REPORT NO. DOT-TSC-OST-75-46

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U.S. DOT

A STUDY OF TECHNOLOGICAL IMPROVEMENTS TO OPTIMIZE TRUCK CONFIGURATIONS FOR FUEL ECONOMY

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SEPTEMBER 1975

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
OFFICE OF THE SECRETARY
Office of the Assistant Secretary for
Systems Development and Technology
Office of Systems Engineering
Washington DC 20590

TECHNICAL REPORT STANDARD TITLE PAGE

ìeport No.	2. Government Accession No.	3. Recipient's Catalog No.
-TSC-OST-75-46		

ítle and Subtitle

;TUDY OF TECHNOLOGICAL IMPROVEMENTS
OPTIMIZE TRUCK CONFIGURATIONS FOR FUEL ECONOMY

5. Report Date
September 1975

6. Performing Organization Code

ıthor(s)

ıald A. Hurter, W. David Lee

8. Performing Organization Report No.
DOT-TSC-OST-75-46

'erforming Organization Name and Address

:hur D. Little, Inc*
›rn Park
ıbridge MA 02140

10. Work Unit No.
OS614/R6506

11. Contract or Grant No.
DOT-TSC-627

Sponsoring Agency Name and Address

;. Department of Transportation
:ice of the Secretary
:ice of the Asst. Sec. for Sys. Dev. & Tech.
:ice of Systems Engineering
shington DC 20590

13. Type of Report and Period Covered
Final Report
May 1974 - January 1975

14. Sponsoring Agency Code

Supplementary Notes

ıder contract to: U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge MA 02142

Abstract

A study of truck fuel economy was undertaken for the U.S. Department of ansportation as a continuation of the Study of Technological Improvements in tomobile Fuel Consumption, report number DOT-TSC-OST-74-40.I-IV. The truck pes that accounted for most of the fuel consumed were identified and modeled computer analysis. Baseline fuel consumption was calculated for the major uck types over specific duty cycles. Design improvements in the truck were en modeled, and the effect on fuel economy was estimated. Those improvements nsidered cost effective and capable of meeting manufacturing and performance iteria were examined further for their economic impact. Total life cycle costs r the incorporation of improvements were developed for single improvements and mbinations of improvements.

The study results indicated that fuel economy gains of up to 40% could be de in Classes I and II, 70-80% in Class VI van-type local delivery trucks, -30% in Class VIII depending on the type of truck and use. These four classes count for over 85% of the fuel consumed by the entire truck fleet.

It appears that the technological changes required to mass produce these e fuel efficient vehicles could be accomplished in the 1980's.

Key Words	18. Distribution Statement
el economy, power plants, ansmissions, drive trains, tires, cessories, aerodynamics, fuel nsumption improvement.	DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	168	

DOT F 1700.7 (8-69)

PREFACE

This report, prepared by Arthur D. Little, Inc., for the U.S. Department of Transportation, Transportation Systems Center (DOT-TSC) presents a study of technological improvements to optimize truck configuration for fuel economy.

This study is a continuation of the work performed as part of the DOT-TSC Automotive Energy Efficiency Program to identify technological improvements to optimize automobile configuration for fuel economy gains (Report No. DOT-TSC-OST-74-40.1, 40.2, and 40.3).

Section 1 of this report presents a summary of the technical improvements considered and summarizes the important conclusions and recommendations pertaining to truck fuel economy improvement. The main body of the report provides a comprehensive discussion of each improvement option, the various constraints considered, the results of combining improvements, the possible fuel economy gains and comparative cost effectiveness of the approaches.

The status of the technology reported is that available in the time period of July 1974 to January 1975.

Arthur D. Little, Inc., wishes to acknowledge the guidance and assistance provided by Mr. W.H. Close, Department of Transportation, Office of Noise Abatement, Washington, D.C., Mr. H. Gould, Department of Transportation, Transportation Systems Center, Mr. R. Mason, Department of Transportation, Transportation Systems Center, Cambridge, Massachusetts, and Mr. Max Roensch and the many truck manufacturers, engine and component manufacturers.

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ion adopted for this study is based on the classifications used manufacturers and the Motor Vehicle Manufacturers Associa- ıe sale of new trucks according to the following weight classes:

;	Weight (lb) GVW
	0- 6,000
	6,001-10,000
	10,001-14,000
	14,001-16,000
	16,001-19,500
	19,501,26,000
	26,001-33,000
	33,001 and over

n, though far more detailed than the Census Bureau classifica- :t variations within the classes, particularly Class VIII. Further nd function within a class was necessary as defined later.

' trucks, their fuel economy, and their annual fuel consump- : the total fuel consumption by class. The fuel consumed by s shown by class in Figure 1.1. Note the break in scale for the sed in local driving where local refers only to driving similar the Federal Test Procedure for Automotive Emissions. Short- ned as a trip under 200 miles returning to base each night. s defined as a trip over 200 miles a day, i.e., interstate-type

EHICLES AND DRIVING CYCLES

n trucks representative of the popular truck types and their attern from a complete list of manufactured vehicles. The n indicated that trucks from weight classes I, II, VI, and VIII 5% of the fuel consumed by the entire fleet of trucks. The listed in Table 1.1. An explanation of the selection proce- :d in Section 3. A description of the truck classes modelled

– The pickup truck, though used primarily for local :d for short- and long-distance driving. A mixture of the des was used in the study, dominated by local service, endix B. (Duty and operating life considered identical)

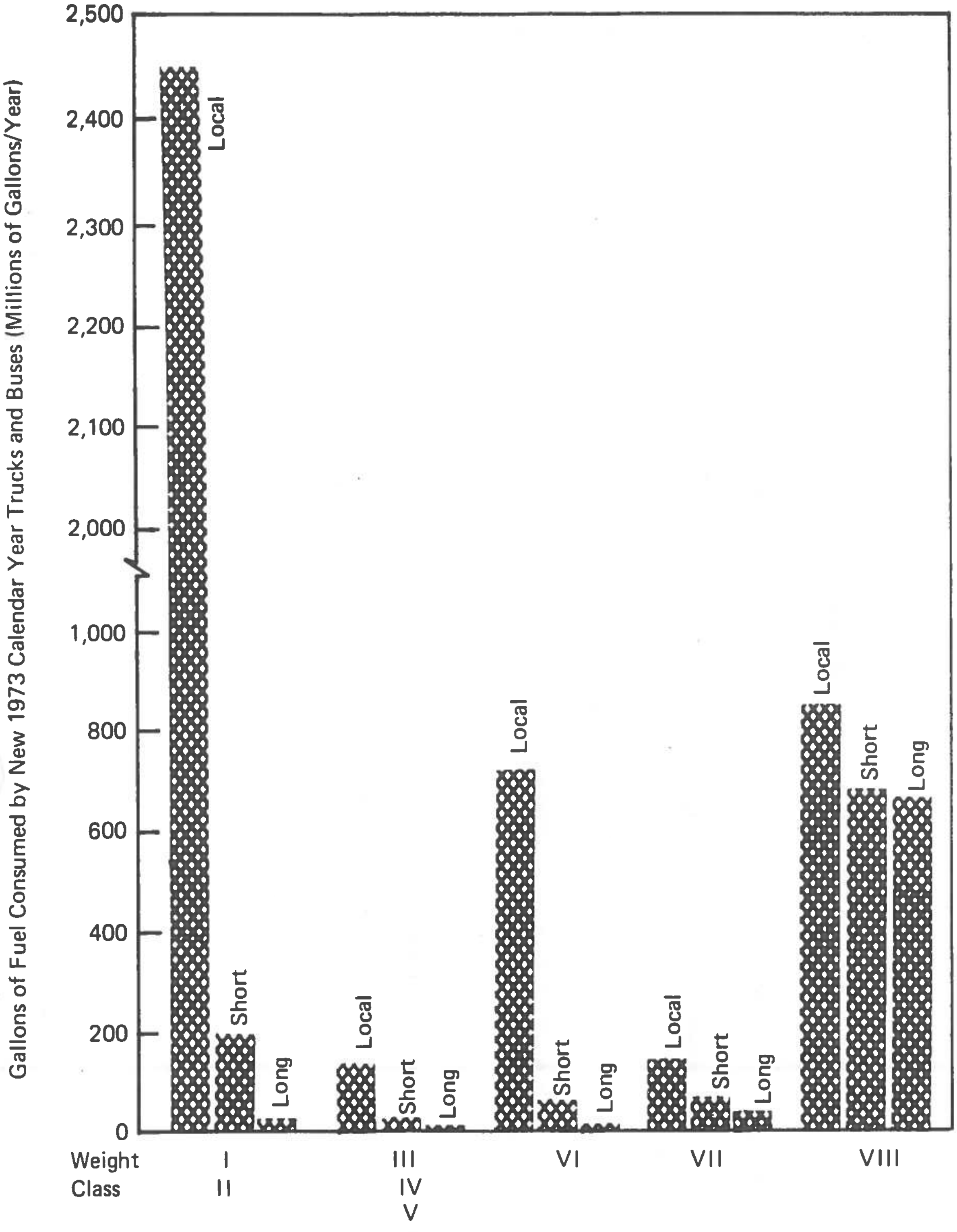

FIGURE 1.1 FUEL CONSUMPTION BY WEIGHT CLASS AND DRIVING MODE FOR NEW 1973 CALENDAR YEAR, TRUCKS AND BUSES

TABLE 1.1

SELECTED REFERENCE TRUCKS

Class	Driving Mode	Make	Model	Engine	Transmission	Gross Vehicle Wt. (lb)
I	Mixture of local, short, and long	Chevrolet	C-10 Pickup	Chev. 350 CID	3-Speed Auto	6,000
II	Mixture of local, short, and long	Ford	F-250 Camper Special Pickup and Camper	Ford 361-CID	3-Speed Heavy Duty Auto	10,000
VI	Local	International Harvester	1800 Van 1850 Van	IH DV 392 Cummins 8VE 170 HT	5-Speed T-35 5-Speed T-36	22,500 24,500
VIII	Local and Short	Mack	DM-600 Dump Body	Mack End-673E	10-Speed TRD-722	62,000
VIII	Short	International Harvester	Fleetstar F-2070 4x2 Tractor Trailer	Cummins NTC 290	10-Speed-RT-910	48,860
VIII	Long	International Harvester	Transtar F-4379 6x4 Tractor Trailer	Cummins NTC 290	10-Speed RT-910 Manual	73,000

These vehicle classes account for 88% of truck fleet fuel consumption.

Classes III, IV, V and VII – Vehicles in these classes were not included in this study because of their small use factor and number.

Class VI – This class is primarily a van used for city delivery. For this vehicle class, ADL considered replacing the popular 350-400 CID gasoline engine with a light/medium duty diesel. At present, no diesel engine explicitly designed for light/medium duty for this vehicle class is available, though there are indications that two major diesel engine manufacturers may offer such engines soon. The diesel used in this study was an existing medium- to heavy-size engine derated in horsepower for use in this vehicle.

Class VIII – As mentioned earlier, class VIII actually consists of several subcategories based on operational requirements. We have taken the position, in consultation with truck industry experts, that there are three such groups, one for each driving cycle. This supports the generally accepted concept that heavy trucks are built for a specific task and driving cycle. All three trucks are diesel-powered, and all use 10-speed manual transmissions.

Computer simulation was employed in the study to determine both baseline operating characteristics and the effect of improvements on fuel consumption. Two programs were used: the Cummins Engine Company "Vehicle Mission Simulator" VMS(T) and the Arthur D. Little, Inc. (ADL) fuel consumption model. The Cummins simulator, which can provide over 150,000 miles of actual road conditions, was used for weight classes VI and VIII, while the ADL fuel consumption model was used for classes I and II and for analysis of energy partitioning for all vehicles under steady state driving conditions. Baseline performance of the reference vehicles is shown in Table 1.2 and baseline energy partitioning is shown in Figures 1.2, 1.3, 1.4, and 1.5.

Individual Fuel Economy Improvements

1.2.1 Conditions and Constraints of Study

Before we summarize the study findings with regard to reduction in fuel consumption by individual improvement, the conditions which improvements had to meet before being considered should be examined. Each improvement in vehicle design had to be:

- Adaptable to the reference vehicle without causing reduced effectiveness. Loss in acceleration capability or gradability, driver control, or cost effectiveness of the vehicle would rule out the innovation.

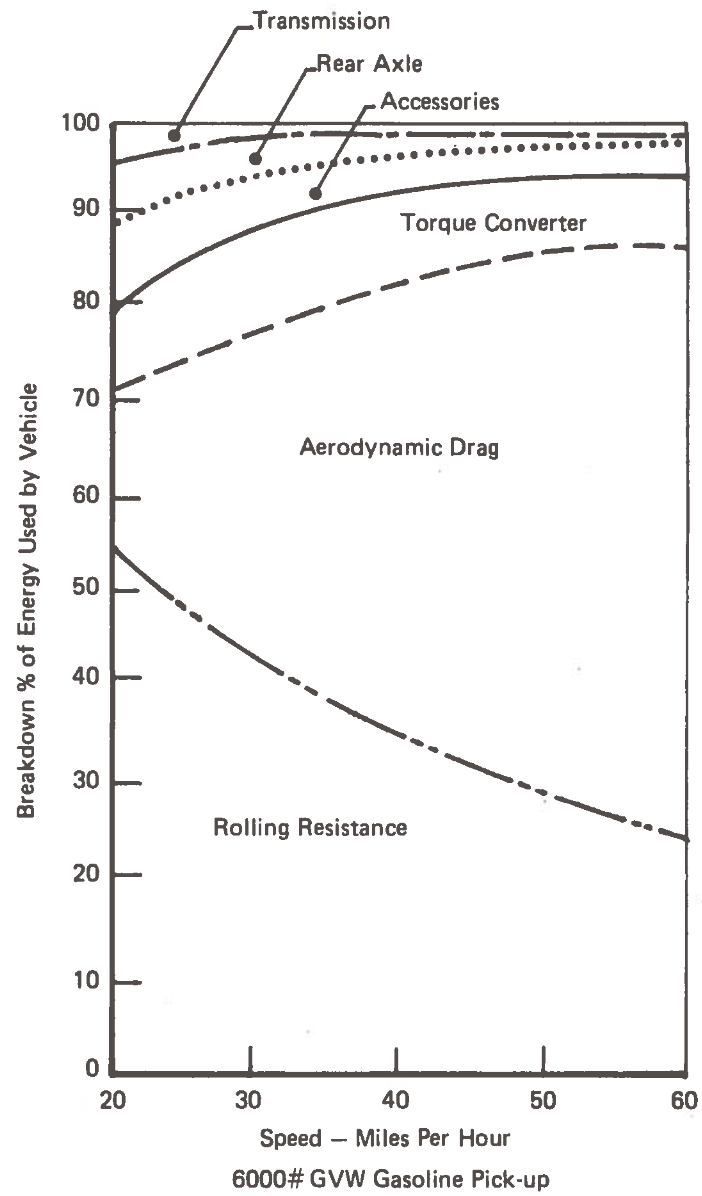

FIGURE 1.2 ENERGY PARTITIONING OF 6000# GVW PICK-UP VEHICLE DURING STEADY CRUISE

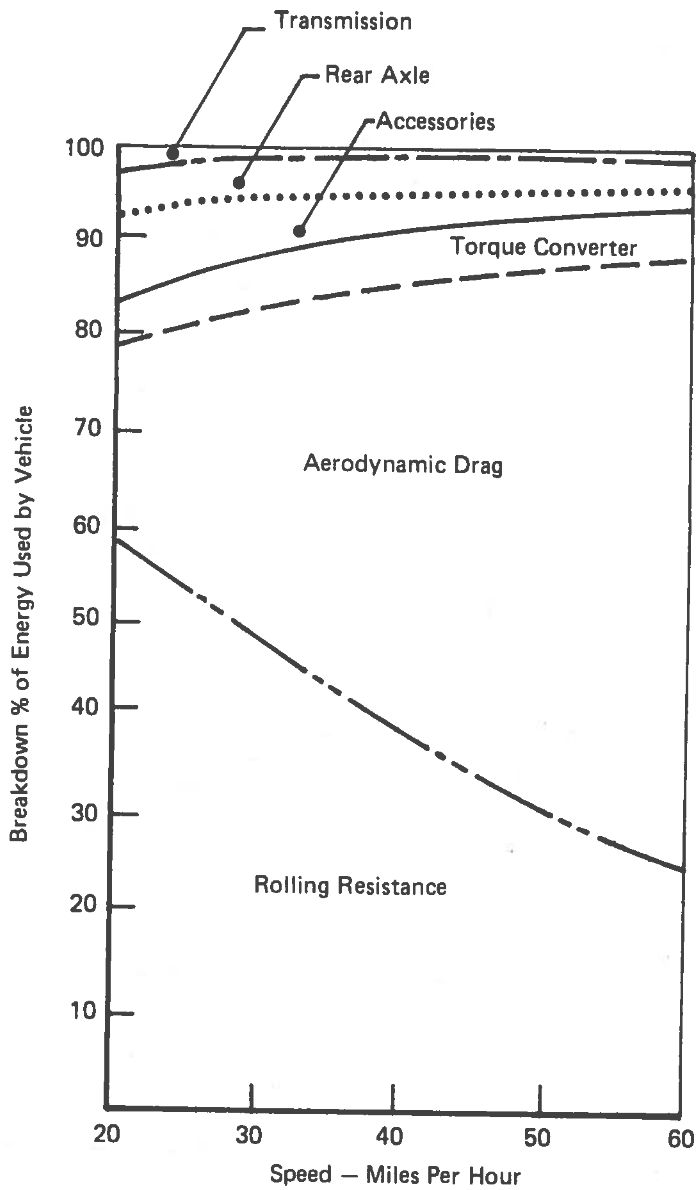

FIGURE 1.3 ENERGY PARTITIONING DURING STEADY CRUISE FOR 10,000# GVW CAMPER VEHICLE

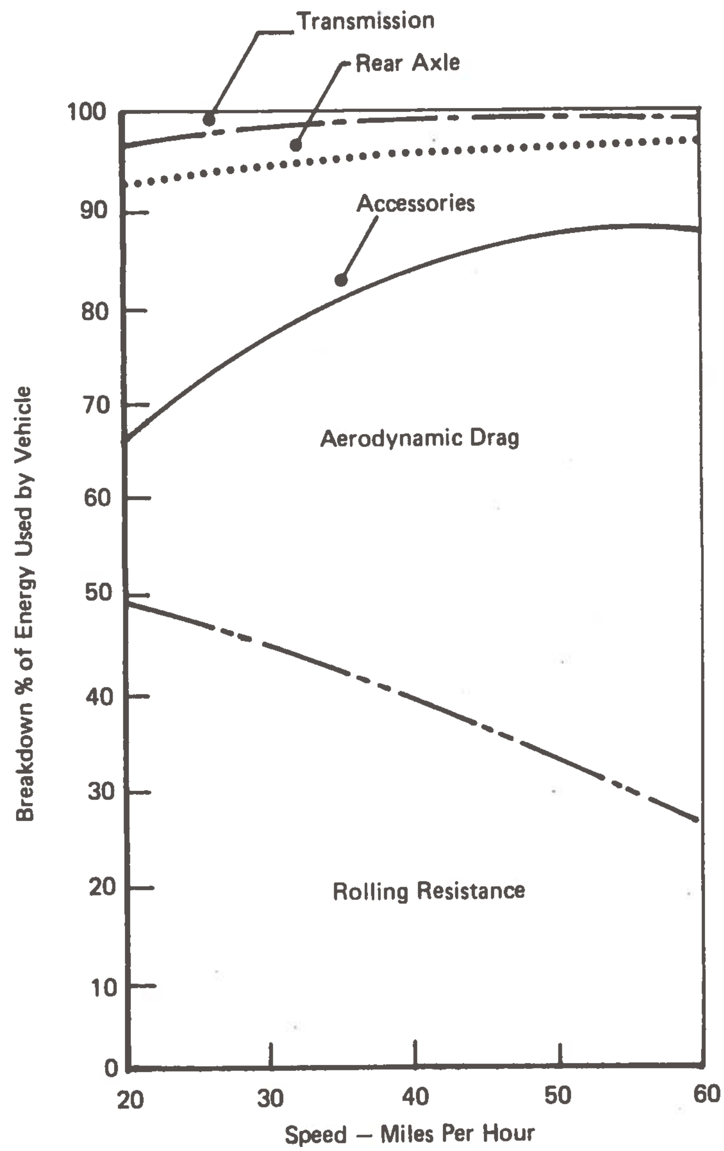

FIGURE 1.4 ENERGY PARTITIONING DURING STEADY CRUISE OF 22,500# GVW GASOLINE VAN TRUCK

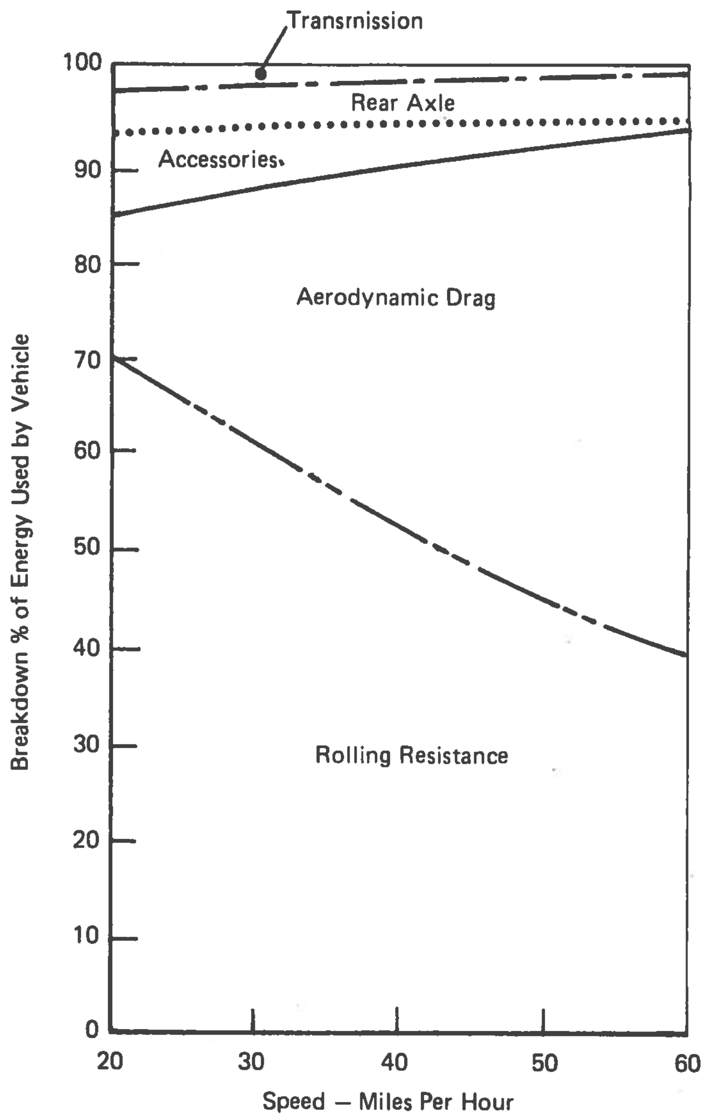

FIGURE 1.5 ENERGY PARTITIONING DURING STEADY CRUISE OF 73,000# GVW TRACTOR–SEMITRAILER

- Manufacturable by 1980 so that a significant number of new 1980 and 1981 trucks could incorporate the innovation.

