Figure 4-9, which illustrates the fuel economy and performance compromise. A decision then has to be made to determine the significance of each. This decision is beyond the scope of this paper, since it involves different routes, component availability, passenger capacity, maintenance, capital costs, etc. The fuel economy model is, in fact, only one of a number of inputs used to make a decision concerning the selection of the subsystems and/or the entire vehicle.

The application of the previous sections can be illustrated by comparing some of the simulated fuel economy numbers of the six baseline buses over the ADB cycle. The input data is too cumbersome to include here, but some of the characteristics were presented in Table 3-1.

The fuel economy numbers shown in Table 5-3 are not based on identical ambient conditions. The important point to consider is not the absolute numbers, but the reasons for the relative differences among similar phases.

In the commuter phase, aerodynamics is the most significant factor, but drag coefficients and frontal areas are all nearly identical. Similarly, the weights are also nearly identical, but the accessory loads due to differing designs and duty cycles diverge by as much as 60 percent and the attendant mpg differences are reflected in the table.

Bus D has the lowest accessory load, which is one reason for its relatively high fuel economy. Another reason is that, at cruise, Bus D operates in the lowest BSFC region as compared to the other five buses. In contrast, Bus B has the highest accessory load and an intermediate BSFC value, giving it the lowest fuel economy. Bus E has the highest BSFC and an intermediate accessory load that results in a low fuel economy. The other three buses have fuel economies which are in the middle of the group.

TABLE 5-3. SIMULATED ADB PHASE FUEL ECONOMY

Bus	Fuel Economy of ADB Phases (mpg)			Performance		
	CBD	ART	COM	0-30 MPH (sec)	0-50 MPH (sec)	Top Speed (mph)
A	3.95	4.15	5.69	15	40	57
B	3.63	4.17	5.36	16	42	54
C	3.18	4.18	5.52	13	33	55
D	3.38	4.39	6.25	14	36	62
E	3.60	4.21	5.57	14	35	54
F	3.65	4.25	5.80	15	38	57

In the CBD phase, weight and gearing are primary considerations for good fuel economy. Bus A, which is the lightest, achieved the best fuel economy. Bus C had the worst fuel economy, despite its intermediate weight, mainly because of its high average BSFC. Bus D also had a poor fuel economy, due to a relatively high BSFC caused by the gearing. The influence of gearing compensated for the fairly high weight of Bus E, enabling it to achieve a good fuel economy. Buses B and E have intermediate fuel economies.

In the ART phase, the simulated fuel economies were within 6 percent of each other, which makes comparisons more difficult. Bus D had a low BSFC combined with a low accessory load, and obtained the best fuel economy. Explanation of small fuel economy differences among the other buses would require a more lengthy description involving specific components. Although this could be done, the detail required would not enhance the previous examples.

The performance schedule used for comparison is the 0-to-50 mph time. This particular schedule is used because it minimizes the effects of shift logic and N/V ratio inflections. One of the factors in determining acceleration is the maximum available power from the engine, which differs by injector sizes.

Buses C and E have the largest injectors and therefore potentially the greatest power outputs. Gearing enables Bus C to obtain a slightly better level of performance than Bus E. Buses D and E both use the 70 mm injectors and achieve mid-range performance levels, with Bus D performing somewhat better, again due to gearing.

Buses A and B, which use 65 mm injectors, have the lowest performance levels. Bus A is lighter and therefore reaches a better performance level than Bus B. The compromise between one measure of performance and ADB fuel economy can be seen in Figure 5-2.

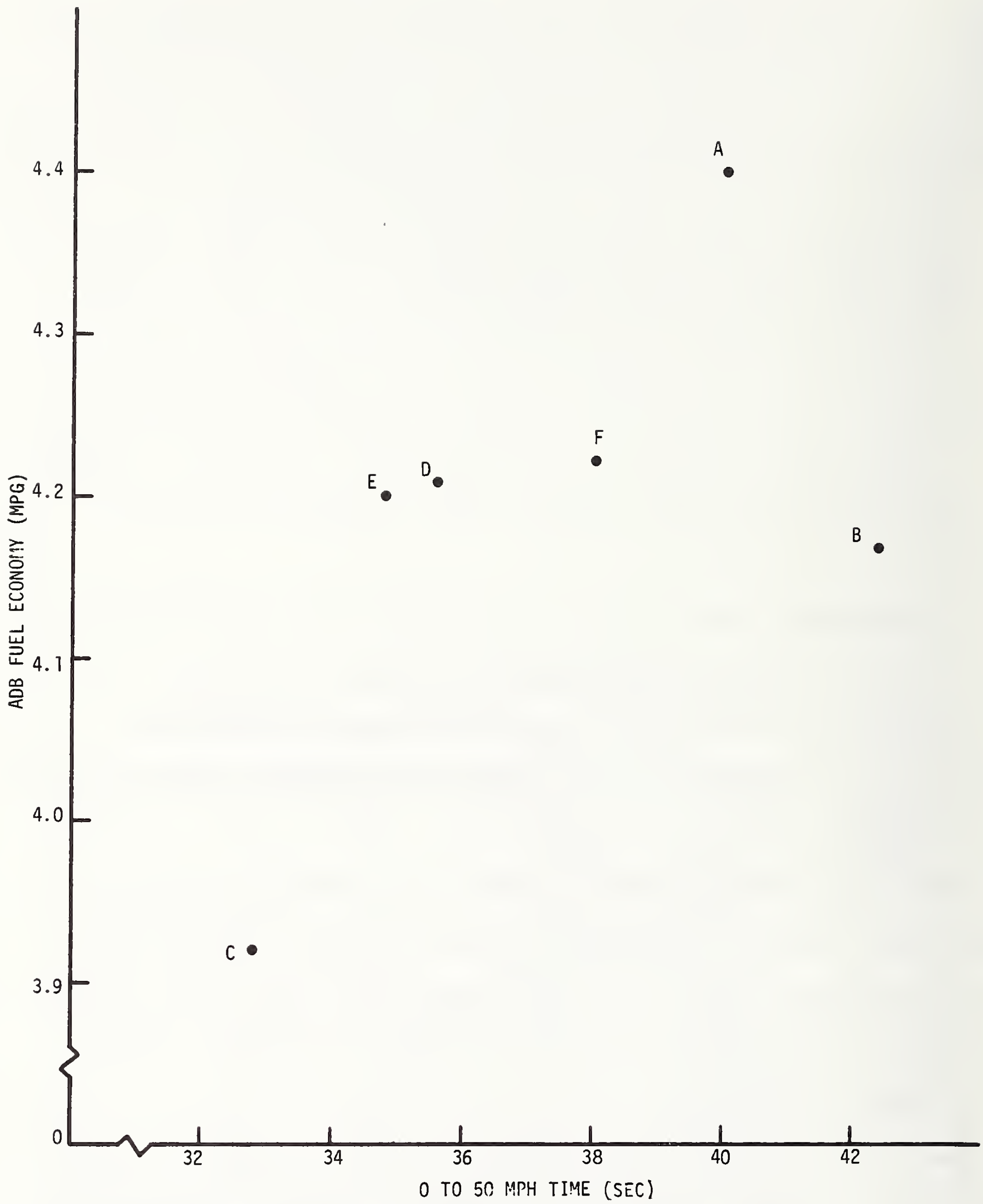


FIGURE 5-2. ADB FUEL ECONOMY VS. 0-50 MPH ACCELERATION TIME

6. COMPARISON OF SIMULATION TO TEST TRACK RESULTS

Although no tests have been exclusively designed to validate the HEVSIM computer model, results of recent bus fuel economy tests conducted by the Transportation Research Center of Ohio under the supervision of Battelle Columbus Laboratories are compared to the model results. The specific details of the testing are provided in a separate report (2).

The purpose of developing the empirical data was to improve the credibility of the HEVSIM model in the urban bus community and not to calibrate or validate the model. The track tests, conducted in compliance with SAE procedure J1321 (4), were designed to measure relative fuel consumption differences attributable to a series of weight and component changes of two buses. Similar changes were made to the model and the results compared. It should be noted that the calculation of fuel consumption and fuel economy for a component or weight change will produce slightly different results for small changes in weight or components. For comparison purposes the simulation results are presented in terms of percent fuel saved as well as percent change in fuel economy.