- Implementable without any reduction in a vehicle's ability to meet emission and smoke requirements as spelled out in Table 1.3.

- Implementable without impairing ability of vehicle to meet applicable noise regulations.

- Likely to yield a significant improvement in fuel consumption.

TABLE 1.2

BASELINE PERFORMANCE OF REFERENCE VEHICLES

Vehicle	Miles Per Gallon Over Driving Mode		
	Local	Short	Long
Class I (6,000-lb Pickup)	11.7	Annual Mix of Local and Steady State Driving	
Class II (10,000-lb Camper)	8.8		
Class VI (22,500-lb Van)	5.1	5.4	–
Class VIII (62,000-lb Dump)	5.0	5.0	–
Class VIII (48,000-lb Tractor Trailer)	–	4.8	4.9
Class VIII (73,000-lb Tractor Trailer)	–	4.0	4.5

When each of the screening criteria was met, the improvement was incorporated into the vehicle simulation and compared to the baseline performance of the reference vehicle. All comparisons were based on the percent improvement in fuel economy, miles per gallon (MPG), and/or fuel consumption (gpm).

Each innovation with its attendant fuel economy improvement was then evaluated on the basis of cost effectiveness to ensure that the fuel savings compensated for the initial and continuing incremental investment attributed to the innovation. Those innovations which would "pay for themselves" in the lifetime of the vehicle were incorporated into a synthesized vehicle of combined improvements and re-evaluated for fuel savings and cost effectiveness.

Table 1.4 presents a summary of the impact of the improvements on fuel economy. These improvements are based on computer simulations and not vehicle testing, though many of the figures have been verified by tests performed by others. A brief explanation of each improvement follows:

TABLE 1.3

TRUCK EMISSION REQUIREMENTS

For 1975 – 1976

Vehicles 6,000 lb and Less	gm/mile	Vehicles Over 6,000 lb	gm/BHP-hr
HC	1.5	HC + NO_x	16
NO_x	3.1		
CO	15.0	CO	40

For 1977

Vehicles 10,000 lb and Less	gm/mile	Vehicles Over 10,000 lbs	gm/BHP-hr
HC	0.41	HC + NO_x	16
NO_x	2.0* (0.4 in 1978)		
CO	3.4	CO	40

*Arthur D. Little, Inc., estimate.

1.2.2 Power Plant Improvement

1. Diesel engine substitution. i.e., the development and incorporation of a light-weight diesel for pickup trucks (classes I and II) and a light-medium-weight diesel for the city van (class VI).

2. Lean burn engine – the principal feature of which is an air/fuel ratio of 18:1 or greater. Increased compression ratio, lean mixture carburetors and fuel injection systems were examined.

3. Closed-loop stoichiometric engine in which close control of the fuel/air mixture near its stoichiometric value is maintained. This permits use of a dual-purpose catalyst which serves to reduce emissions of three common pollutants – CO, HC, and NO_x. Most proponents of this approach agree that closed-loop control of the mixture requires sensing of exhaust gas for feed-back control.

TABLE 1.4

SUMMARY OF PERCENT IMPROVEMENT IN FUEL ECONOMY (MPG) BY INNOVATION

Weight Classes I and II

	Light Duty Annual Mix %
Substitute Diesel	20-35
Lean Burn	10-15
Closed-Loop Stoichiometric	10-15
Turbocharge (gasoline)	5-10
Stratified Charge	15-25
Cooling System	2- 3
Transmission/Engine Matching	
4-Speed Auto with Lock-Up	7-15
Continuously Variable Ratio Transmission (CVRT)	12-30
Radial Tires	2- 3
Aerodynamics (10% reduction in Drag)	1- 2
10% Weight Reduction	2- 3

Weight Class VI – Van Truck Type*

	Duty Cycle	
	Local (%)	Short (%)
● Gas Engine		
Reduce Aero Drag	2	2
Substitute Radial Tires	6	9
Modulated Fan Control	3	4
● Substituted Diesel	60	55
4-Speed Auto. Trans. with Lock-Up**	(0-10)	

*90% of the fuel consumed by this Class VI vehicle is in local service.
**Arthur D. Little, Inc., estimate.

Weight Class VIII – Heavy Duty Trucks

	Dump Truck Duty Cycle		Tractor-Trailer 50,000-lb GVW Duty Cycle		Tractor-Trailer 70,000-lb GVW Duty Cycle	
	Local (%)	Short (%)	Short (%)	Long (%)	Short (%)	Long (%)
Reduce Aero Drag	1	1	1	3	1	2
Substitute Radial Tires	9	6	6	6	9	8
Derate Engine Speed	-0-	1	1	2	<1	4
Modulated Fan	3	4	5	4.5	5	4
Tag Axle	2	2	–	–	2	2
Turbocharge**	(1)	(3)	(3)	(4)	3	4
CVRT**	(10-15)		(10-15)	–	(10-15)	–

**Arthur D. Little, Inc., estimate.

4. A turbocharged, spark-ignited gasoline engine allows use of a smaller size engine for equivalent horsepower, and when properly matched will improve fuel economy. A turbocharger for a gasoline engine must be controlled so that cylinder pressure does not exceed the point of pre-ignition which causes severe knocking. Techniques for reducing the turbocharge pressure ratio during use generally rely on wastegating the exhaust gas, thereby lowering turbine power and pressure ratio. Another presurizing technique is the Comprex* approach which uses the exhaust gas pressure wave to compress the intake air directly. Both techniques have severe economic drawbacks when applied to gasoline engines.

5. The stratified-charge engine, in essence, a lean-burn engine is distinguished from traditional lean-burn concepts by a non-homogeneous charge distribution in the cylinder accomplished by the fuel delivery systems and modifications in the combustion chamber. Recent embodiments of this concept are the Ford "Proco" engine, the Honda "CVCC." and the Texaco stratified charge engine. Each of these assures a rich fuel mixture in the vicinity of the spark and a very lean mixture elsewhere. The stratified charge engine, as a lean mixture engine, has all the combustion attributes of "lean burn" engine but tends to be less prone to mis-firing usually associated with lean-burn concepts.

1.2.3 Cooling System

Cooling system improvements principally involve demand actuation of the fan system. Studies have shown need for fan actuation as low as 2% of total vehicle operating time on interstate diesel truck duty. Class VIII truck fans use between 12 and 20 horsepower, an energy waste under most vehicle operating conditions. The improvements shown in Table 1.4 reflect only the effect of the thermostatic fan. Further improvements, though probably of less impact, could arise from improving the water coolant side of the system. Traditional design of diesel engines calls for large volume rates of coolant through tortuous passageways in the block. Water pump power consumption may reach 10 horsepower in a 290-HP diesel. Though work on reducing coolant power demands is no doubt under way, no published reference to this work was found.

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*Developed and manufactured by the Brown, Boveri & Company, Ltd., Baden, Switzerland.

1.2.4 Power Train Improvements

Included in the power train are both the transmission and the tires, each of which has been examined to assess the improvement potential. Transmission improvements are summarized in Table 1.5 which show the improvements considered for each truck examined. Two are discussed below:

1. The 4- or 5-speed automatic transmission with a torque converter, which is locked up in all but first gear, is considered for all trucks, except the short- and long-haul heavy trucks. A torque converter lockup is a device which bypasses the fluid torque converter element, thus eliminating fluid coupling losses. In the conventional automotive type automatic transmission, torque converters are required to permit startup, torque multiplication for acceleration. for improving driveability and transmission shifts. The 4- or 5 speed automatic transmission was not considered to be competitive with the present 10- to 13-speed manual transmission used in the short- and long-haul heavy trucks.

TABLE 1.5

TRUCK TYPES TO WHICH TRANSMISSION IMPROVEMENTS WERE MADE
(X Denotes Areas Considered for Transmission Improvement)

	Truck Duty Types					
	Light I & II	Medium VI		Heavy VIII		
Improvement	Annual Mix	Local	Short	Local	Short	Long
4 or 5 speed auto with lockup	x	x	x			
Continuously Variable Ratio Transmission CVRT	x	–	–	x	x	–
Baseline Transmission Normally Used	3- Speed Automatic	4-Speed Manual		10-Speed Manual		

2. The constantly variable ratio transmission (CVRT) provides an infinite number of gear ratios within a certain range. The CVRT was not examined for the medium-duty truck since there is no known development under way for such a truck class. However, work under EPA sponsorship is under way to develop a CVRT for automotive use. This device if successful could penetrate the light-duty truck field. Limited versions of heavy-duty CVRT transmissions* are available for local and short use in the heavy-duty fleet.

1.2.4.1 Differential Gear Losses

As can be seen in Figures 1.2-1.5 the losses in the rear axle differential range from 3% to 5%. It may be possible to reduce this by better manufacturing and assembly procedures; however, this possibility was not considered for this study.

1.2.4.2 Substitution of Radial Tires for Bias Ply Tires

Radial tires have less rolling resistance than bias ply tires which results in less power consumption which accounts for fuel economy gains of between 5 to 9% depending on type of truck and duty cycle.

Reported results indicate that radial tire life may be as much as 50-75% greater than bias ply tire life depending on type of truck and duty.

1.2.5 Aerodynamic Improvements

We considered several improvements in body design to achieve better fuel economy. In the case of the light-duty truck, it was felt from discussions with truck manufacturers that aerodynamic styling improvements could lead to a 10% drag coefficient reduction. In the heavier trucks, devices providing reduced turbulence between cab and semi-trailer were considered to decrease the drag as well. The innovations reported in this paper are those most adaptable to the fleet as a whole.

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*Cummins Sunstrand Responder.

1.2.6 Weight Reduction

A weight reduction of 10% of the vehicle weight was considered for the light-duty truck. Weight reduction was not specifically considered for the medium- and heavy-duty trucks, since it was assumed that for every pound of reduced vehicle weight an additional pound of cargo would be substituted. Such consideration led to efficiency studies based on productivity defined as gallons consumed per cargo ton-mile.[1]

1.3 IMPROVEMENT COST TO BREAK EVEN

Each individual innovation was assessed for cost effectiveness using the following inputs:

1. Incremental initial cost of modification

2. Incremental maintenance and repair cost to first owner of vehicle where the following parameters were used:

	Miles	**Years**
Light Duty (used for personal vehicle)	50,000	3
Medium Duty		
Local	50,000	5
Short	50,000	5
Heavy Duty		
Local	100,000	5
Short	250,000	5
Long	500,000	5

3. The total incremental cost (1 plus 2).

4. Total savings of fuel in gallons due to modification.

5. Breakeven fuel cost in $ per gallon was then computed dividing 3 by 4. The results of this are shown in Figures 1.6 through 1.11.

6. Consideration was not given to the incremental value of these modifications on a resale basis because these costs would have to be established in the market place rather than through production cost markups.

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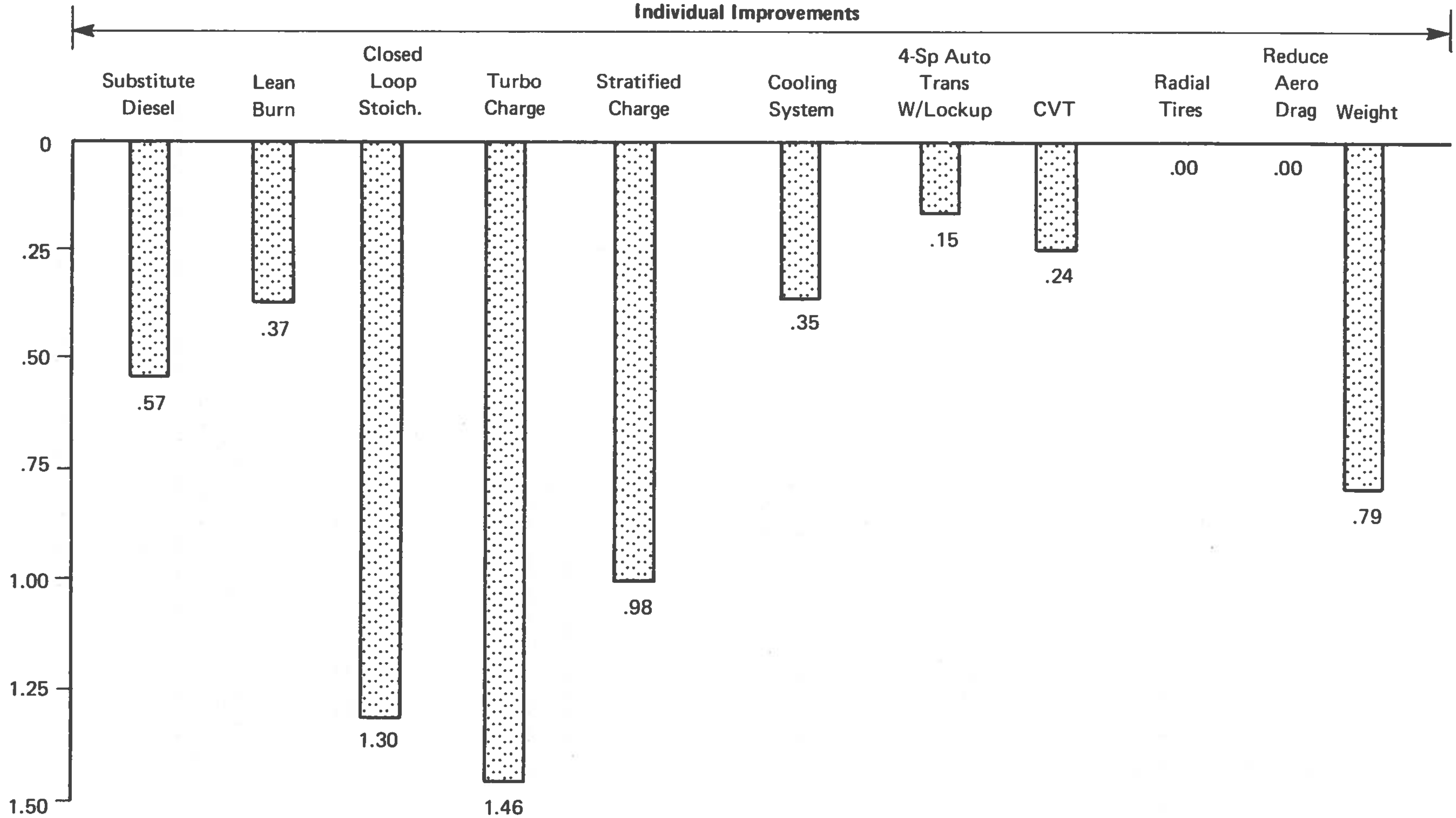
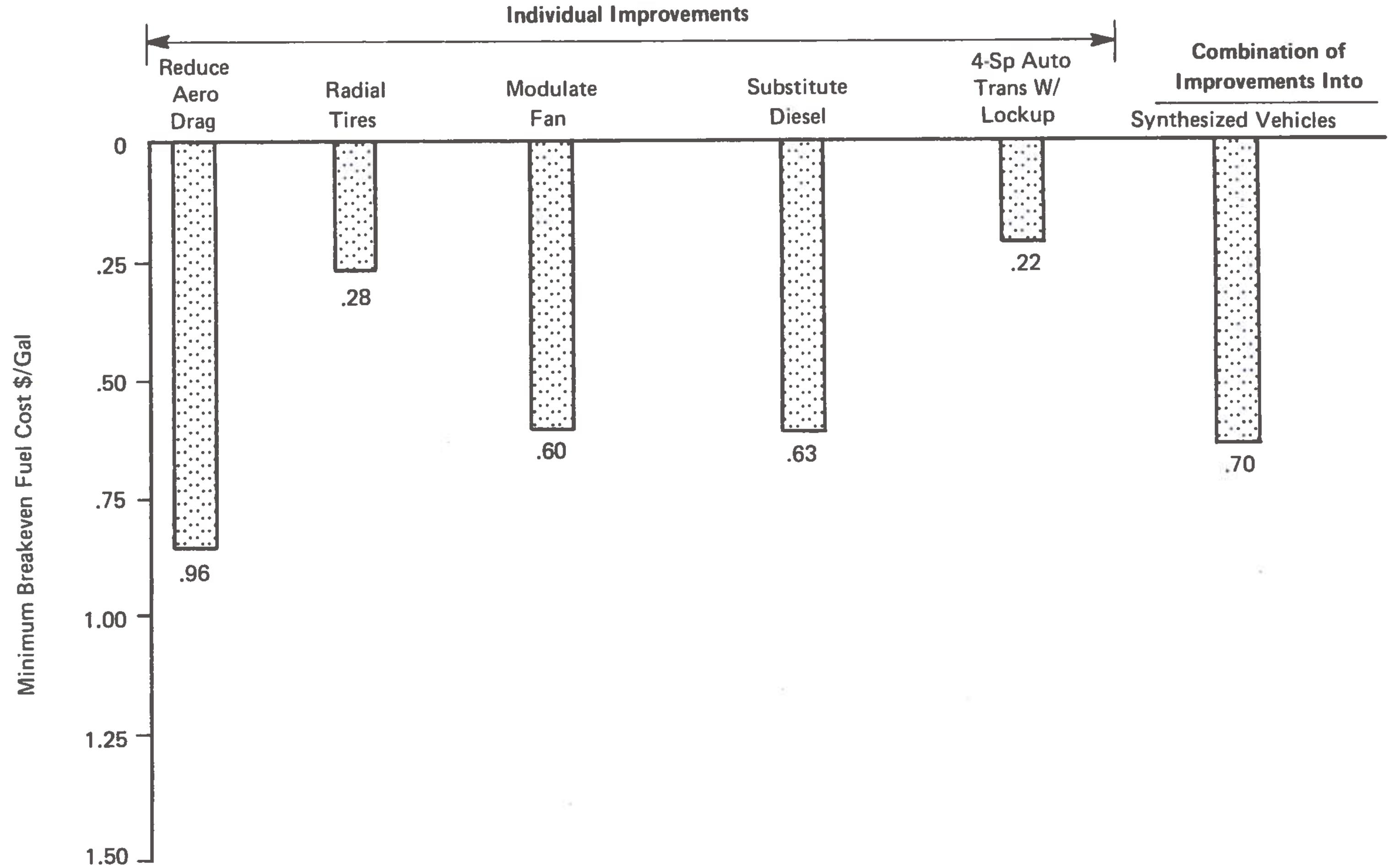
1. "Study of Potential for Motor Vehicle Fuel Economy Improvement, Truck and Bus Panel Report," Report No. DOT-TSC-UST-75-16 by U.S. DOT and U.S. EPA, January 10, 1975, PB241777/AS, 112 pp., 20 May, 1975.