From a computer simulation perspective, it is extremely important that the bus hardware being tested is accurately described by the model. The bus component data used to simulate the track tests was obtained from the bus manufacturers and component suppliers to ensure that the model results were representative of the bus tested. Since the individual components simulation in the model are based on nominal values, the simulation results have been examined on a relative basis. The specific components evaluated for comparative testing were selected because they represent items that appeared to have an impact on fuel consumption and are of interest to the transit properties. The drivetrain specifications of the test buses are shown in Table 6-1 and a brief description of each test and the corresponding computer simulation input data follows.

TABLE 6-1. TEST TRACK BUS DRIVELINE CONFIGURATION

Component	Transverse Mounted Engine Test Bus	In-Line Mounted Engine Test Bus
Engine	6V92TA	6V92TA
Injectors	7G75	7G75
Converter	TC-490	TC-495
Axle	4.56	4.89
Transmission	V-730	HT-740

Table 6-2 provides a comparison of the sensitivity results of the tests conducted in July and August of 1983, at the nsportation Research Center of Ohio, with the HEVSIM model. The following paragraphs provide additional detail and analysis to support the conclusions. For each section, the test track results are first identified and then the corresponding HEVSIM simulation results are described.

WEIGHT

After establishing a seated load weight baseline fuel consumption in test T-1, the first change from the baseline was to increase the weight to one and one half times seated load weight in test T-2 and then in test T-3 the weight was reduced to the bus curb weight as shown in Table 6-2. Simulated fuel economy sensitivities to weight change (percent change in fuel economy/percent change in weight reduction) for test T-2 and T-3 are 0.60 and 0.64 respectively,

TABLE 6-2. COMPARISON OF TEST TRACK AND HEVSIM RELATIVE FUEL CONSUMPTION AND ECONOMY CHANGES

Corresponding Track Test No.	Configuration Change	Test Track % Fuel Saved	HEVSIM % Fuel Saved***	HEVSIM % Δ Fuel Economy***
T-1	BASELINE*	--	--	--
T-2	WEIGHT 32,940 lb to 36,870 lb	-7.0%	-6.4%	-6.1%
T-3	WEIGHT 32,940 lb to 26,180 lb	+11.5%	+11.5%	+13.1%
T-4	AXLE RATIO 4.556 to 5.375	-2.0%	-2.6%	-2.6%
T-5	SHIFT SCHEDULE STD hydraulic to electronic OPT	-1.8%	+1.0%	+1.0%
T-6	SHIFT SCHEDULE STD hydraulic to electronic fuel economy	+2.5	+3.0%	+3.1%
T-7	BASELINE Repeat No Change	-1.1%	0%	0%
I-2	BASELINE **			
I-1	RETARDER	0%	-0.5%	-0.5%
I-3	WEIGHT 34,130 lb to 37,680 lb	-2.2%	-4.2%	-4.1%
I-4	WEIGHT 34,130 lb to 28,150 lb	+10.4%	+9.6%	+10.6%
I-5	TIRES bias to radial ply	+9.2%	+3.4 to 4.4%	3.5 to 4.6%
I-6	BASELINE REPEAT No Change	-1.1%	0%	0%

*letter T indicates transverse mounted engine
**letter I indicates in-line mounted engine
***the difference in the values of these two measures is due to the computation using different units (lbs of fuel vs. miles per gallon).

which is near the 0.60 calculated in Section 4.2.1 of this report. Also, plots of the simulated fuel consumption vs. weight and T/C ratio (see reference 4) vs. weight for test T-1, T-2 and T-3 are linear, indicating consistency between the test track and simulated results.

A similar series of weight changes were tested for the in-line mounted engine for test I-3 and I-4. The 37,680 lb corresponds to one and one half times seated load weight and 28,150 lb represents the curb weight. The simulated fuel economy sensitivity to weight change of the in-line mounted engine for test I-3 and I-4 are 0.45 and 0.61 respectively. Although this configuration was not simulated in Section 4.2.1 of this report, a plot of simulated fuel consumption vs. weight is nearly linear. The slope between I-2 and I-3 decreases slightly. A plot of T/C ratio vs. weight, however is not linear and the slope between I-2 and I-3 approaches zero. This implies that the simulation and test procedure evaluate this weight change differently. Because of the consistency of the previous results (T-1, T-2, T-3 and I-4) and the inconsistency between simulated I-3 and test I-3(-2.2 percent vs. -4.1 percent), test I-3 raises some questions although no conclusions can be made unless a larger sample of weights are tested.