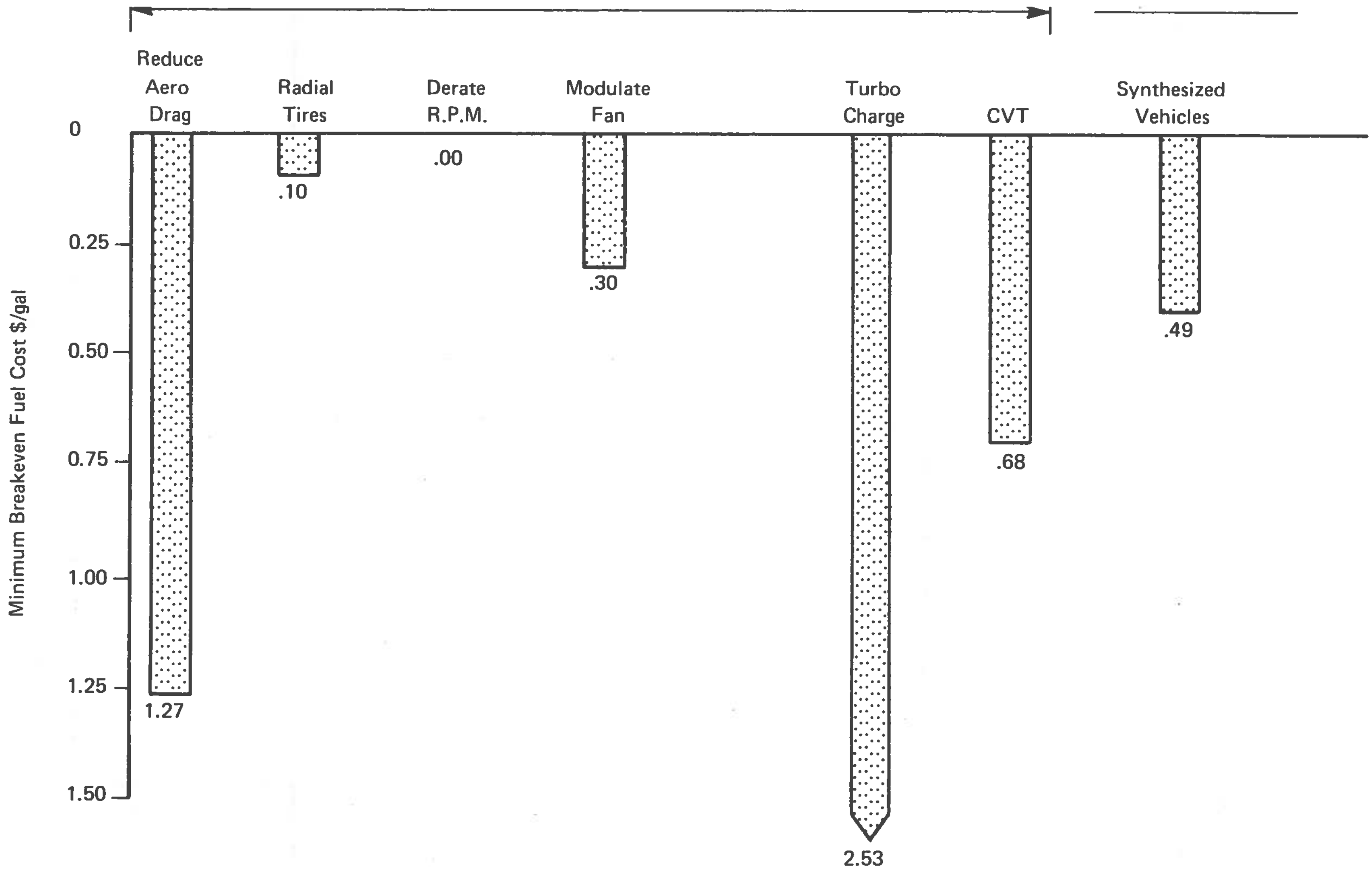
Based on: 1. Annual driving cycle when used as a personal vehicle is a mixture of 35% urban (FTP) 65% steady state 30-70 mph
2. 3 years = 50,000 miles of use (first owner)
3. Cost is at 0% discount rate
4. Minimum breakeven fuel cost is cost per gallon that will generate sufficient savings to offset all incremental cost for the improvement

FIGURE 1.6 WEIGHT CLASS I AND II — LIGHT DUTY PICK-UP TRUCK



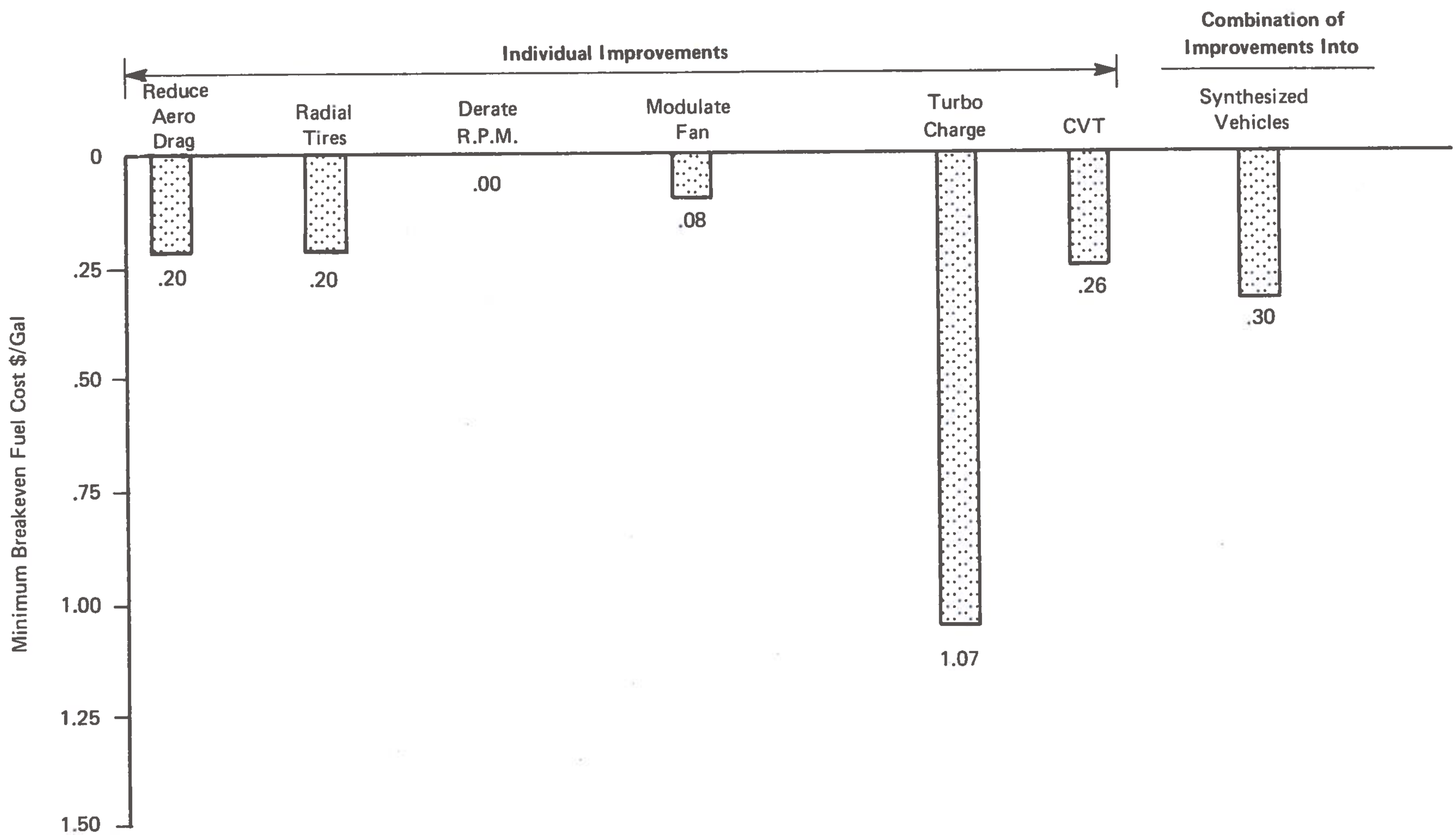
Based on: 1. Local Duty Cycle is Comparable to 100% F.T.P. for Light-Duty Vehicles
2. 5 Years = 50,000 Miles of Use (First Owner)
3. Cost is at 0% Discount Rate
4. Minimum Breakeven Fuel Cost is Cost per Gallon that will Generate Sufficient Savings to Offset all Incremental Cost for the Improvement

FIGURE 1.7 WEIGHT CLASS VI – VAN TYPE – LOCAL-DUTY CYCLE

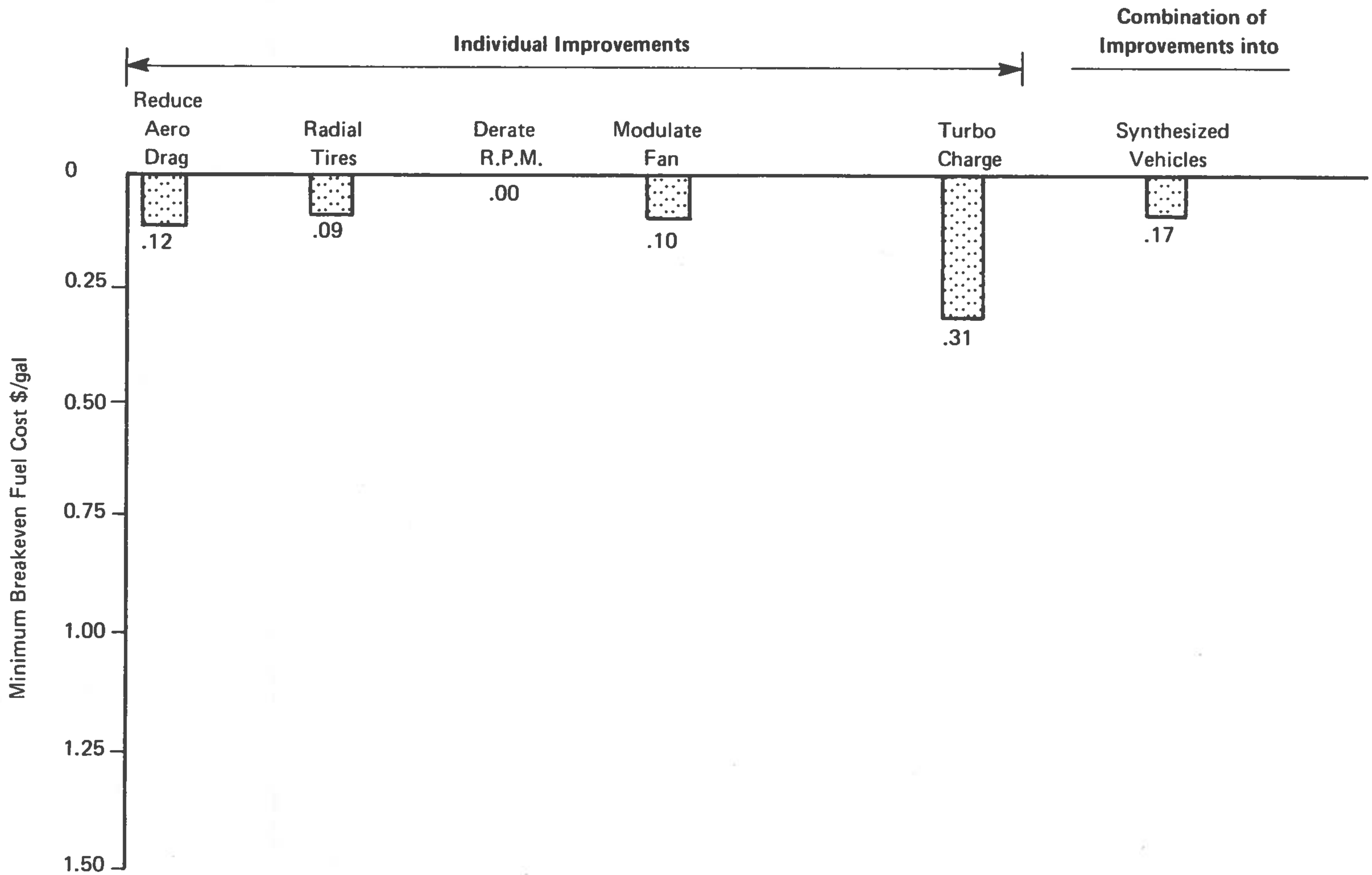


Based on:
1. Local duty cycle is comparable to 100% FTP for light duty vehicles
2. 5 years = 100,000 miles of use (first owner)
3. Cost is at 0% discount rate
4. Minimum breakeven fuel cost is cost per gallon that will generate sufficient savings to offset all incremental cost for the improvement

FIGURE 1.8 WEIGHT CLASS VIII – DUMP TRUCK – LOCAL-DUTY CYCLE

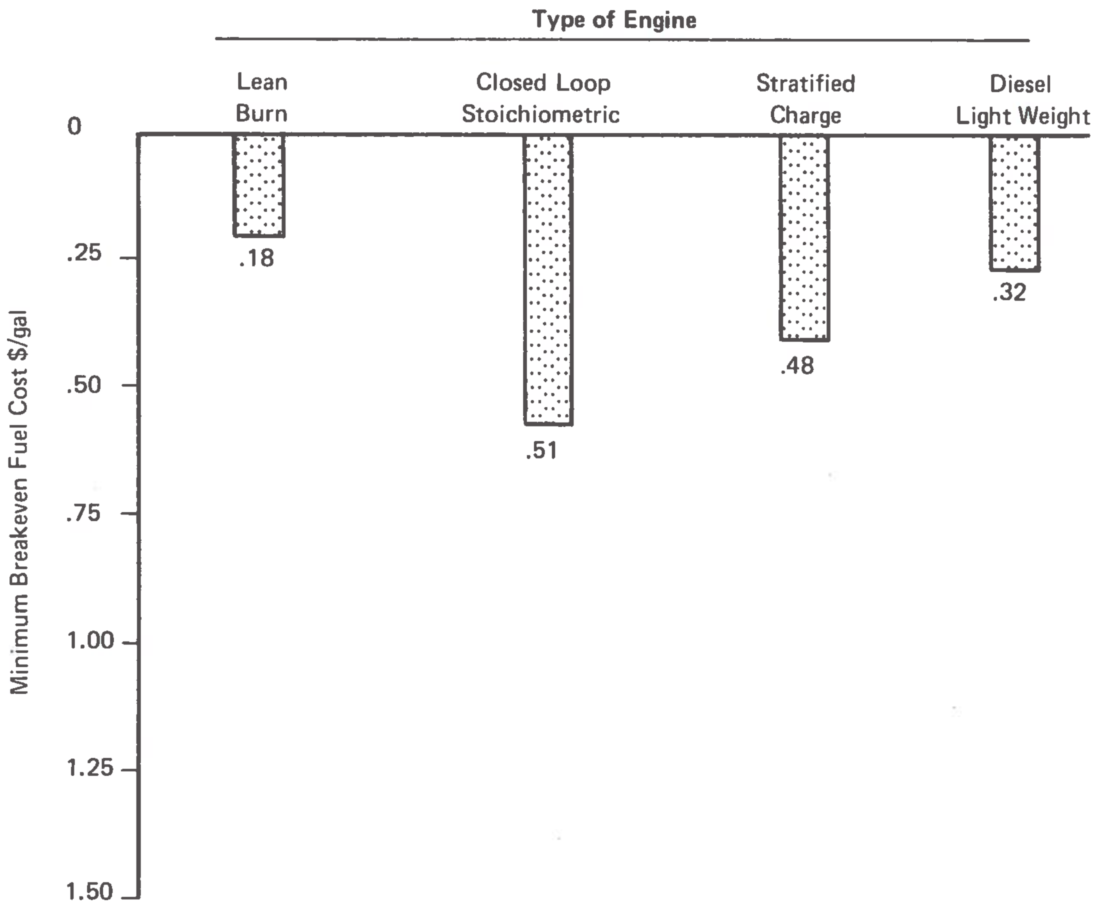


Based on:
1. Short Trip Duty Cycle is Round Trip from Base Returning at Night with a Mixture of Urban, Suburban and Highway Driving Between Cities
2. 5 Years = 250,000 Miles of Use (First Owner)
3. Cost is at 0% Discount Rate
4. Minimum Breakeven Fuel Cost is Cost per Gallon that will Generate Sufficient Savings to Offset all Incremental Cost for the Improvement



Based on:
1. Long trip duty cycle-one-way-line haul high speed freight delivery
2. 5 years = 500,000 miles of use (first owner)
3. Cost is at 0% discount rate
4. Minimum breakeven fuel cost is cost per gallon that will generate sufficient savings to offset all incremental cost for the improvement

FIGURE 1.10 WEIGHT CLASS VIII – 70,000 LBS TRACTOR TRAILER – LONG DUTY-CYCLE



Includes: Cooling System
4-speed Auto. Transmission
Radial Tires
Aerodynamic Drag Reduction
Weight Reduction

Based on:
1. Annual driving cycle when used as a personal vehicle, is a mixture of 35% urban (FTP) 65% steady state 30-70 mph
2. 3 years = 50,000 miles of use (first owner)
3. Cost is at 0% discount rate
4. Minimum breakeven fuel cost is cost per gallon that will generate sufficient savings to offset all incremental cost for the improvement

FIGURE 1.11 WEIGHT CLASS I AND II – LIGHT DUTY PICK-UP TRUCK – SYNTHESIZED VEHICLES USING COMBINATION OF INDIVIDUAL IMPROVEMENTS

1.4 SYNTHESIZED VEHICLES (Combined Innovations)

Figures 1.6 through 1.10 also show the results of the simulations and cost effectiveness figures of synthesized vehicles. Those innovations, combined to form the synthesized vehicle, were selected from the list of individual improvements on the basis of breakeven cost. The innovations which were combined to make up the respective vehicles are given in Table 1.6 and Figure 1.11 (for light-duty Class I and II).

TABLE 1.6

PERCENT IMPROVEMENT IN FUEL ECONOMY WITH OPTIMUM COMBINATION OF OPTIONS

Class	Driving Cycle	Specific Options	% Gain in Fuel Economy (MPG)
I & II	Annual Mix 35% FTP – 65% 30-70MPH when used as a personal vehicle	• Improved S.I. Engine or Diesel Substitution • 4-sp Auto Trans • Radial Tires • Modulated Fan • Reduced Weight	25-40
VI	Local	• Diesel Engine Substitution • Modulated Fan • 4-sp Auto Trans • Radial Tires	70-80
VIII	Local	• Derated RPM • Modulated Fan • CVRT	15-20
VIII	Short	• Radial Tires • Derated RPM • Modulated Fan • Tag Axle • CVRT • Reduced Aero Drag	20-30
VIII	Long	• Radial Tires • Derated RPM • Modulated Fan • Tag Axle • Reduced Aero Drag • Turbocharged	18-23

1.5 CONCLUSIONS AND RECOMMENDATIONS

1.5.1 General Conclusions and Recommendations

We conclude that for the classes of trucks (I, II, VI & VIII) which consume the majority of fuel (85%), improvements can be made in fuel economy in a reliable, cost-effective manner within approximately 10 years. Table 1.7 illustrates the improvement potential for the 1975-1980 period and 1980-1985 period. All these improvements are based on established technology and therefore carry a low degree of risk and are being used or could be introduced very quickly. However, great emphasis must be placed on the development of extremely reliable devices which can be maintained and repaired by the truck driver and mechanics as presently trained and equipped.

While fuel savings are very important to the Class VI and VIII truck operator, equipment reliability, maintainability, and repairability are of more importance because of the significant leverage these factors have on the reduction of downtime and subsequent loss of income.

TABLE 1.7

SUMMARY OF FUEL ECONOMY GAIN

Class of Truck	Type of Duty	1975-1980 Fuel Economy Gain %	1975-1980 Breakeven Cost $/Gal*	1980-1985 Fuel Economy Gain %	1980-1985 Breakeven Cost $/Gal*
I & II	Annual Mix of local, short, long	10-15 (Gas)	.18	20-35 (Diesel)	.32
VI	Local	15-25 (Gas)	.38	70-80 (Diesel)	.70
VIII	Local	15-20	.49	–	–
	Short	20-30	.27	–	–
	Long	18-23	.18	–	–

$$* \quad \frac{\text{Total Incremental \$ for Improvement}}{\text{Gallons Saved by the Improvement}}$$

Truck owner/operators unlike the average automobile owner in many cases repair their units themselves to reduce out-of-pocket expenses, without relying or paying for on-road servicing with attendant downtime. The present owner/operator is experienced in operation, maintenance, and the repair of present equipment which is basically mechanical in nature. Therefore owners will be slow in equipping fleets with trucks using highly sophisticated electro-mechanical devices.

Devices which require heavy investment in repair or maintenance equipment will be slowly accepted by the small fleets or owner/operators. As an example, some wheel designs for tubeless bias ply or radial tires require changing equipment costing many thousands of dollars which inhibits use of such tires by small fleets or single owner/operators.

Many large fleet owners avail themselves of advanced business methods using computers for analyzing operating costs, deciding when to replace equipment, and aiding engineering with vehicle specifications for a particular set of operating conditions. These techniques are not used by the single owner/operator because of his inability to afford such sophistication.

Recommendations

- The truck manufacturing industry must continue to meet the challenge to develop and produce reliable fuel efficient devices at a price that allows their cost effective application to the commercial vehicle user industry.

- The industry, perhaps with governmental assistance, should develop methods for transferring technical and economic information on fuel saving equipment and its use to the truck owners, particularly to the small fleet of owner/operator. This information should be used at the time of initial or subsequent purchase, for maintainance and repairs, and for training and upgrading of the mechanics' skills.

- The Society of Automotive Engineers in cooperation with the Department of Transportation has begun a comprehensive program to investigate and improve the knowledge and status in the following areas:

— Vehicle Classification and Cycles

Vehicle Classification — local, short and long haul

Determination of vehicle types

Measurement of fuel economy should it be MPG, ton-MPG or something else

- Techniques for component evaluation

  Basic engine modification
  Fan and accessories
  Aerodynamics
  Rolling resistance
  Driveline components and modifications

- Measurement technique for total vehicle simulation

  Total vehicle testing
  Correlation with other tests and/or computer results

We applaud this effort and recommend that it continue and be used as a major input to business and governmental decisions vis-à-vis energy conservation implementation.

1.5.2 Conclusions and Recommendations Regarding Specific Technological Improvement

1.5.2.1 Power Plant Improvement

For Classes I and II the lean burn concept offers a near-term cost-effective solution to fuel economy. Longer term gains can be made providing that a light weight, light duty diesel is developed for automotive use.

- To promote these concepts the emission standards for NO_x must be set at 2 grams/mile.

Class VI can benefit greatly from a low cost diesel specifically developed for its duty cycle and operation. However, at present it does not appear that major effort is being applied in this area owing to the lack of incentive for the owner to make an investment which is unlikely to be returned within his ownership.

Recommendations

- The Federal government should study its *own* needs as well as those of state and local governments, to determine if a large enough market exists for a manufacturer to launch engine development and manufacture. Such applications should include military, post office, school transportation, etc.

- Studies should be made to determine if a suitable market base could be established if other than trucking industry companies using this class truck could more economically *lease* a diesel truck than outright purchase of a gasoline powered truck.

Class VIII truck owners know the value of turbocharging and are using this approach more and more. Similarly the so-called "high torque" rise diesel engine has been given a great deal of attention recently.

Recommendations

- Continued effort and attention should be given to turbocharged high torque rise diesel engines for Class VIII. Manufacturer should develop data and information on fuel saving, operating experience and cost/benefits for ready assimilation by owner/operators.

1.5.2.2 Radial Tires

Most classes of trucks benefit from the use of radial tires, in fuel saving, total life-cycle costs, and ease of driver handling and factual data on the benefits are now becoming available to the truck owner to help him make informed business decisions as to their purchase.

- We recommend that the tire industry concentrate on collecting data and providing to the truck owners information for all types of tire operating conditions. Such information should include retreading, tire life, maintenance equipment, puncture resistance, as well as fuel saving.

1.5.2.3 Transmissions and Drive Train

Much attention is now being given to automatic transmissions which more accurately match engine operation to road load requirements. These transmissions, when developed, will improve fuel economy, require less driver skills, and reduce driver fatigue.

- We recommend that in the development of these transmissions, particularly for Classes VI and VIII, full consideration be given to ease of maintenance, simplicity of repair, and in particular, equal or improved reliability over manual transmission. For full acceptance by the trucking industry, changes should be introduced gradually with emphasis on overall operational cost rather than fuel savings alone.

- As these transmissions gain favor, more sophisticated feedback systems can be developed to permit more accurate matching of engine speed to road load.

- We recommend that examinations be made into the economic justification of possible fractional improvements in gear and bearing efficiency in Class VIII truck differentials. Roughly 3% of mechanical energy is lost in the remainder of the drive train.

1.5.2.4 Cooling Systems

The modulated fan clutch has reached a stage of development where many vehicle owners will accept its reliability in addition to its fuel economy benefits.

- We recommend, as a next step, that engine cooling be analyzed as a complete system that is:

  - Matching of radiator configuration and positioning in relation to the engine.

  - Determine if parasitic horsepower losses can be reduced by optimizing, together, both air side and water side coolant flow systems.

  - Oil cooler design must be integrated with the total cooling system.

1.5.2.5 Aerodynamic Drag Reduction

Devices are currently available for reducing drag and improving fuel economy. However, they are add-on devices which solve specific fleet problems – we conclude that substantive gains in this area are limited by present height, length, and width, legislated restrictions. Some states include the dimensions of the devices in the overall trailer dimensions, e.g., locating the device on the front of the trailer would extend its length but not the overall combination length.

- We recommend that studies be made to determine what tradeoffs could be made between dimensional regulations, aerodynamics, cargo space, and passing turbulence effects for the entire truck-trailer system.

- If such studies conclude that dimensional changes are warranted, then we recommend that the impact of such changes upon the total transportation system be evaluated.

1.5.2.6 Improved Lubricants

Reduction in mechanical friction losses has been demonstrated with special synthetic lubricants (2-4%).

- We recommend continued research in this area to both reduce the cost of these materials and demonstrate their reliability under all operating conditions.

2. WHY STUDY TRUCKS

In 1973 trucks consumed 725 million barrels of petroleum representing 12 to 15 percent of the total petroleum product consumed in the United States. The concept of the President's Project Independence is to reduce the consumption of petroleum products to guarantee both economic and political freedom. A 40% reduction in fuel consumed by the U.S. truck fleet will mean a 4-5% reduction in petroleum consumption. Reduced truck fuel consumption is clearly not the whole answer but it is part of the solution. Recognizing this, the Department of Transportation initiated this study to examine means of reducing truck fuel consumption and bring us a step closer to the goals of energy independence. There are many approaches to reducing truck fuel consumption. Presently there is a move in Congress to increase weight limitations on trucks (culminating in new legislation at the time of this writing. January 6, 1975). While this legislation does not affect light duty trucks in terms of fuel economy, the heavy duty commodity carrier will be affected substantially. For the heavy duty truck fleet heavier loads means fewer trips, and though the fuel consumption per trip is slightly increased, the net effect is to reduce the number of gallons consumed to move the required cargo. Other approaches have been implemented or suggested to reduce fuel consumption; they include: reduction of speed limits, driver education, tax penalties based on engine horsepower, increased gasoline tax and other regulatory action. This study concentrates on reducing fuel consumption by technological improvements on the vehicle system itself. Engine and drivetrain developments are considered here along with aerodynamic and tire considerations – all examined for their impact on fuel consumption.

2.1 WHAT IS A TRUCK

When asked casually about trucks, most people feel certain that they know what trucks are. However under closer examination it is found that, unlike automobiles used primarily for personal transportation which may vary somewhat in weight, seating capacity, body style and engine displacement, the trucks on America's roads come in many shapes and sizes, and are used for many different purposes. It is not sufficient to speak of a truck alone without further qualifications. A simple diagram can explain some of the inadequacies of the nomenclature for trucks. Figure 2.1 shows silhouettes for various vehicles that make up only a few of the shapes belonging to the currently accepted eight truck weight classes. In addition there are a variety of urban/suburban delivery trucks, fuel delivery trucks, over-the-road vans and tractor semitrailer combinations and recreational vehicles. We therefore established a method for selecting those types and classification of trucks which account for a major percentage of fuel consumption.

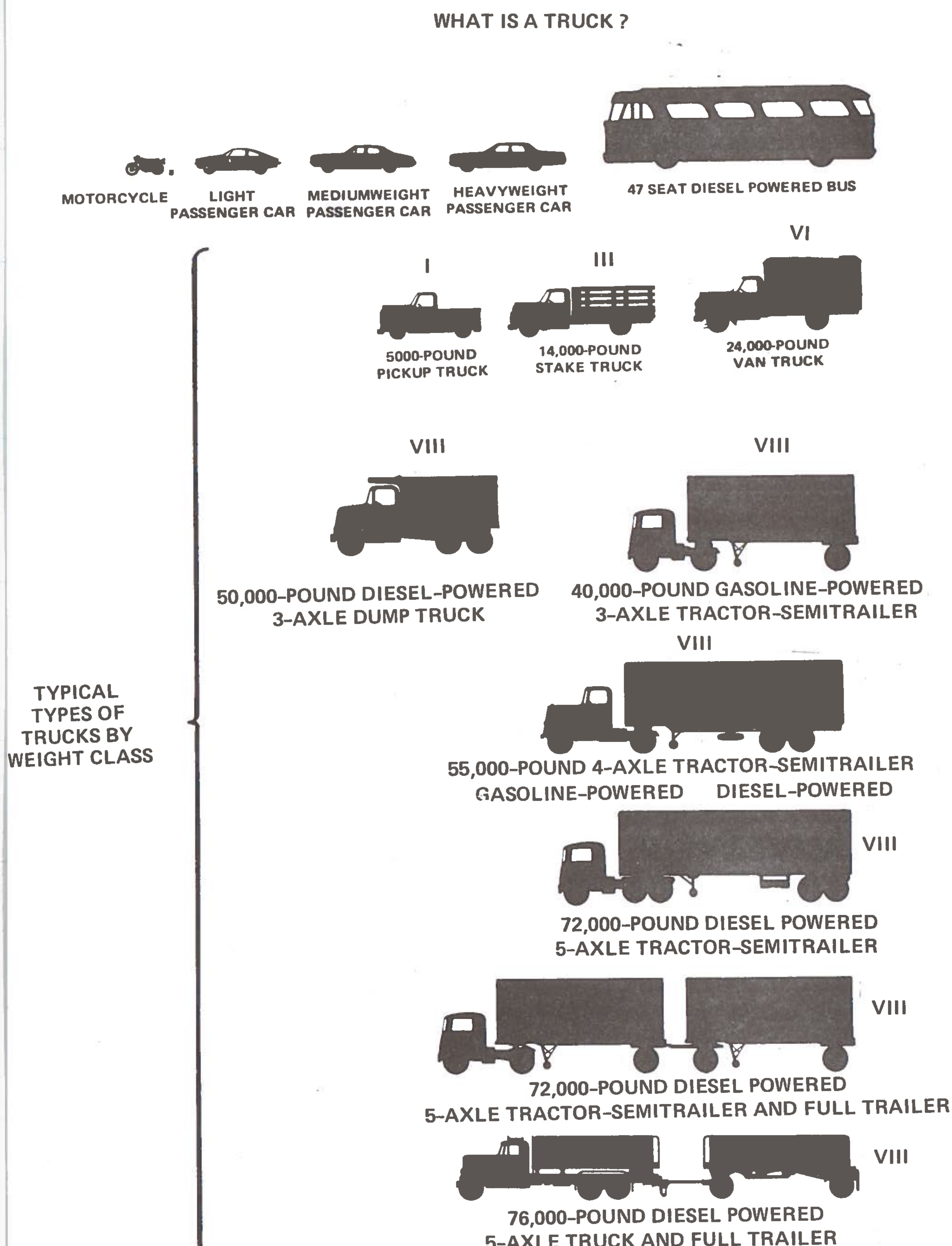


FIGURE 2.1 SILHOUETTE OF TRUCK TYPES

First of all, let us examine the major elements of a truck. Figure 2.2 shows a chassis including engine, drivetrain, front and rear axle and suspension. This chassis is for a gasoline medium-duty truck. Each truck sold in the United States has a design axle loading. In a particular model several types of axles may be available differing in weight carrying capacity. Therefore, trucks may be classed as to the number of tires and the axle weight rating. For example, a heavy-duty dump truck may not provide sufficient load capability with only a single dual tired rear axle and a tandem rear axle as shown in Figure 2.3 is used. The particular rear axle shown in the figure is a dual-driven tandem rear axle in that both axles are drive axles. In other cases, tandem rear axles are available with only one driven axle. These variations in the design of the truck lead to a further classification based on a number of axles and the number of driven axles. All told, a variety of specifications are necessary in order to completely describe a truck. A summary of standard nomenclature for truck description is given in Table 2.1.

As a further complication, major truck manufacturers offer a wide variety of options for all of their trucks. The options for lighter weight trucks are predominantly the manufacturer's own components. In the heavier vehicle categories, the manufacturer will likely fabricate only the frame and the cab, the engine, transmission, axle and suspension all being supplied to the truck manufacturer by components manufacturers. Table 2.2 illustrates the variations made available by a single manufacturer for a fleet of trucks, 10,000 pounds gross vehicle weight and above. The numbers in the Wheelbase (WB) column indicate the variety of different wheel bases available for each model vehicle. Clearly classifications based on individual components would be unmanageable and lead to thousands of categories. For the purposes of this study, classification by vehicle use and weight have proven sufficient. In addition reference vehicles incorporating the most popularly used combinations of components have been developed for fuel economy synthesis studies for this report.

2.2 APPROACH TO STUDY

The dissemination of information on the fuel saving effects of various vehicle modifications or 'add-on' devices has been clouded in the informed buyer's mind by sales departments of some manufacturers of these devices, with over-optimistic benefit predictions. Evaluation of the fuel reduction potential of many modifications or devices is further complicated by the sensitivity to the speed/load regime (drive cycle) in which the vehicle is operated. Also some innovations have significant fuel reduction potential but severely limit the usefulness for which the truck was developed. Therefore, the advantages and disadvantages of the improvements must be uncovered. The following is the approach used to examine the potential of fuel economy improvements for this report:

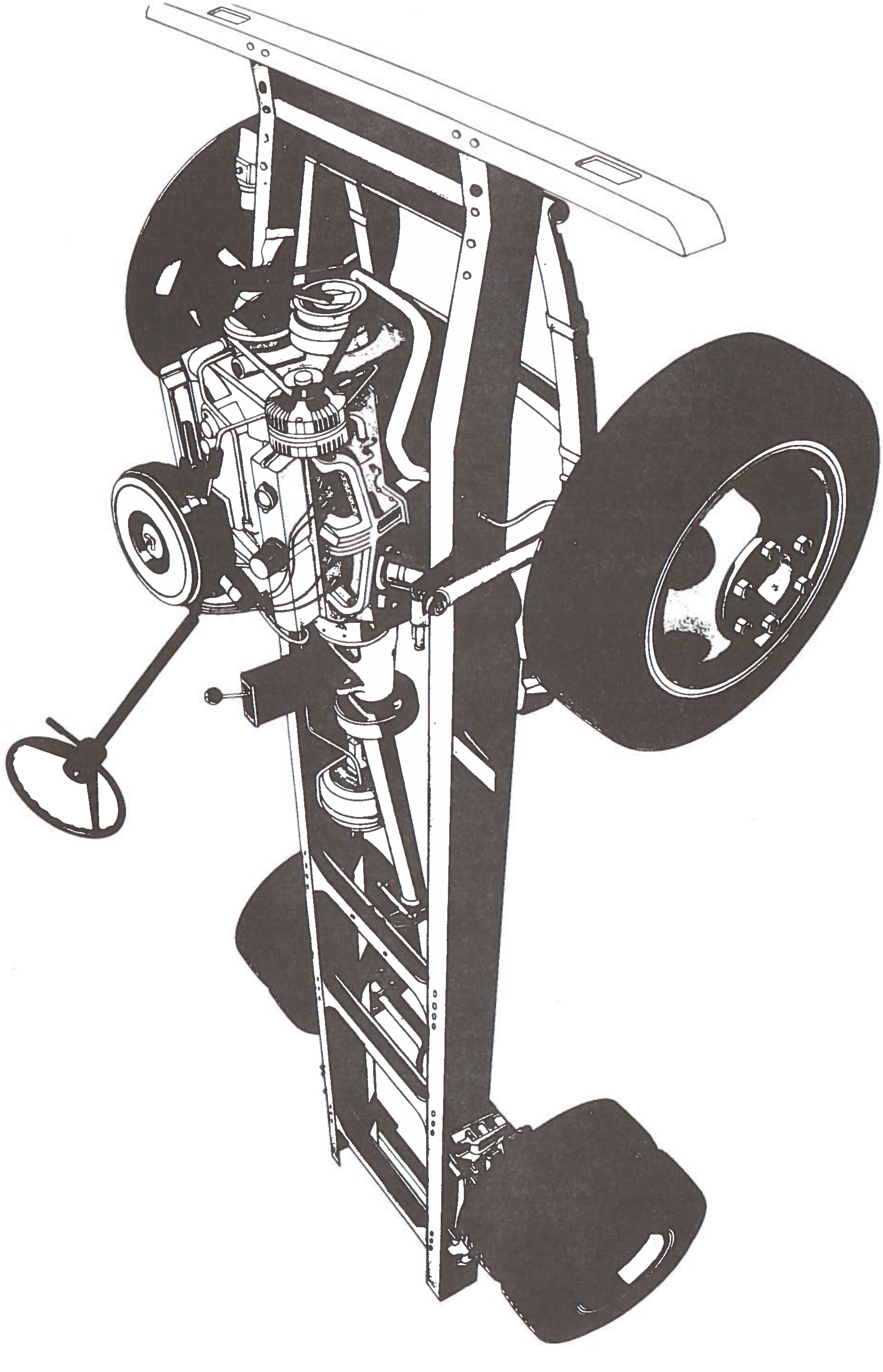


FIGURE 2.2 A TYPICAL MEDIUM DUTY TRUCK WITH DUAL TIRED REAR AXLE

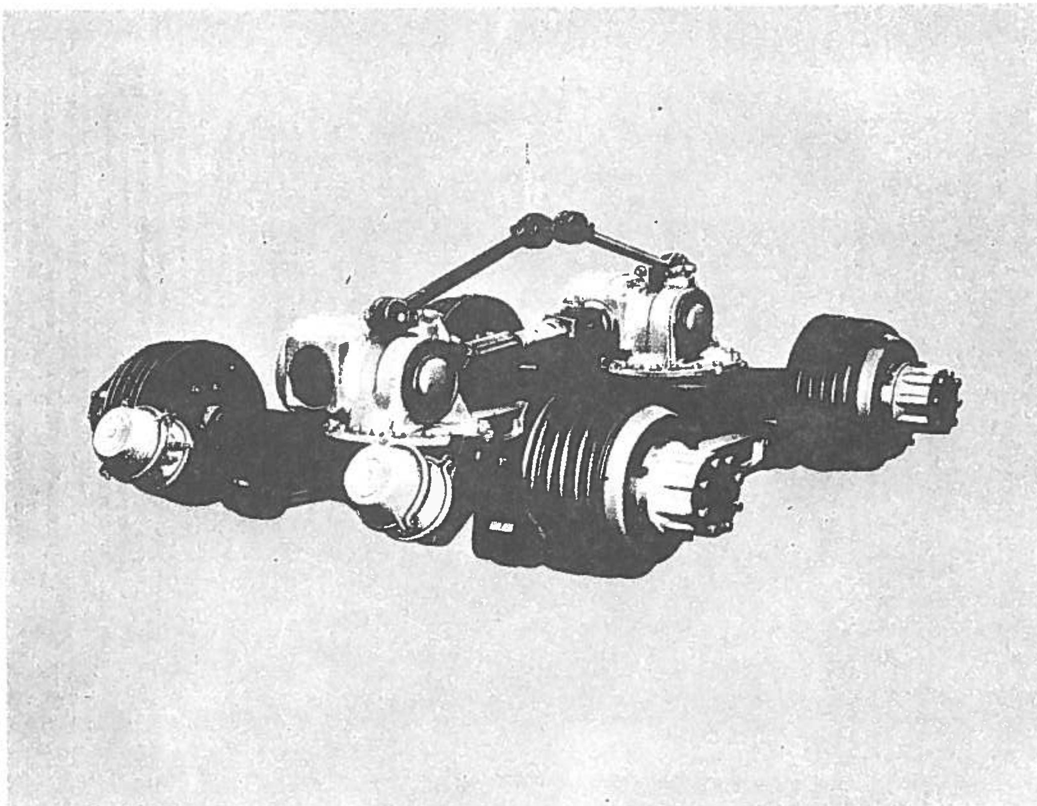


FIGURE 2.3 A TYPICAL TANDEM REAR AXLE

TABLE 2.1

STANDARD VEHICLE NOMENCLATURE VEHICLE CONFIGURATION

Abbreviation	Description
4x2	2 axle truck, 1 drive axle
6x2	3 axle truck, 1 drive axle
6x4	3 axle truck, 2 drive axles
8x4	4 axle truck, 2 drive axles
8x6	4 axle truck, 3 drive axles
4x2-1S	2 axle tractor (4x2), 1 axle semitrailer
4x2-2S	2 axle tractor (4x2), 2 axles semitrailer
4x2-1S-2T	2 axle tractor (4x2), short doubles
6x2-2S	3 axle tractor (6x2), 2 axle semitrailer
6x4-2S	3 axle tractor (6x4), 2 axle semitrailer
6x4-2S-4T	3 axle tractor (6x4), long dlbs, dbl dolly
4x2-2T	2 axle truck (4x2), 2 axle full trailer
6x2-2T	3 axle truck (6x2), 2 axle full trailer
6x2-3T	3 axle truck (6x2), 3 axle full trailer
6x4-2T	3 axle truck (6x4), 2 axle full trailer
6x4-3T	3 axle truck (6x4), 3 axle full trailer