AXLE RATIO

The selection of a bus axle ratio will vary depending upon the particular bus and the operator's driving schedule. The axle ratio change from 4.556 to 5.375 was selected to represent common options being offered. The test results for T-4 show a 2.0 percent loss in fuel consumption for the change. The simulation of the axle ratio change from 4.556 to 5.375 reduced the ADB fuel consumption by 2.6 percent which is similar to that shown in Section 4.2.5.

SHIFT SCHEDULE

There is currently a great interest by both bus manufacturers and transit properties in the use of shift schedules to optimize fuel economy. Although there have been numerous tests conducted by the transmission manufacturer and in service tests conducted by several transit properties, test T-5 and T-6 were conducted because of the wide variation in fuel economy claims from these previous tests. Test T-5 was performed by changing the hydraulic standard (STD) shift schedule to a universal electronic control (UEC) optional (OPT) shift schedule. Test T-6 was conducted by changing the baseline hydraulic STD shift schedule to a UEC fuel economy shift schedule.

The simulation of a universal electronic control (UEC) emulation of an optional (OPT) hydraulic shift schedule was accomplished by modeling the shift lines provided by the manufacturer. The baseline (T-1) STD shift schedule 1 to 2 upshift was lowered slightly to match that of the test bus. Shift points were recorded at the test track in an attempt to identify the precise shift point for input into the HEVSIM model. The analysis of the fuel consumption change is similar to that presented in Section 4.2.4.

In the COM phase the fuel saved due to the OPT UEC is relatively small because the bus cruises for most of the phase at 55 mph in third gear regardless of which shift schedule is used. The simulated percent fuel saved is 0.8 percent and the test track fuel savings is 1.1 percent as shown in Table 6-3. In the ART phase the percent fuel saved is 3.1 percent because of the earlier upshift speeds. The test results show a 1.9 percent fuel saved. In the CBD phase there is a slight decrease in the upshift speed from 1 to 2, but the bus cruises in second lockup for both shift schedules. Because of this it would appear that there would be only a slight fuel consumption change in the CBD phase for test T5. The simulation computes -0.2 percent while the test results

TABLE 6-3. COMPARISON OF TEST TRACK AND HEVSIM PERCENT FUEL SAVED FOR SHIFT LOGIC CHANGES BY DRIVE SCHEDULE

HEVSIM COMPARISON	PHASE			COMBINED ADB
	COM	ART	CBD	
T-5 to T-1	0.8%	+3.1%	-0.2%	+1.0%
T-6 to T-1	+1.0%	+10.6%	-0.8%	+3.0%
T-6 to T-5	+0.5%	+8.4%	+0.5%	+2.1%
TEST COMPARISON				
T-5 to T-1	+1.1%	+1.9%	-5.4%	-1.8%
T-6 to T-1	+1.5%	+10.7%	-1.3%	+2.5%
T-6 to T-5	+0.4%	+7.7%	+3.9%	+4.2%

show a 5.4 percent decrease. The reason for the large test decrease is not apparent, although it is possible that the bus may not have been in second gear lockup at cruise.

Test T6 was simulated by changing the shift lines in the model to represent a UEC fuel economy shift schedule based upon specifications provided by the manufacturer. In the COM phase the percent fuel saved is small with the simulation showing a 1.0 percent improvement and the test results a 1.5 percent* improvement. In the ART phase the upshift lines of the UEC fuel economy shift schedule vs. the STD shift schedule are earlier and the UEC fuel economy schedule allows the bus to cruise in third gear instead of second lockup. This creates a significant fuel savings with the simulation showing a 10.6 percent savings and the test results a 10.7 percent savings. In the CBD phase the 0.8 percent increase in fuel used shown by the simulation is due to the earlier upshift causing the torque converter to operate in a slightly more inefficient region. The test results indicate an increase in fuel used of 1.3 percent.