VEHICLE WEIGHT CLASSIFICATION

Class	Weight Range
I	0 – 6000#
II	6001 – 10000
III	10001 – 14000
IV	14001 – 16000
V	16001 – 19500
VI	19501 – 26000
VII	26001 – 33000
VIII	33001 – over

TABLE 2.2

VARIATIONS AVAILABLE FOR EACH COMPONENT

Chassis	Wheel Base (WB)	Number of Gross Vehicle Weight Ratings	Max Gross Load	Axle Ratio	Tire Size	Engine	Trans	Aux. Trans.
10,001 GVW & Above								
1510	2	2		9	2	5	3	
1600	8	4	4	16	4	1	5	
1600 (4x4)	4	2		1	2	1	5	
1700	9	4	4	14	3	2	5	
1700 (4x4)	4	2		2	2	2	5	
1750	9	4	1	14	3	1	5	
1800	9	4	2	14	3	3	8	
1850	9	5	2	10	2	2	10	
F-1800	4	4	2	9	3	3	7	5
F-1850	4	4		6	5	3	7	5
CO-1610A	9	4	3	14	3	1	5	
CO-1710A	9	4		14	3	2	8	
CO-1750A	9	4	3	14	2	1	4	
CO-1810A	9	4	3	14	3	2	6	
CO-1850A	9	4	3	14	2	2	4	
COF-1810A	9	4	3	18	3	2	5	
CO-1910A	8	4	1	16	2	6	10	
CO-1950A	8	4	1	14	2	3	10	
COF-1910A	8	4	2	18	2	6	10	
COF-1950A	8	4	2	18	2	3	10	
1910A	5	4	2	20	5	4	11	
2010A	5	4	2	20	5	5	12	2
2050A	5	4		20	5	4	15	3
2110A	5	4	2	20	4	4	17	3
F-1910A	5	4	2	33	5	4	12	4
F-2010A	5	4	1	33	7	7	18	7
F-2050A	5	4		14	7	2	16	7
2000 D	3	4	1	22	4	5	11	
F-2000D	5	4	1	27	4	5	15	3
2070A	4	4	1	16	4	8	6	
F-2070A	7	4	1	26	6	8	7	2
4270	3	3	1	18	4	6	14	
4370	3	3	1	18	4	14	14	
1-4370	6	4	3	33	4	14	15	3
CO-4070A	5	3	1	14	4	17	8	
COF-4070A	4	4	1	27	4	17	9	
5050 (4x4)	3	2		6	5	3	6	
5070 (4x4)	3	2		6	5	17	4	
F-5050 (6x4)	6	4		26	4	3	7	5
F-5050 (6x6)	4	3		11	4	3	5	
F-5070 (6x4)	6	4		23	4	18	15	2

1. Examine fleet fuel consumption and select those vehicle types which account for more than 70% of truck fuel consumption.

2. Contact manufacturers of these vehicle types for a comprehensive description of the vehicle.

3. Develop a driving cycle for each reference vehicle and analytically simulate the selected vehicle performance to establish baseline fuel consumption information.

4. Examine this baseline information to determine the most productive areas for fuel conservation.

5. Develop a list of improvements to lower the energy consumption focusing on the partitioning of vehicle energy usage determined in 4 above.

6. Contact manufacturers for detailed engineering information on innovations.

7. Simulate the reference vehicle performance with innovations individually and in combination.

8. Summarize findings.

The following section highlights the method used to examine the economic constraints considered when adapting the innovations.

2.3 MARKET AND ECONOMIC CONSTRAINTS

The requirements of the user/market places constraints on acceptance of an individual improvement. Since in general purchasers of trucks are composed of two groups, those who purchase trucks for personal use (Class I and II) and those who purchase them as a business investment, either fleet owners or owner/operators (Class III through VIII). The acceptance of an improvement by a purchaser depend on its ability to meet a personal need or business requirement.

Vehicles purchased for personal use are generally those in weight Class I and II. They are used essentially as private vehicles whose additional carrying capability is a convenience. By determining the additional initial investment and the additional maintenance costs over the life of an improvement, a breakeven fuel cost can be established based on the fuel saved over the vehicle lifetime divided into total incremental cost for the improvement.

Vehicles in weight classes III through VIII are purchased by either fleet owners or owner/operators. The economic evaluation of the fuel economy improvement is based on operating the truck as a business enterprise returning a profit. The total operating cost for a heavy duty line haul Class VIII vehicle can be broken down in the following cost groups (Table 2.3):

TABLE 2.3

REPRESENTATIVE COST BREAKDOWN FOR HEAVY DUTY TRUCK OPERATOR

	% of Total Operating Cost
Repair and Maintenance Costs	28
Fuel Costs	5
Labor Cost (Driver's wage and subsistence)	26
Indirect and Overhead	22
Depreciation and Interest	19

Source: Alan M. Voorhees and Associates, Inc. *An Analysis of the Economics of Truck Sizes and Weights for Motor Vehicles Manufactures Association,* McLean, Va. February 1973.

While the improvement will result in a decrease in the fuel portion of the operating costs, there may be further effects in the other areas of operating costs. The reliability or durability of the improvement may result in a change up or down in overall repair and maintenance costs. The initial assumed requirements for a viable improvement include the stipulation that the performance of the vehicle will not be materially changed, therefore the total trip time should not change significantly.

There may be a net change in replacement costs of the improvement (related to the initial costs) if its lifetime is less than that of the vehicle.

Cost considerations were subdivided into three categories: change in initial cost, total operating costs, and change in replacement costs. By combining these costs, a breakeven fuel cost was established, based on an average truck life and average annual mileage. This is obtained by dividing the total incremental cost for the improvement by the gallons of fuel saved expressed in dollars per gallon ($/gal.).

When an improvement is incorporated in a vehicle, it will affect both fuel consumption and economic productivity over the course of the vehicle's lifetime. Thus, for the improvement to be beneficial, the savings that accrue over any period – up to and including the life expectancy of the vehicle – should be greater than the initial investment in the improvement and the interest changes on the incremental increase in capital costs.

The relationships between the initial cost and the other related costs and/or benefits vary as a function of the improved fuel economy for each improvement or combination of improvements. The savings generated are directly proportional to the cost of fuel, i.e., the higher the cost of fuel, the greater the potential savings. Table 6.1 of Chapter VI describes the specific payback period baseline parameters which were used to measure cost effectiveness for each class of vehicle.

For each vehicle the following parameters were determined by analyzing how the average vehicle was used.

1. *Payback period in years* – the number of years of first ownership or total depreciation period

2. *Average vehicle miles per year*

3. *Total miles traveled during payback period*

4. *Average vehicle fuel economy in miles per gallon*

5. *Total gallons of fuel consumed* during payback period – obtained by dividing total miles traveled (3) by average miles per gallon (4).

As an example if an improvement results in 2,200 gallons of fuel saved in 3 years or 50,000 miles of use and the total incremental cost for the improvement was $1,500 then the fuel breakeven cost during the period of use would be $1,500/ 2,200 gallons or $0.68/gallon.

3. REFERENCE AND REPRESENTATIVE VEHICLE SELECTION

Evaluation of technological improvements in trucks is predicated on the selection of classes of vehicles which represent larger fuel users. This selection process, a fundamental element of the study, is complicated by the diversity of design and use of trucks in America. As discussed in Section 2.2 there is a convenient weight classification breakdown of trucks which we have used as the framework.

A collection of vehicle statistics was used to develop the statistics reported in the following two figures, Figure 3.1 and Figure 3.2, in which new truck registrations and fuel consumption are shown. Supporting data follows in Tables 3.1 through 3.4. It is clear that new truck sales in weight Class I, VI and VIII overshadow the sales in other weight classes and that Classes I, II, VI and VIII stand out as major fuel users. While the number of heavy duty trucks is relatively small the annual vehicle miles traveled by such trucks is in excess of 70,000 miles per year making this type of vehicle an important fuel consumer.

As evidenced in Figures 3.3 through 3.10 sales of trucks in weight Classes I, II, VI and VIII are projected to continue in future (1975-1980) sales as they have in the past few years, indicating that these four weight classes comprise much of the existing fleet population. It is our opinion, obtained from discussion with truck manufacturers and the trucking industry, that this trend is expected to continue and by analyzing present (1972-1973) fuel consumption for these classes it was determined that weight Classes I, II, VI, and VIII were the principal weight classes to be used as reference vehicles for this study. The present depressed 1975 market conditions, we feel, should not affect the above assumptions for the purpose of this study.

A survey of the literature and manufacturers indicated the specific reference vehicle type for each of the weight classes. Table 3.5 summarizes the selected vehicle, and gives pertinent characteristics of the selected vehicles.

In Weight Class I sales are currently dominated by gasoline engine powered Chevrolet and Ford pickup trucks, as given in Table 3.6. For both of these pickup trucks automatic transmissions are the popular choice (greater than 70% penetration). The statistics of fuel consumption given in the earlier Figures indicate that for light duty weight classes most fuel is consumed in local travel. (These statistics were specifically gathered from those using this vehicle class for business purposes.) However, as distinct from the heavy duty weight class, the pickup truck is designed for local, short and long haul driving. As will be discussed in the following subsections a driving mode to test the performance of each of the vehicles was determined and in the case of the two light duty vehicles a mix of local, short, and long type driving was used in an attempt to represent both business and personal usage for this Class.

As in the case of the Class I pickup truck, the Class II pickup truck is primarily a Ford or Chevrolet with a three-speed automatic transmission, with the additional aspect that a camper body may be substituted on the conventional chassis. This size/weight class was selected since campers generally fall in this weight class. This is not to say that the camper is the most representative of the

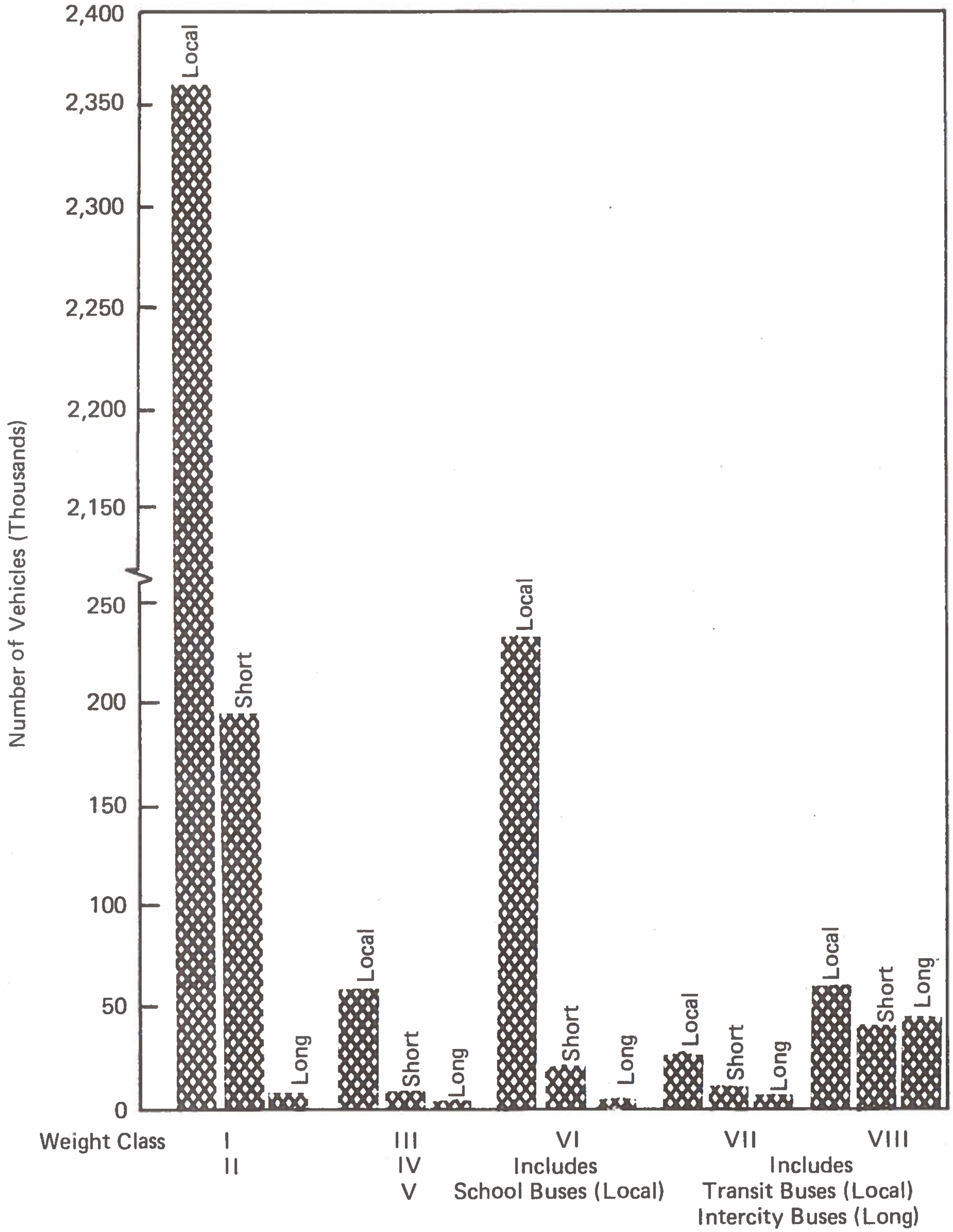


FIGURE 3.1 NEW TRUCK AND BUS REGISTRATIONS, 1973 CALENDAR YEAR, BY WEIGHT CLASS AND DRIVING MODE

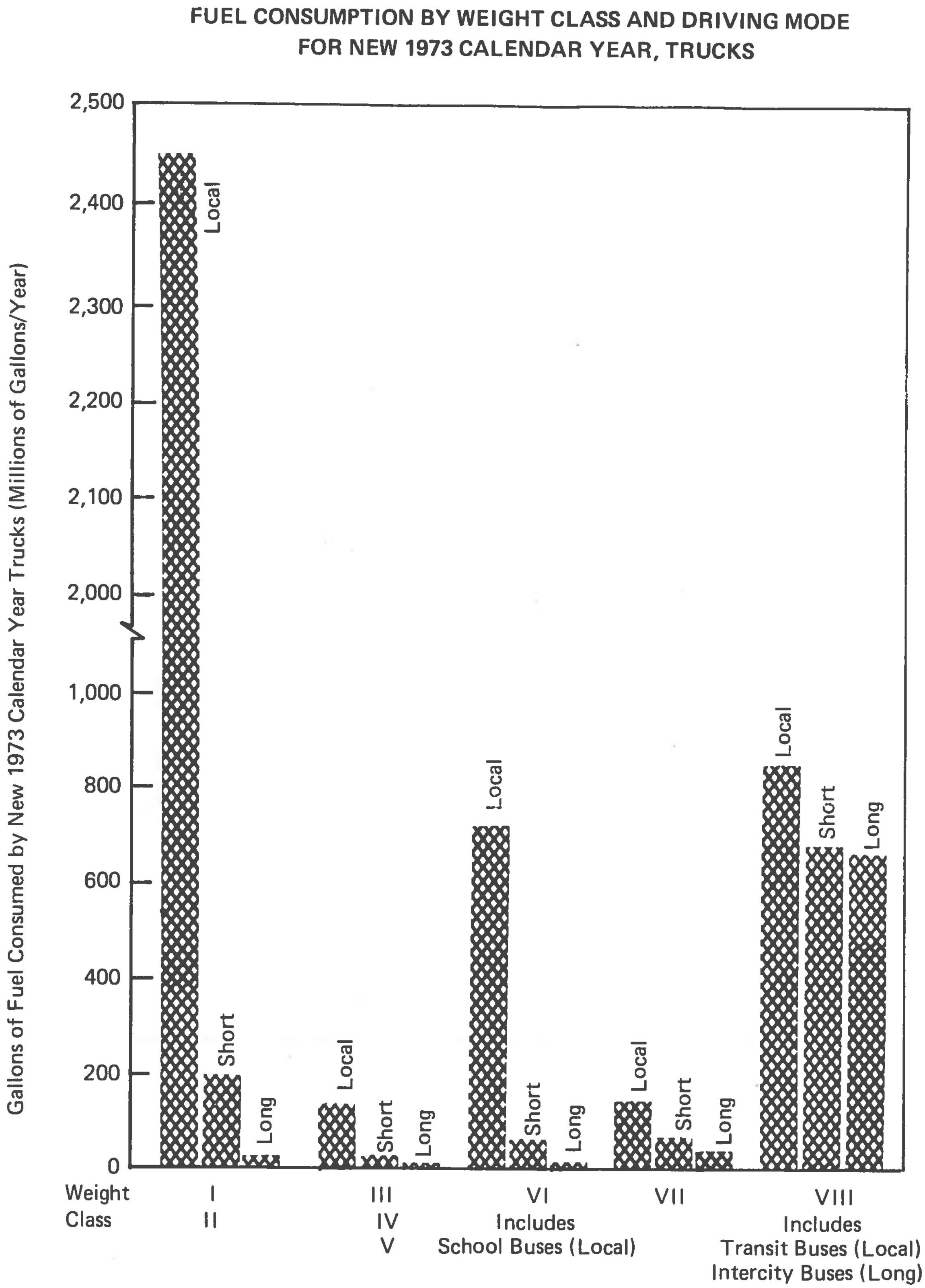
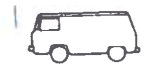


FIGURE 3.2 FUEL CONSUMPTION BY WEIGHT CLASS AND DRIVING MODE FOR NEW 1973 CALENDAR YEAR, TRUCKS AND BUSES

TABLE 3.1
TRUCK FUEL CONSUMPTION DATA*

Industry - Duty Class	Light Duty	
Category - Weight Class	I	II
Gross Vehicle Weight #	6,000 & less	6,001-10,000
Most Popular Model	 Pickup  Van  Van	
Principal Use	Personal Transportation	Personal Transportation
Principal Type of Fuel Currently Being Used	Gas	Gas
New Truck Registrations 1973 Calendar Year** (1) (5)		
By Weight Class	1,842,891	716,534
By Duty Class	2,559,425	
Total Light Duty Trucks (2)		
By Weight Class	11,168,000	4,200,000
By Duty Class	15,368,000	
Gallons of Fuel Consumed by New 1973 Calendar Year Trucks (Million Gals/Year)(3)		
By Weight Class	1,890	782
By Duty Class	2,672	
Gallons of Fuel Consumed By Total In-Service Fleet (Million of Gals/Year)(4)		
By Weight Class	10,100	4,052
By Duty Class	14,152	
% of Fuel Consumed(Based on Total Fuel Used by all Automotive Sources)(5)		
By Weight Class	9.3%	3.8%
By Duty Class	13.1%	
Truck Miles Traveled Per Year (Miles/Year) For New Trucks By Weight (6) Class	12,000	12,000
% of Total Trucks For Each Duty Class By Primary Use (3)		
Local-Urban	92.3%	
Short Range	7.5%	
Long Range	.2%	
Average Miles/Per Year Traveled (6) for Each Duty Class by Specific Driving Mode		
Local-Urban***	10,000	
Short Range	17,400	
Long Range	13,000	
Weighted Average	10,600	
Average Truck Fuel Economy For Each Weight Class By Specific Driving Mode (MPG)(6)	Gas	Gas
Local-Urban	12.2	11.7
Short Range	11.0	9.8
Long Range	11.9	11.5
Weighted Average	11.7	11.0
Vehicle Ton Miles Per Gal for Each Duty Class By Specific Driving Mode (Ton-Miles/ (6)		
Local-Urban	1.2	1.8
Short Range	1.1	1.5
Long Range	1.2	1.7
Weighted Average	1.2	1.6

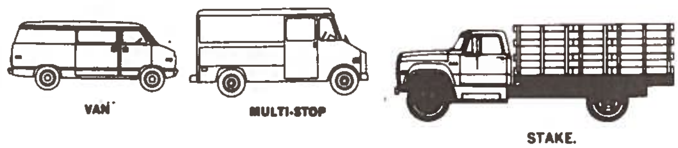
*See page 3-8 for sources

**Calendar Year from 1/1/73 to 12/31/73

*** Local-Urban - Similar to Federal Testing Procedure (F.T.P.)
Short Range - Under 200 Mile Round Trip-Returning to Base Each Night
Long Range - Over 200 Mile - in Line Hauling Across Country

TABLE 3.2
TRUCK FUEL CONSUMPTION DATA*

Industry - Duty Class		Medium Duty	
Category - Weight Class	III	IV	V
Gross Vehicle Weight (Pounds)	10,001-14,000	14,001-16,000	16,001-19,500
Most Popular Model			



Principal Use	Pick-Up and Delivery Agriculture Motor Homes		
Principal Type of Fuel Currently Being Used	Gas	Gas	Gas
New Truck Registrations 1973 Calendar Year** (1) (5)			
By Weight Class	47,607	2,216	18,185
By Duty Class		68,008	
Total Medium Duty Trucks (2)			
By Weight Class	227,000	224,000	1,144,000
By Duty Class		1,595,000	
Gallons of Fuel Consumed by New 1973 Calendar Year Trucks (3) (Million Gals/Year)			
By Weight Class	84	5	58
By Duty Class		147	
Gallons of Fuel Consumed By Total In-Service Fleet (Million of Gals/Year) (4)			
By Weight Class	217	253	1,647
By Duty Class		2,117	
% of Fuel Consumed (Based on Total Fuel Used by all Automotive Sources) (5)			
By Weight Class	.2%	.2%	1.5%
By Duty Class		1.9%	
Miles Traveled Per Year (Miles/Year) For New Trucks By Weight Class (3)	15,000	17,000	19,000
% of Total Trucks For Each Duty Class By Primary Use (6)			
Local-Urban		88%	
Short Range		9%	
Long Range		3%	
Average Miles/Per Year Traveled for Each Duty Class by Specific Driving Mode (6)			
Local-Urban***		8,900	
Short Range		20,800	
Long Range		16,000	
Weighted Average		10,400	
Average Truck Fuel Economy For Each Weight Class By Specific Driving Mode (MPG)(6)	Gas	Gas	Gas
Local-Urban (6)	8.3	6.8	5.8
Short Range	8.8	7.1	6.1
Long Range	8.8	7.1	6.1
Weighted Average	8.5	7.0	6.0
Vehicle Ton Miles Per Gal. for Each Duty Class By Specific Driving Mode (Ton-Miles/Gal.) (6)			
Local-Urban	16.6	15.6	17.4
Short Range	17.2	16.3	18.3
Long Range	17.2	16.3	18.3
Weighted Average	17.0	16.1	18.0

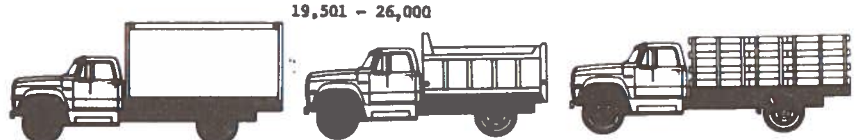
*See page 3-8 for sources

** Calendar Year from 1/1/73 to 12/31/73

*** Local-Urban - Pickup and Delivery Service within the City
Short Range - Under 200 Mile Round Trip-Returning to Base Each Night
Long Range - Over 200 Mile - in Line Hauling Across Country

TABLE 3.3
TRUCK FUEL CONSUMPTION DATA*

Industry - Duty Class		Light Heavy Duty	
Category - Weight Class		VI	
Gross Vehicle Weight (Pounds)		19,501 - 26,000	
Most Popular Model			



VAN. DUMP. STAKE.

Principal Use	Wholesale & Retail Beverage Delivery Dump Truck Agriculture		
Principal Type of Fuel Currently Being Used	Gas		Diesel
New Truck Registrations 1973 Calendar Year ** (1)			
By Weight Class	213,569		4,270
By Duty Class		217,839	
Total Light Heavy Duty Trucks(2)			
By Weight Class	2,070,000		73,000
By Duty Class		2,143,000	
Gallons of Fuel Consumed by New 1973 Calendar Year Trucks (3) (Million Gals/Year)			
By Weight Class	736		17
By Duty Class		753	
Gallons of Fuel Consumed By Total In-Service Fleet (Million of Gals/Year) (4)			
By Weight Class	3,340		240
By Duty Class		3,580	
% of Fuel Consumed(Based on Total Fuel Used by all Automotive Sources) (5)			
By Weight Class	3.1%		0.2%
By Duty Class		3.30%	
Truck Miles Traveled Per Year (Miles/Year) For New Trucks By Weight (6) Class	20,000		28,000
% of Total Trucks For Each Duty Class By Primary Use (6)			
Local-Urban	88%		74%
Short Range	10%		23%
Long Range	2%		3%
Average Miles/Per Year Traveled for Each Duty Class by Specific Driving Mode (6)			
Local-Urban***	8,700		15,400
Short Range	20,400		28,400
Long Range	29,500		53,000
Weighted Average	10,500		20,000
Average Truck Fuel Economy For Each Weight Class By Specific Driving Mode (MPG) (6)	Gas		Diesel
Local-Urban	5.7		6.8
Short Range	5.7		7.0
Long Range	6.0		7.0
Weighted Average	5.8		6.9
Vehicle Ton Miles Per Year for Each Duty Class By Specific Driving Mode (Ton-Miles/Gal.) (6)			
Local-Urban	39.9		47.6
Short Range	39.9		49.0
Long Range	42.0		49.0
Weighted Average	40.6		48.3

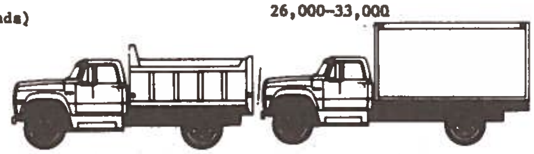
*See page 3-8 for sources

** Calendar Year from 1/1/73 to 12/31/73

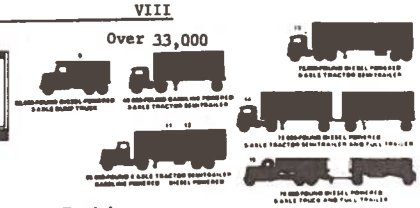
*** Local-Urban - Pickup and Delivery Service within the City
Short Range - Under 200 Mile Round Trip-Returning to Base Each Night
Long Range - Over 200 Mile - in Line Hauling Across Country

TABLE 3.4
TRUCK FUEL CONSUMPTION DATA*

Industry - Duty Class	Heavy Duty	
Category - Weight Class	VII	VIII
Gross Vehicle Weight (Pounds)	26,000-33,000	Over 33,000
Most Popular Model		



DUMP. VAN.



	VII		VIII
Principal Use	Freight Dump Truck Ready Mix Concrete Garbage Fuel Delivery		Freight

	VII Gas	VII (Duty Class)	VII Diesel	VIII Gas	VIII (Duty Class)	VIII Diesel
Principal Type of Fuel Currently Being Used	Gas		Diesel	Gas		Diesel
New Truck Registrations 1973 Calendar Year ** (1) (7)						
By Weight Class	27,000		14,000	15,000		127,000
By Duty Class		41,000			142,000	
Total Heavy Duty Trucks (2)						
By Weight Class	324,000		100,000	434,000		700,000
By Duty Class		424,000			1,134,000	
Gallons of Fuel Consumed by New 1973 Calendar Year Trucks (3) (Million Gals/Year) (3)						
By Weight Class	137		124	131		2,000
By Duty Class		261			2,131	
Gallons of Fuel Consumed By Total In-Service Fleet (Million of Gals/Year) (4)						
By Weight Class	773		807	2,344		8,627
By Duty Class		1,580			10,971	
% of Fuel Consumed (Based on Total Fuel Used by all Automotive Sources) (5)						
By Weight Class	.7%		.7%	2.2%		8.0%
By Duty Class		1.4%			10.2%	
Truck Miles Traveled Per Year (Miles/Year) For New Trucks By Weight (6) Class	27,000		53,000	43,000		90,000

% of Total Trucks For Each Duty Class By Primary Use (6)	Gas	Diesel
Local-Urban	76%	35%
Short Range	20%	33%
Long Range	4%	32%

Average Miles/Per Year Traveled for Each Duty Class by Specific Driving Mode (6)	Gas	Diesel
Local-Urban***	12,700	22,500
Short Range	26,800	53,000
Long Range	42,900	90,000
Weighted Average	16,800	54,000

Average Truck Fuel Economy For Each Weight Class By Specific Driving Mode (MPG) (6)	Gas	Diesel	Gas	Diesel
Local-Urban	5.3	6.0	4.9	5.7
Short Range	5.3	6.0	4.9	5.7
Long Range	5.3	6.0	4.9	5.7
Weighted Average	5.3	6.0	4.9	5.7
Vehicle Ton Miles Per Year for Each Duty Class By Specific Driving Mode (Ton-Miles/Gal.) (6)				
Average	58.7	66	73.5	85.5

*See page 3-8 for sources

** Calendar Year from 1/1/73 to 12/31/73

*** Local-Urban - Pickup and Delivery (Service within the city)
Short Range - Under 200 Mile Round Trip-Returning to Base Each Night
Long Range - Over 200 Mile - in Line Hauling Across Country

SOURCES OF DATA TABLES (3-1, 3-2, 3-3, 3-4)

Category I, II, III-V (Medium Duty)

(1) 1973 Registration	*Wards Automotive Yearbook 1974*
(2) Total in Service	American Trucking Association (ATA) Data for 1972 updated to 1973 by factor of 1.025 plus *1973 Motor Truck Facts,* Motor Vehicle Manufacturers Association (MVMA)
(3) Fuel Consumed 1973 Model	Estimate based upon average mileage per year and fuel consumption data of typical vehicles. Road user and property taxes on selected vehicles 1973 U.S. Dept. of Trans., ATA data
(4) Fuel Consumed, All Years	ATA data for 1972 updated to 1973 by a factor of 1.025, road user and property taxes on selected vehicles 1973, U.S. Dept. of Trans. and ADL estimates
(5) % of Total Fuel for All Automotive Sources	Estimate based upon 1972 ATA data, and 1972 highway statistics (DOT)
(6) Mileage per Vehicle per Year	ATA data, 1972
Average Fuel Consumed per Vehicle, Miles/Gallon	ATA data, 1972
Ton Miles per Gallon	ATA data, 1972

Category VI-VIII (Light Heavy Duty and Heavy Duty)

(1) (2) (3) (4) (5) (6)	References same as above except for 1973 production and registration.
(7) 1973 Registration	Estimate based upon *Wards Automotive Yearbook 1974,* and *1973 Motor Truck Facts.*

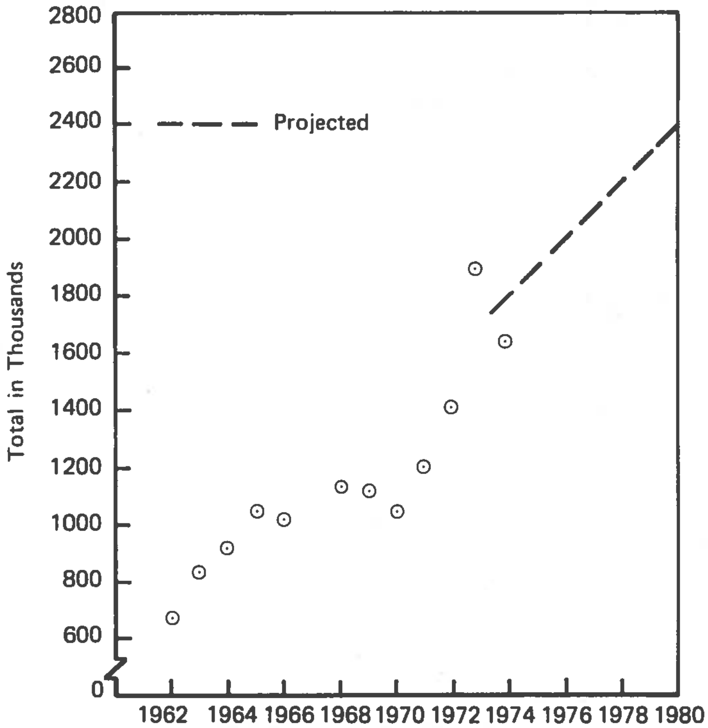


FIGURE 3.3 NUMBER OF G.V.W. 6,000 OR LESS TRUCKS REGISTERED

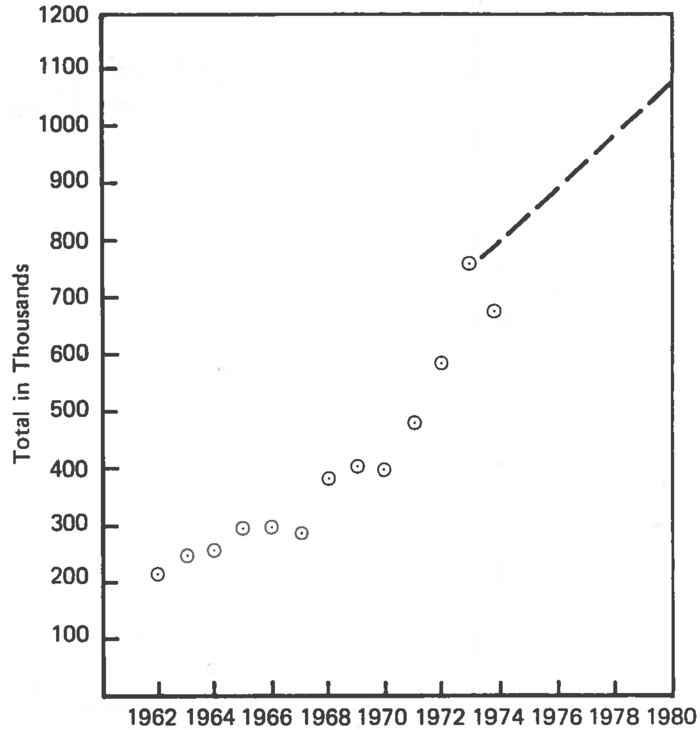


FIGURE 3.4 NUMBER OF G.V.W. 6,001–10,000 TRUCKS REGISTERED

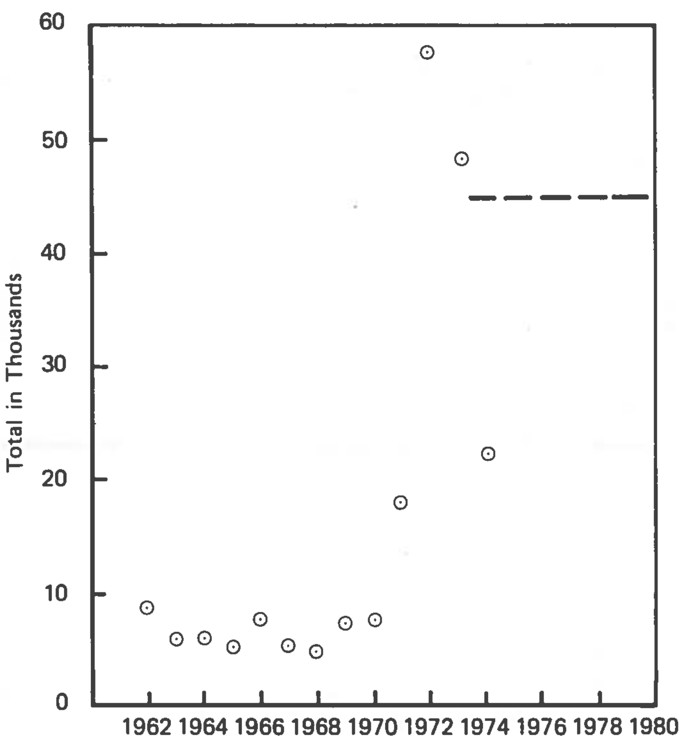


FIGURE 3.5 NUMBER OF G.V.W. 10,001–14,000 TRUCKS REGISTERED

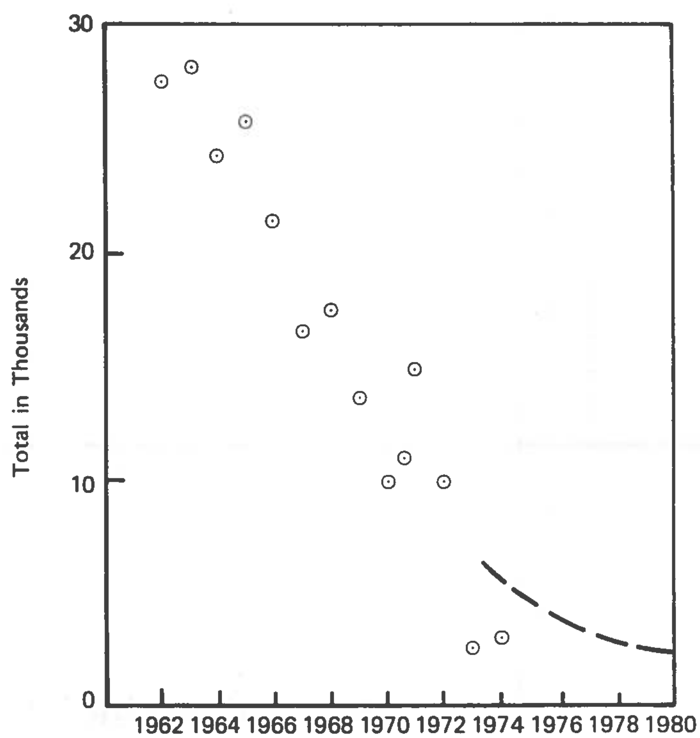


FIGURE 3.6 NUMBER OF G.V.W. 14,001–16,000 TRUCKS REGISTERED

Sources: Wards Automotive Yearbooks and Arthur D. Little, Inc., estimates.