A similar approach can be used for comparing test T6 with T5 which would translate into the percent fuel saved using the fuel economy schedule for transmission shifts. Again, the greatest discrepancy between simulated and test results occurs in the CBD phase. Since the wide open throttle 1 to 2 upshift points for test T5 and T6 are close, and cruise is in second lockup in both cases, a slight improvement might be expected. The simulated percent fuel saved (0.5 percent) is much less than the 3.9 percent calculated from the test. By examining Table 6-3 it can be seen that the COM and ART phase test and simulation comparisons show close agreement while the CBD phase results are very remote. It appears that there may be a systematic error between the simulation

*Test results reported in the Battelle report were rounded to the nearest whole number. The raw data, however, was used in this analysis.

and test results over the CBD phase. It is interesting to note that when the baseline retest was conducted, the CBD phase fuel consumption was -3 percent. This will be discussed in more detail later.

ELECTRIC RETARDER

There has been an increase in the use of electric retarders in the domestic transit industry. In the previous two years, one manufacturer has sold over 2000 units. It appeared that the rotating mass, increased electrical load and the increased weight of the bus would degrade fuel economy. Test I-1 was conducted by installing the retarder and instrumenting the alternator. As shown in Table 6-2, there was no measurable difference in fuel consumption.

The use of the retarder in test I-1 is simulated by increasing the weight of the vehicle 320 lb, simulating the retarder rotor inertia of 1.22 ft lb sec^2, and increasing the electrical load of the alternator. Test recordings, of the amp-hrs with and without the retarder, translated into an increase in alternator duty cycle of only 2 percent in the ADB cycle when the retarder was in use. As shown in Section 4.2.11 of this report, this has a negligible effect on fuel economy. Therefore, the fuel consumption penalty of 0.5 percent is the result of the weight and inertia increase. The test track results showed no fuel consumption change with the use of the retarder.

TIRES

Steel-belted radials are uncommon in the domestic transit industry although automobiles and trucks have been experiencing improved fuel economy for years with radial design tires. The test and simulation analysis conducted under this program should be useful in assessing the fuel consumption impacts of changing to radial tires. Test I-5 was performed by changing the six bias ply tires to radial ply tires. The test results shown in Table 6-2 show a fuel savings for this change of 9.2 percent.

From a simulation perspective, using steel-belted radials in place of bias ply tires as shown in test I-5 required modifying the simulated rolling resistance input. The manufacturer of the bias ply tires submitted test results in accordance with procedure SAE J1379 for bias ply tires. The radial tire used in the test was manufactured by a different company which did not have test results for the radial tires. Therefore, both manufacturers submitted their estimates of the rolling resistance reduction using the radial tires. Both estimated that the rolling resistance would be reduced 30-40 percent using radials in place of bias ply tires. Since the rolling radius of the bias and radial tires measured at the test track were identical, the 30-40 percent savings translates into an ADB fuel consumption savings of 3.4 to 4.4 percent, estimated by the simulation model. The test track result shows a fuel reduction of 9.2 percent which means that the simulated radial tire rolling resistance would have to be reduced approximately 80 percent from the bias ply to correspond to the test result. Alternatively, some other phenomenon is occurring that is not recognized.

Two corrections of the tire simulation results were made concerning ambient temperatures. The first correction (5) was to adjust the simulated bias rolling resistance value to reflect the average ambient temperature during test I-2. Similarly, the radial rolling resistance value was compensated for the ambient temperature during test I-5. The result of these corrections changed the fuel consumption difference due to radials from the range of 3.4 to 4.4 percent to the range of 2.7 to 3.9 percent. This correction makes the difference between the test results and simulated results even larger. The second correction is based on results that indicate bias and radial tire rolling resistances respond to temperature changes differently (5). This difference, which was calculated for the average ambient temperature during test I-2 and I-5, was found to be less than 1 percent.

An explanation of the disparity between the test track and simulated results may be derived from the results of the individual phases. The simulation results discussed earlier in this report will be referenced for this purpose. Section 5.2 lists the fuel economy change due to a rolling resistance reduction for each phase, which is dependent on how much the rolling resistance extracts from the entire engine output. In Section 4.2.6 this was illustrated by the COM phase showing the largest fuel economy gain (2.1 percent) for a 10 percent reduction in rolling resistance. The simulation results for a 40 percent reduction translated into fuel economy gains of 3.6 percent, 5 percent and 7.3 percent for the CBD, ART and COM phases respectively. The difference between the fuel economy gain in the COM and CBD is approximately 2 to 1 in favor of the COM which is consistent with previous simulations shown in Section 4.2.6. The test track results, based on T/C ratios showed fuel consumption reductions of 9.5 percent, 7.9 percent and 10.2 percent for the CBD, ART and COM phases respectively. Clearly, the magnitude of the impact on fuel consumption from this reduction in rolling resistance is dissimilar between the model and test results. A possible reason why the simulation and test track results are not consistent is that the test track results are not as dependent on the drive schedule.

BASELINE REPEAT

Repeating the baseline bus tests yielded -1.1 percent fuel consumption decreases for both T-7 vs. T-1 and I-6 vs. I-2. The baseline simulation repeat, as expected, showed identical fuel consumption as shown in Table 6.2. The question of how and when, throughout the series of tests, the -1.1 percent occurred should be answered with respect to the test accuracy. Is the baseline test difference (-1 percent) to be used in addition to the 1 percent suggested by the SAE procedure? Section 6.1 of SAE procedure J1321 Type II states that properly conducted tests using portable weigh methods, based on test experience with a long-haul test route, can be expected to have an overall accuracy within 1 percent (for example, 6 percent measured difference can be from 5-7 percent actual difference (4)). The The CBD phase is obviously not a long-haul schedule and the CBD phase fuel consumption repeat (T-5) as shown in the Battelle report (2) is -3 percent. Additionally, since the COM repeat is +1 percent and the ART repeat is 0 percent the combined repeatability is composed of fuel gains and losses to yield a -1.1 percent ADB repeatability. The previous discussion in the section on shift schedules concentrates on this point. Although the total baseline retest is -1.1 percent, the CBD phase is -3 percent.

Further testing will have to be conducted to determine test accuracy for bus testing, particularly in the CBD phase. Other tests using the same procedures have resulted in questions concerning the entire procedure being accurate to ±1 percent (6). Also, further testing and analysis will be required to explain the differences shown in tests T-5 and I-5. Although the focus of most of this analysis has been on the three test and simulation comparisons greater than 1 percent, it should not preponderate the fact that six of the nine test and simulation comparisons were within ±1 percent.

7. SUMMARY

The results presented illustrate the use of the HEVSIM computer model for analyzing relative fuel economy and performance of transit buses. When using the model or the results presented here, the following should be observed:

- Before any computer results are used all the inputs should be identified, particularly the driving schedule. The user should be confident that the input data represents the bus being modeled.
- Fuel economy sensitivities should be used judiciously when evaluating fuel economy and performance compromises. It has been shown that sensitivities are not necessarily numerically additive and that different engines can yield different sensitivities.
- Any single change should be evaluated with respect to its effect on the system performance. It has been shown that changing individual powertrain components can affect the performance of other components.
- The results presented in this report are intended for relative comparisons only. The absolute numbers are listed solely as a reference to illustrate a relative change. The use of this model or other models for predicting absolute fuel economy or performance is not recommended unless the model has been validated for this purpose.
- The fuel economy of buses should be compared only if performance levels are indicated.

Based on the simulation of the buses previously identified, the following ADB fuel economy results are presented in the same order that they appear in the text. The reader should consult the text for the individual ADB phase changes and performance differences.