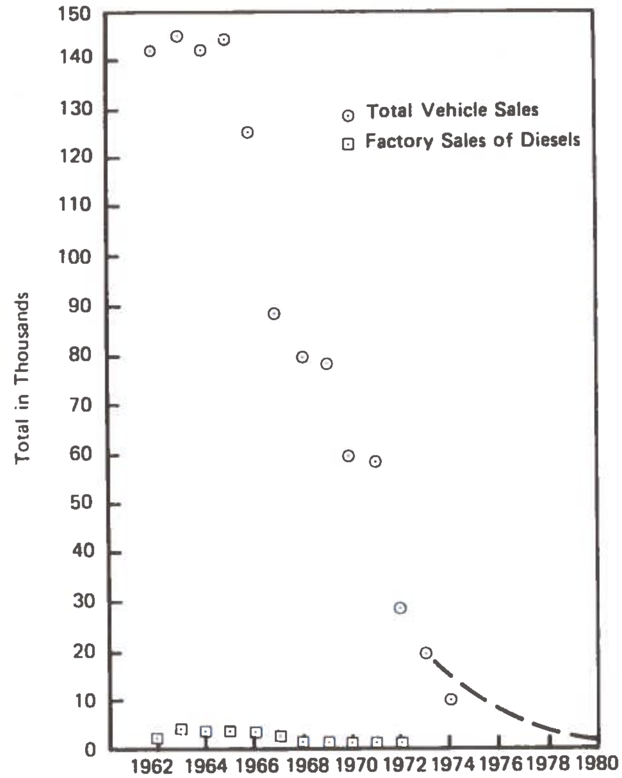


FIGURE 3.7 NUMBER OF G.V.W. 16,001–19,500 TRUCKS REGISTERED

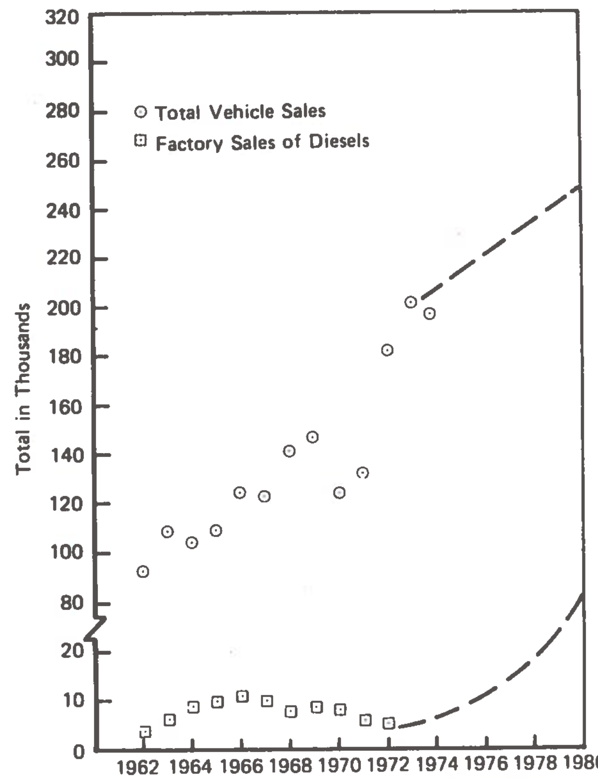


FIGURE 3.8 NUMBER OF G.V.W. 19,501–26,000 TRUCKS REGISTERED

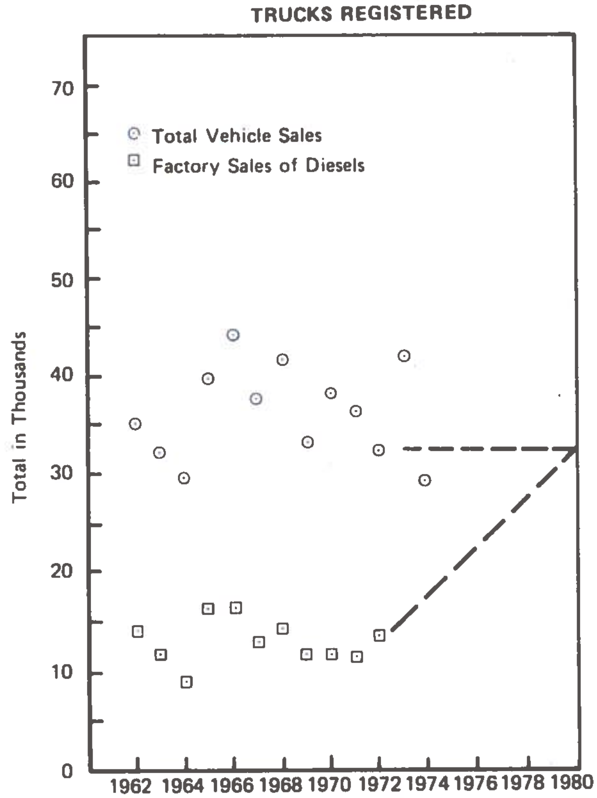


FIGURE 3.9 NUMBER OF G.V.W. 26,001–33,000 TRUCKS REGISTERED

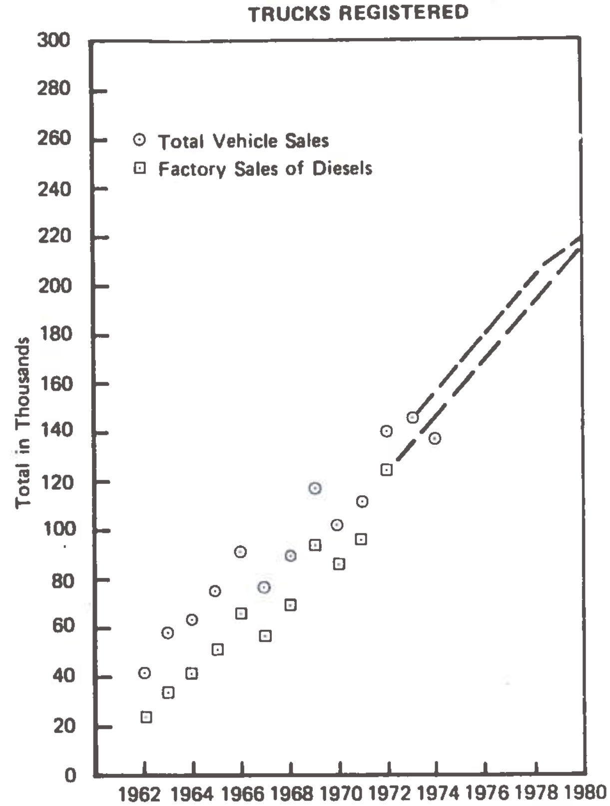


FIGURE 3.10 NUMBER OF G.V.W. OVER 33,000 TRUCKS REGISTERED

Sources: Wards Automotive Yearbooks and Arthur D. Little, Inc., estimates.

TABLE 3.5

SELECTED REFERENCE TRUCKS

Class	Driving Mode	Mfg	Model	Engine	Transmission	Gross Vehicle Wgt
I	Mixture of local, short and long	Chevrolet	C-10 Pickup	Chev. 350 CID	3-Speed Auto	6,000
II	Mixture of local, short and long	Ford	F-250 Camper Special Pick-up and Camper	Ford 351-CID	3-Speed Heavy Duty Auto	10,000
VI	Local	Interna. Harvester	1800 Van 1850 Van	IH DV 392 Cummins 8VE 170 HT	5-Speed T-35 5-Speed T-36	22,500 24,500
VIII	Local and Short	Mack	DM-600	Mack End-673E	10-Speed TRD-722	62,000
VIII	Short	Interna. Harvester	Fleetstar F-2070	Cummins NTC 290	10-Speed-RT-910	48,860
VIII	Long	Interna. Harvester	Transtar F-4379	Cummins NTC 290	10-Speed RT-910 Manual	73,000

These vehicles account for 88% of truck fleet fuel consumption

Local = City and Suburban driving usually pick ups & delivery

Short = 200 miles round trip-mixture or city & intercity driving (return to base at night)

Long = Over 200 miles Inter State Highway – (line haul)

The above driving modes were used in analysis and selected with industry concurrence as being representative of typical truck use.

TABLE 3.6

VEHICLE REGISTRATIONS BY MANUFACTURER 1973

6,000 and Under

Registrants	Number	% of Total
Chevrolet	662,795[1]	35.9
Ford	617,598[1]	33.5

Selection of Model

Chevrolet

Pickup – Fleetside C-10	193,640
Automatic Transmission	132,032

Ford

Pickup – F-100 5,500 GVW	152,947
Automatic Transmission	96,510

6,000 – 10,000

Registrants	Number	% of Total
Chevrolet	260,394	36.3
Ford	257,992	36.0

Selection of Model

Chevrolet

Pickup – Fleetside C-20, 8,200 GVW	79,977
Automatic Transmission	57,888

Ford

Pickup – F250, 8,100 GVW	56,585
Automatic Transmission	32,650

1. Wards Automotive Yearbook 1974.

6,001-10,000 pound vehicle, but as the study will indicate, most if not all of the conclusions reached for the innovations pertaining to the 6,000 and below pickup class are applicable to the 6,001-10,000 pound pickup class. Therefore, to encompass a somewhat wider variety of light duty vehicles the camper was selected for the 6,001-10,000 pound recognizing the limited number of campers. As in the case of the 6,000 pound pickup truck, the camper truck is also used for local, short and long haul and a mix of driving modes was used for the evaluation of this vehicle performance.

Weight Class VI as shown in Table 3.3 is comprised of three major manufacturers: Ford, Chevrolet and International. Since Ford and Chevrolet representative vehicles were used in the pickup and camper size trucks the International was chosen for representation of the van/truck. As indicated in Table 3.3 the van/truck is used primarily in local and short haul deliveries. As was the case of the light duty pickup the weight Class VI medium duty van is designed for both short and local use.

Weight Class VIII comprises those vehicles 33,000 pounds GVW and over. In this weight class, International, White, Mack, Ford and GMC account for much of the sales. Unlike the lighter duty vehicles this weight class is made specifically for a type of use. In addition 94% of the fuel consumed by trucks in this weight class is diesel fuel as seen in Tables 3.7 and 3.8. For local use, dump trucks, fuel delivery trucks, and large vans are the dominant species. For short haul use a combination of vans, dump trucks and tractor trailers are intermixed. In the case of the long haul the tractor trailer dominates the scene. In all cases a diesel was selected as the reference vehicle, a dump truck was selected for local use and a tractor semi-trailer for short and long hauls. A Mack DM series dump truck was selected as a representative vehicle for which evaluations would be made. For short and long haul the International Harvester tractor combined with a standard semi-trailer was examined.

The selection of the weight Class I, II, VI, and VIII reference vehicle types completes the screening process to establish the types of vehicles to be studied.

Miles Traveled by weight class and driving mode:

- First year miles per year for new trucks
- Average miles per year traveled by specific driving mode and weighted average

These data were developed for this report and also used for the "Study of Potential for Motor Vehicle Fuel Economy Improvement," Truck and Bus Panel Report No. 7, prepared by U.S. Department of Transportation and the U.S. Environmental Protection Agency, January 10, 1975 and from source information referenced in the report.

3.1 DESCRIPTION OF COMPUTER SIMULATIONS

For calculating the fuel consumption of the various vehicles considered in the study two different digital computer programs were used. Medium and heavy duty trucks were simulated using the Vehicle Mission Simulation program developed by Cummins Engine Company, Inc. Light duty trucks were simulated using a program developed by ADL. For the study of technological improvements in automobile fuel consumption – DOT-TSC OST-74-40 I, II, III, IV.

TABLE 3.7

CONSUMPTION OF FUEL BY WEIGHT CLASS FOR NEW (1973) REGISTRATIONS (BASED ON ADL ESTIMATES)

Gross Vehicle Weight Class		% of Total Gallons Consumed by Weight Class	
		Gas	Diesel
I	6,000 and under	31.6	–
II	6,001-10,000	13.1	–
III	10,001-14,000	1.4	–
IV	14,001-16,000	0.1	–
V	16,001-19,500	0.9	–
VI	19,501,26,000	12.3	0.3
VII	26,001-33,000	2.4	2.1
VIII	33,000 and up	2.2	33.6
	Total	64.0	36.0

TABLE 3.8

NEW TRUCK REGISTRATION IN 1973 FOR MEDIUM AND HEAVY CLASSES

Medium 19,500-26,000# – Gas

Total 1973 Registration – 214,000

Registrants	Number	% of Total
Ford	81,000	37
Chevrolet	56,000	26
International	51,000	24
All Others (4)	26,000	13
Total	214,000	100

Heavy 33,000# and Over (Diesel and Gas)

Total 1973 Registration – 142,000

Registrants	Number	% of Total
International	31,000	22
White	24,000	17
Mack	23,000	16
Ford	18,000	13
GMC	14,000	10
All Others (4)	32,000	22
Total	142,000	100

Source: Wards Automotive Yearbook 1973

The ADL program calculates the fuel consumption of a vehicle with a single drive axle. The required input data is shown in Table 3.9. The road grade and wind velocity are assumed negligible.

The flow chart shown in Figure 3.11 depicts the scheme used to calculate the fuel consumed during a time interval in the simulation. First the vehicle velocity and the angular velocity and acceleration of the wheels are determined. Then the forces necessary to overcome the vehicle inertia, aerodynamic drag, rolling resistance and gravity are calculated. The velocity and the required tractive force determine the torque which must be transmitted to the drive wheels.

Next the torque and RPM at the transmission output shaft are determined considering the rear axle ratio and efficiency. The torque and RPM at the transmission input are next calculated by applying the gear ratio and efficiency of the transmission. If the vehicle has a torque converter the torque and RPM at the input shaft are calculated using the appropriate correction (K-Factor). The torque loss due to accessory loads is added at this point to obtain the engine output torque. The torque loss due to the accessories is considered to be a function of engine speed. A check is then made to ensure that the transmission and rear axle are set in the appropriate gears. If not, a fix is made and the calculations are repeated. Rotary inertia terms are included in the calculation wherever they are significant.

After it has been determined that the gear ratios are set correctly the fuel consumption for the time step is calculated and the vehicle speed indicated for this time step. If the calculation is for a constant speed condition the fuel consumption in gallons per mile is calculated and the next constant speed condition is begun. If the calculation is for a finite acceleration situation the fuel consumption is integrated over the total time span of the calculation to obtain a total fuel consumption.

Calculations are done for constant speeds of 20, 30, 40, 50, 55, 60 and 70 miles per hour. It was recognized that speeds over 55 mph are in violation of present speed limits but were included for study purposes. The finite acceleration conditions to be handled are specified in the input data for each execution.

For each condition considered the fuel consumptions due to rolling resistance, axle inefficiency, transmission inefficiency, torque converter dissipation, accessory loads, aerodynamic resistance, gravity and inertia loads are calculated and separately reported. A total fuel consumption is also reported for each condition.

Finally the program calculates a total annual tank mileage based on the driving cycle specified in Section 4.14.1 of this report. The information required as input data is listed in Table 3.9, and a sample output is illustrated in the Appendix.

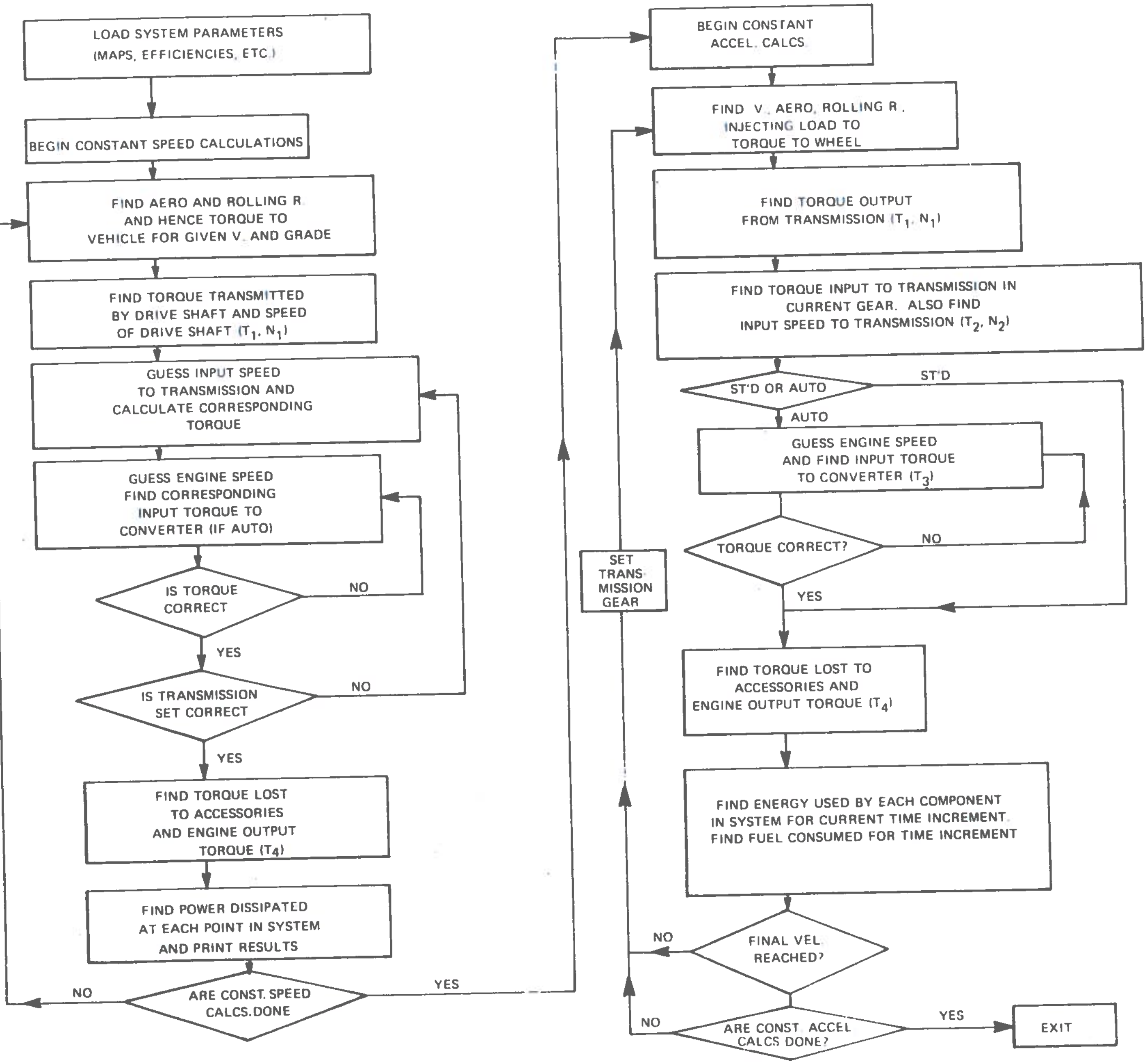


FIGURE 3.11 ADL PROGRAM FLOW CHART

It must be understood that the individual improvements in this simulation and in actual operation do not combine arithmetically but are somewhat dependent upon each other to produce a final resultant vehicle fuel economy improvement.

TABLE 3.9

INPUT DATA REQUIRED FOR ADL SIMULATION

1. a. Engine fuel map (fuel consumption versus RPM and torque)
   b. For vehicles having an automatic transmission percent wide open throttle (WOT)
   c. Idle fuel consumption

2. Size factor (K) and torque ratio as functions of speed ratio for torque converter

3. Shift logic for transmission and rear axle ratio data

4. Efficiency data for transmission and rear axle

5. Vehicle mass and rotary inertias for rotating components of system

6. Frontal area, air density, drag coefficients, rolling resistance coefficients, wheel revolutions per mile

7. Operating conditions (accelerations, road grade, wind velocity)

8. Coefficients relating accessory torque loss and engine speed

The Vehicle Mission Simulation Program developed by Cummins was used to simulate medium and heavy duty trucks considered in this study. The capabilities of this program are described in the Appendix.

Since there are no published driving cycles for vehicles in these weight classes we found it necessary to choose actual highways which we felt were representative of the routes on which the vehicles normally travel.

To use the VMS program one merely chooses the vehicle which is to be simulated and enters the appropriate code numbers for the vehicle and each of its components on an input coding form. The items specified by code number include the manufacturer's model number, the type of truck or tractor, the type body or trailer, the transmission, the drive axle, and the engine. The type of truck refers to the number of wheels and drive axles. The body type refers to the shape which determines aerodynamic resistance characteristics.

Also specified by code number are the routes over which the vehicle is to be simulated. One may specify as many as five different routes for a single simulation.

In addition to the information that is entered by code number, one also specifies the wind speed and direction, the ambient temperature, the gross vehicle weight, the vehicle width and height, the number of wheel revolutions per mile, the axle ratio and, if desired, a governed maximum vehicle speed.

A sample coding form is shown in the Appendix.

Tables 3.1, 3.2, and 3.3 display for each weight class additional information about the reference vehicles such as:

Vehicle Description

- Gross vehicle weight; minimum and maximum limits
- Most popular models in use
- Principal uses such as pickup and delivery
- Principal type of fuel used by new vehicles and the entire fleet

Fuel Consumption

- Gallons of fuel consumed by new 1973 calendar year trucks
- Total fleet fuel consumption
- Percent of fuel consumed based on all automotive consumption
- Average fuel economy (MPG) for each duty cycle
- Type of fuel used, gasoline or diesel
- Vehicle ton-miles/gallon or passenger-miles/gallon

Driving Mode has been divided into three categories:

- *Local*

  As typified by urban stop and go driving somewhat similar to the federal test procedure for emission certification testing of automobiles

- *Short Trip*

  Under 200 mile round trip from base returning at night with a mixture of urban, suburban and highway driving.

- *Long Trip*

  One way – line haul high speed freight delivery or passenger carrying service.

Percent of the total vehicles by number for each of the three modes is shown.

3.2 BACKGROUND AND PURPOSE OF TANK MILEAGE MEASUREMENT

As discussed fully in the Automobile Fuel Consumption Study[2] the development of a reasonable test procedure for measurement of yearly fuel consumption is mandatory for a study such as this. Without a uniform technique of measuring changes in fuel consumption the evaluation of innovations is impossible. In 1973 when the Automobile Fuel Consumption Study was conducted there was no uniform procedure for estimating the yearly fuel consumption of a vehicle. At this writing there still is no uniform procedure to estimate annual fuel consumption for heavy duty truck operations. However, since the end of the automotive study several federal test procedures for certain driving modes have been developed along with SAE standards on testing of vehicles for fuel consumption. In both cases the test procedures are for a limited mileage representing the use of the vehicle over a narrowly defined pattern such as urban, suburban, rural or interstate usage. These fuel economy measurement driving cycles are for light duty vehicles while heavy duty vehicles have no comparable standard fuel economy measurement procedures.