- Decreasing the bus weight by 10 percent results in a fuel economy improvement of 6-6.5 percent in the ADB cycle.
- Comparisons between the fuel economy and performance associated with a V-drive transmission and a bus with an in-line transmission should be made at equivalent performance levels. In reality, the two drivetrain geometries often differ in shift logic, converter, and axle ratio, making direct comparisons difficult.
- Decreasing the load-dependent gear efficiency by 4.8 percent yields a 2.4-percent improvement in fuel economy.
- The ADB fuel economy change attributable to the use of a TC-490 torque converter is approximately 1 percent better than for the TC-470 converter.
- The ADB fuel economy change due to different shift schedules is dependent upon the axle ratio.
- Although there are inflections in the N/V (rpm/mph) vs. fuel economy curve, the overall ADB fuel economy changes by as much as 7 percent in the N/V range studied.
- Decreasing tire rolling resistance by 10 percent improves the ADB fuel economy by approximately 1.3 percent.
- A tire pressure of 10 percent under the recommended inflation level decreases ADB fuel economy by 0.5 percent.
- The fuel economy change for an aerodynamic drag coefficient change is 1.75 mpg/1.0 C_D (aerodynamic drag coefficient).
- Using No. 2 diesel fuel instead of No. 1 diesel fuel improves fuel economy by 2 percent and also improves performance.

- Increasing injector size improves performance. The fuel economy difference among different size injectors is dependent upon the selection of an equivalent performance level.
- When the engine fan changes from "off" to its fastest operating mode, the bus fuel economy decreases by 1 to 3.2 percent.
- Decreasing the alternator load by 43 percent improves the fuel economy by 1 percent.
- Doubling the simulated operating load of the power steering reduced the fuel economy by less than 1 percent.
- Increasing the duty cycle of the air compressor by 50 percent reduced the fuel economy by less than 1 percent.
- The average fuel economy decrease due to a simulated air conditioning load in three different cities is 10.5 percent.
- The drive cycle has the largest impact on fuel economy, which changed from 5 to 105 percent depending upon the particular drive schedule.

The comparison of test track relative fuel consumption to HEVSIM relative fuel consumption was performed with six of the nine simulations agreeing within the ±1 percent band of the tests results. The test, conducted by Battelle Columbus Laboratories at the Transportation Research Center of Ohio, is the SAE Type II J1321 test procedure. The following observations concerning the comparisons are listed below.

- Three of the four weight reduction sensitivities were within 1 percent of the test track results. The fourth test point appears to be inconsistent with the previous three, therefore a further sample would be required to form any conclusions.

- The simulation of an axle ratio change increased fuel consumption by 2.6 percent. The test track results showed an increase in fuel consumption of 2.0 percent.
- The comparison of the simulated and test track relative fuel consumption change for different shift schedules correlated within 1.2 percent in the ART and COM phases but differed by as much as 5.2 percent in the CBD phase. This difference must be considered with the fact that the test track retest showed a -3 percent change in the CBD phase.
- The use of the electric retarder showed a simulated fuel consumption penalty of 0.5 percent. The test results indicated no measurable fuel consumption penalty.
- Both the simulation and test track results showed reduced fuel consumption going from bias to radial ply tires. An analysis of the difference between the test (9.2 percent) and simultion (3.4 to 4.4 percent) suggested that the test results are less dependent on drive schedule than the model results. Further testing and analysis is required to evaluate the magnitude of the test and simulated tire changes.
- The simulation of the baseline retest showed no change as expected. The test track baseline retest indicated a -1.1 percent fuel consumption in both repeat tests.

REFERENCES

1. U.S. Department of Transportation, Urban Mass Transportation Administration, "National Urban Mass Transportation Statistics 1982 Section 15 Annual Report," UMTA-MA-06-0107-84-1, November 1983.

2. Test Bed Transit Bus Fuel Economy Tests, Battelle Columbus Laboratories, UMTA-IT-06-0219-11-2, December 1983.

3. United States Air Force, Facility Design and Planning Engineering Weather Data, AFM88-29, July 1978.

4. Joint TMC/SAE Fuel Consumption Test Procedure - Type II - SAE J1321 October 1981.

5. Knight, R.E., Correlation of Truck Tire Rolling Resistance as Derived From Fuel Economy and Laboratory Tests, SAE Paper 821266, November 1982.

6. Seiff, Henry, Testing for Improved Truck and Bus Fuel Economy, SAE Paper 821257, November 1982.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1984--500-324--572

300 copies

U.S. Department
...nsportation

...arch and
...ial Programs
...inistration

... Square
...ge, Massachusetts 02142

Official Business
Penalty for Private Use $300

Postage and Fees Paid
Research and Special
Programs Administration
DOT 513

U.S. MAIL