In the referenced study[2] a rationale was developed to apply a standard test to evaluate the fuel consumption of a vehicle at the end of a year's operation calling this the tank mileage. A similar driving cycle was developed for the light duty and heavy duty trucks based on a statistical mix of driving cycles. For the light duty vehicles three EPA vehicle test procedures are combined to approximate the variety of driving conditions a vehicle might reasonably experience in a year of operation. This statistical mix is discussed in Section 3.3.3.

Since no testing standards exist for vehicles of 10,000 pounds and over, a new approach was taken for the evaulation of the fuel economy of such

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2. Hurter, D.A. et al, "A Study of Technological Improvements in Automobile Fuel Consumption," DOT-TSC-OST-74-40, Vol. I, II, III and IV Dec. 1974.

vehicles. An 'over-the-road' vehicle simulator was used for the evaluation of the fuel economy of trucks 10,000 pounds and above based on statistics developed at ADL. The statistical mix for vehicles of 10,000 pound GVW and above is given in Section 3.3.4.

The considerations which go into the development of year-end fuel consumption and tank mileage (the annual mileage divided by the yearly fuel consumption) are discussed in Reference 2. However, several new test procedures have come on the scene and certain of the test procedures are applicable to the heavy duty vehicles. Before we go on to develop the methodology of the light duty and heavy duty fuel economy statistical mix we would like to update the list of existing test standards for vehicles which may be used in synthesizing a year-end fuel consumption and tank mileage test procedure.

3.2.1 Light Duty Standard Test Procedures

A summary of the standard fuel economy testing procedures for light duty vehicles is given in Table 3.10. Four test procedures are described, two of which are used by the EPA in emissions and fuel economy measurements, the fourth being the recommended Society of Automotive Engineers (SAE) procedures for evaluation of the fuel economy of light duty vehicles. A breakdown of the characteristics of the three Federal Test Procedures (FTP) is shown in Table 3.11. Details of the SAE procedures are reproduced in Table 3.13.

As indicated in Table 3.11 the FTP fuel economy for the urban driving and the highway driving cycles use carbon balance calculated fuel economy rather than actual measured fuel consumption. These FTP's are formulated to evaluate the vehicle emissions and are not specifically designed for fuel economy measurements. Measuring the carbon weight fraction of the feed gasoline or unburned hydrocarbons and comparing it with the carbon weight fraction of CO and CO_2 in the exhaust can be used to estimate the fuel consumption of the vehicle using a chassis dynamometer test. The calculation procedure is shown in Table 3.12.

The FTP for fuel economy differs from the SAE recommended test procedure which utilizes equipment specifically designed to measure fuel consumption. In addition, the FTP tests are performed on chassis dynamometers and therefore do not account for the effects of aerodynamics while the SAE procedure is a vehicle road test. The SAE procedure has three components; namely, urban, suburban, and interstate driving cycles. These are described in Table 3.13.

TABLE 3.10

SUMMARY COMPARISON OF FUEL ECONOMY TESTING PROCEDURES FOR LIGHT DUTY VEHICLES

Test Load Added to Curb Weight	Vehicle Preparation and Operating Conditions	Type of Cycle	Type of Test	Data Adjustment	Description of Cycle: Length (miles)	Description of Cycle: Time (minutes)	Description of Cycle: Average Speed (mph)
$\simeq$175 lb	12-hr soak @ 70°F one test w/70°F start 10-min stop, another test w/hot start Test run at zero and at each 4000 miles until 50,000 miles accumulated	EPA – F.T.P. urban driving	Dynamometer	Reported fuel economy calculated rather than measured	7.5	22	19.4
$\simeq$175 lb	Used to accumulate mileage between each 4000-mile emissions test	11-lap durability	Test track	No fuel mileage taken	40.7	81.5	30
$\simeq$175 lb	Run immediately after F.T.P. or with preconditioning cycles as specified	EPA – Highway Fuel Economy Test (HWFET)	Dynamometer	Reported fuel economy calculated not measured		12.75	
300 lb	2000-mile break-in 20 miles at 55 mph warmup	SAE recommended procedures	Road test	measured fuel consumption			
		Urban	Road test	measured fuel consumption	2.0	7.68	15.6
		Suburban	Road Test	measured fuel consumption	5.2	7.58	41.1
		Interstate	Road Test	measured fuel consumption	4.0	5.13	55.0

TABLE 3.11

BREAKDOWN OF FEDERAL TEST PROCEDURE BY MODES FOR LIGHT DUTY VEHICLES*

	Mode of Operation					
	Accel	Decel	Cruise	Idle		Total
% Distance	22	18	60	0	=	100%
by Mode	1.64	1.35	4.47	0	=	7.46 miles
% Time	23	20	39	18	=	100%
by Mode	316	274	535	247	=	1372 sec

BREAKDOWN OF 11-LAP TEST FOR LIGHT DUTY VEHICLES**

	Mode of Operation					
	Accel	Decel	Cruise	Idle		Total
% Distance	16	11	73	0	=	100%
by Mode	6.6	4	30	–	=	40.6 miles
% Time	20	12	56	12	=	100%
by Mode	16.33	10.20	46.38	9.75	=	82.6 min

BREAKDOWN OF HIGHWAY FUEL ECONOMY TEST***

	Mode of Operation					
	Accel	Cruise	Decel	Idle		Total
% Time	6	88	6	0	=	100%
by Mode	44	677	44	0	=	765 sec

* La Pointe, C., Factors Affecting Vehicle Fuel Economy, Automotive Emissions Office, Ford Motor Co., Combined SAE Fuel Lubricating Meeting and Manufacturing Forum, Milwaukee, Wisconsin, Sept. 11, 1973

** J.D. Murrell, Internal Memo to J. Brogan AAPS/EPA, Jan. 9, 1973

*** ADL Computation of published Time-MPH Profile

TABLE 3.12

CALCULATION PROCEDURE

The carbon balance method of calculating the fuel economy of a vehicle in miles per gallon (mpg) from data gathered during a highway fuel economy test is of the following form:

$$\text{mpg} = \frac{\text{grams of carbon/gallon of fuel}}{\text{grams of carbon in exhaust/mile}}$$

$$\text{mpg} = \frac{(K_1)\ (\text{grams/gallon})}{(K_1)\ (\text{grams HC/mi}) + (K_2)\ (\text{grams CO/mi}) + (K_3)\ (\text{grams } CO_2\text{/mi})}$$

where:

K_1 = carbon weight fraction of gasoline or unburned HC (mol. wt. C)/(mol. wt. $CH_{1.85}$ = .866)

K_2 = carbon weight fraction of CO, (mol. wt. C)/ (mol. wt. CO) = .429

K_3 = carbon weight fraction of CO_2 (mol. wt. C)/ (mol. wt. CO_2) = .273

grams/gallon = mean density of Indolene (clear or 30) test fuel = 2798 substituting:

$$\text{mpg} = \frac{.866\ (2798)}{.866\ (\text{gpm HC}) = .429\ (\text{gpm CO}) + .273\ (\text{gpm } CO_2)}$$

$$\text{mpg} = \frac{2423}{.866\ (\text{gpm HC}) + .429\ (\text{gpm CO}) + .273\ (\text{gpm } CO_2)}$$

3.2.2 Heavy Duty Test Procedures

At the present time there is no standard test procedure for measuring fuel economy of heavy duty vehicles. The complexity of a heavy duty test procedure for measurement of fuel economy could be a severe limitation on the representativeness of such a test. In the case of 10,000 pound and lighter vehicles the fuel economy of a specific vehicle can be linked to the engine performance, various drivetrain components, and the vehicle inertia. The fuel economy of medium and heavy duty vehicles 10,000 pounds to 80,000 pounds is most intimately linked with the size and load. Since there is a wide variation in vehicle configuration, operating use and terrain conditions a universal test, for the fuel economy of vehicles 10,000 pound GVW and over, would need to accommodate the wide variation in vehicle load and size so that meaningful fuel economy results could be obtained. Therefore a combination of tests may have to be developed to provide meaningful results. At present tests of heavy duty vehicles are limited to engine dynamometer tests alone. Based on the engine dynamometer tests predicted fuel economy levels

TABLE 3.13

FUEL ECONOMY MEASUREMENT – ROAD TEST
APRIL 1974

8.3.2.8 *Urban Cycle Fuel Economy Driving Schedule*—Average speed: 15.6 mph (25.1 km/h); running time: 461 s/cycle. After proper warmup (paragraph 8.1), the urban driving cycle should be run as follows:

Distance		Operation
miles	km	
0.0	0.0	Start fuel meter and timing device, idle 15 s, accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2). Proceed at 15 mph (24.1 km/h) to the 0.2 mile (0.32 km) marker.
0.2	0.32	Stop at 4 ft/s^2 (1.2 m/s^2), accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2). Proceed at 15 mph (24.1 km/h) to the 0.3 mile (0.48 km) marker.
0.3	0.48	Decelerate to 5 mph (8.0 km/h) at 4 ft/s^2 (1.2 m/s^2), accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2). Proceed at 15 mph (24.1 km/h) to the 0.5 mile (0.80 km) marker.
0.5	0.80	Stop at 4 ft/s^2 (1.2 m/s^2), idle 15 s, accelerate to 20 mph (32.2 km/h) at 7 ft/s^2 (2.1 m/s^2). Proceed at 20 mph (32.2 km/h) to the 0.7 mile (1.13 km) marker.
0.7	1.13	Stop at 4 ft/s^2 (1.2 m/s^2), accelerate to 20 mph (32.2 km/h) at 7 ft/s^2 (2.1 m/s^2). Proceed at 20 mph (32.2 km/h) to the 0.8 mile (1.29 km) marker.
0.8	1.29	Decelerate to 10 mph (16.1 km/h) at 4 ft/s^2 (1.2 m/s^2), accelerate to 20 mph (32.2 km/h) at 5 ft/s^2 (1.5 m/s^2). Proceed at 20 mph (32.2 km/h) to the 1.0 mile (1.61 km) marker.
1.0	1.61	Stop at 4 ft/s^2 (1.2 m/s^2), idle 15 s, accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2), then to 25 mph (40.2 km/h) at 5 ft/s^2 (1.5 m/s^2). Proceed at 25 mph (40.2 km/h) to the 1.2 mile (1.93 km) marker.
1.2	1.93	Stop at 4 ft/s^2 (1.2 m/s^2), accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2), then to 25 mph (40.2 km/h) at 5 ft/s^2 (1.5 m/s^2). Proceed at 25 mph (40.2 km/h) to the 1.3 mile (2.09 km) marker.
1.3	2.09	Decelerate to 15 mph (24.1 km/h) at 4 ft/s^2 (1.2 m/s^2), accelerate to 25 mph (40.2 km/h) at 5 ft/s^2 (1.5 m/s^2). Proceed at 25 mph (40.2 km/h) to the 1.5 mile (2.41 km) marker.
1.5	2.41	Stop at 4 ft/s^2 (1.2 m/s^2), idle 15 s, accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2), then to 30 mph (48.3 km/h) at 5 ft/s^2 (1.5 m/s^2). Proceed at 30 mph (48.3 km/h) to the 1.7 mile (2.74 km) marker.
1.7	2.74	Stop at 4 ft/s^2 (1.2 m/s^2), accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2) and then to 30 mph (48.3 km/h) at 5 ft/s^2 (1.5 m/s^2). Proceed at 30 mph (48.3 km/h) to the 1.8 mile (2.90 m) marker.
1.8	2.90	Decelerate to 20 mph (32.2 km/h) at 4 ft/s^2 (1.2 m/s^2), accelerate to 30 mph (48.3 km/h) at 5 ft/s^2 (1.5 m/s^2). Proceed at 30 mph (48.3 km/h).
2.0	3.22	Begin braking at 4 ft/s^2 (1.2 m/s^2) to arrive at stop at 2.0 mile (3.22 km) marker. Stop fuel meter and timing device at stop, record fuel consumed, elapsed time, and fuel temperature.
0.0	0.0	Run recheck cycle.

8.3.3.8 *Suburban Cycle*—Average speed: 41.1 mph (74.9 km/h); running time: 455 s/cycle. After proper warmup (paragraph 8.1), the suburban driving cycle should be driven as follows:

Distance		Operation
miles	km	
0.0	0.0	Approach starting line at 40 mph (64.4 km/h). At line, start fuel measuring and timing devices, accelerate to 60 mph (96.5 km/h) at 3 ft/s^2 (0.9 m/s^2). Proceed at 60 mph (96.5 km/h) to the 0.7 mile (1.13 km) marker.
0.7	1.13	Decelerate to 30 mph (48.3 km/h) at 4 ft/s^2 (1.2 m/s^2). Accelerate to 50 mph (80.5 km/h) at 3 ft/s^2 (0.9 m/s^2). Proceed at 50 mph (80.5 km/h) to the 2.0 mile (3.22 km) marker.
2.00	3.22	Stop at 4 ft/s^2 (1.2 m/s^2), idle 7 s, accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2). Continue accelerating to 25 mph (40.2 km/h) at 5 ft/s^2 (1.5 m/s^2). Continue accelerating to 40 mph (64.4 km/h) at 3 ft/s^2 (0.9 m/s^2). Proceed at 40 mph (64.4 km/h) to the 2.6 mile (4.18 km) marker.
2.60	4.18	Accelerate to 50 mph (80.5 km/h) at 3 ft/s^2 (0.9 m/s^2). Proceed at 50 mph (80.5 km/h) to the 3.3 mile (5.31 km) marker.
3.30	5.31	Stop at 4 ft/s^2 (1.2 m/s^2), idle 7 s, accelerate to 15 mph (24.1 km/h) at 7 ft/s^2 (2.1 m/s^2). Continue accelerating to 25 mph (40.2 km/h) at 5 ft/s^2 (1.5 m/s^2). Continue accelerating to 40 mph (64.4 km/h) at 3 ft/s^2 (0.9 m/s^2). Proceed at 40 mph (64.4 km/h) to the 5.2 mile (8.37 km) marker.
5.2	8.37	Stop fuel measuring and timing devices while driving at 40 mph (64.4 km/h) at 5.2 miles (8.37 km). Record fuel consumed, elapsed time, and fuel temperature.
0.0	0.0	Run recheck cycle.

8.3.4.8 *Interstate Cycle* (55 mph (88.5 km/h))—Average speed: 55 mph (88.5 km/h); running time: 308 s/cycle. After proper warmup (paragraph 8.1), the interstate driving cycle should be driven as follows:

Distance		Operation
miles	km	
0.0	0.0	Approach the starting line at 55 mph (88.5 km/h). At line, start fuel measuring and timing devices. Proceed at 55 mph (88.5 km/h) to the 0.2 mile (0.32 km) marker.
0.20	0.32	Accelerate to 60 mph (96.6 km/h) at 1 ft/s^2 (0.3 m/s^2). Immediately decelerate to 50 mph (80.5 km/h) at 1 ft/s^2 (0.3 m/s^2). Immediately accelerate to 55 mph (88.5 km/h) at 1 ft/s^2 (0.3 m/s^2). Proceed at 55 mph (88.5 km/h) to the 1.2 mile (1.93 km) marker.
1.2	1.93	Repeat accelerations and decelerations as at 0.20 miles (0.32 km). Proceed to the 2.2 mile (3.54 km) marker.
2.2	3.54	Repeat accelerations and decelerations as at 0.20 miles (0.32 km). Proceed to the 3.2 mile (5.15 km) marker.
3.2	5.15	Repeat accelerations and decelerations as at 0.20 miles (0.32 km). Proceed to the 4.7 mile (7.56 km) marker.
4.7	7.56	Stop fuel measuring and timing devices while driving at 55 mph (88.5 km/h) at 4.7 miles (7.56 km). Record fuel consumed, elapsed time, and operating temperature.
0.0	0.0	Run recheck cycle.

can be calculated using road vehicle simulators. Since such simulators are available to the general trucking industry on an ever increasing basis the necessity of a fuel economy testing procedure for heavy duty vehicles is lessened while the reliance on computer techniques for simulating the wide variety of vehicles, use patterns and load characteristics increases.

EPA is currently employing two engine dynamometer test sequences, one for gasoline engines having nine modes of operation at one engine speed and one for diesel engine having thirteen modes at two different engine speeds. The various modes are selected to cover the ranges of expected loading at representative engine speeds. The modes are weighted according to the expected frequency of operation to arrive at a composite emission rate. Fuel flow rate measurements are taken at each mode and are used for engine emission certification. At the present time these engine test schedules represent the only commonly used procedures for engine cycle testing. An expedient, weighted average fuel consumption value can be derived from such tests and used as a limited comparative tool. The major weaknesses in applying current EPA emission test procedures as fuel economy tests include: 1) representative vehicle miles traveled can not be determined since only the engine is involved; 2) the gasoline 9-mode test does not incorporate a full load test point, a characteristic operating mode for heavily weighted trucks; 3) the mode weighting factors may not be representative of *overall* truck usage.

3.2.3 Light Duty Tank Mileage

The approach taken in the determination of a statistical mix representing the driving modes for a light duty vehicle is based on the same data used in the Automobile Fuel Consumption Study. In the Automotive Study a paper generated by Mr. J.D. Murrell, Assistant to the Director of EPA's Advance Automotive Propulsion System Development Division, was used. We refer the reader to the rationale for the light duty tank mileage synthesis discussed in the Automotive Study[2] 1974 report. The synthesized year and tank mileage as given in Table 3.14 is taken directly from the above referenced study. This material was developed prior to the 55-mile an hour speed limit imposed throughout the United States by Executive Order. Subsequent to the 55 mile per hour posted speed limit the average types of driving speeds at the interstate and rural level have been changed to accommodate the lower speed limit. These are based on our best estimate as to a reasonable driving schedule for the year end tank mileage. These estimates are summarized in Table 3.15.

Further study of the FTP and eleven lap driving modes based on breakdown of the driving cycle by modes had led to a simplified composite consisting of

TABLE 3.14

LIGHT DUTY DRIVING PROFILE*

Miles Per Year	Reference Driving Cycle
2,730	F.T.P Federal Test Procedure
2,700	11-lap
1,000	40 mph State rural highways (Bur. Pub. Roads)
840	50 mph Interstate urban highways (Bur. Pub. Roads)
1,840	60 mph U.S. rural highways (Bur. Pub. Roads)
890	70 mph Interstate rural highways (Bur. Pub. Roads)

*J.D. Murrell, verbal communication to John Brogan, AAPS/EPA January 9, 1973.

TABLE 3.15

LIGHT DUTY VEHICLE DRIVING PROFILE BEFORE AND AFTER 55 MPH LIMIT

	Miles Per Year		% by Mode
	Pre 55 mph	Post 55 mph	Post 55 mph
FTP	2,730	2,730	27.3%
11-lap	2,700	2,700	27.0%
40 mph	1,000	1,500	15.0%
50 mph	840	1,870	18.7%
60 mph	1,840	800	8.0%
70 mph	890	400	4.0%
	10,000 total mileage	10,000 total mileage	100%

accelerations, decelerations, idle and cruise modes, designed to represent the various driving cycles. This composite analysis is given in Table 3.16. The merit of such an approximation was demonstrated in the Automotive Study[2] in Section 4.4 in which a simplified breakdown such as this was used to simulate the performance of four reference vehicles verifying the accuracy of such an approximation to within about 10% of the predicted computer results. This accuracy is deemed sufficient for a comparative type analysis for which the simulations are to be used. For further discussion of the nature of the composite driving cycle for light duty vehicles the reader is referred to Section 4.14 of the Automotive Report.*

3.2.4 Heavy Duty Tank Mileage

The statistical mix of driving modes for heavy duty trucks differs from that used in the light duty mileage simulation. This results from not having uniform vehicle testing procedures from which to obtain a composite driving cycle for heavy duty trucks. As discussed earlier current heavy duty tests are conducted on engine dynamometers not vehicle simulations. The rationale developed for handling the heavy duty trucks stems from statistical data[1] developed by ADL for the Department of Transportation by analyzing truck usage data and statistics prepared by the American Trucking Association (ATA).

A fundamental difference in the use of the composite driving cycle for heavy duty trucks became apparent in the desire to formulate a representative driving cycle. Namely, a light duty vehicle is designed to meet driving requirements over all the composite driving cycles, whereas heavy duty vehicles are often specifically designed for certain types of operation. Therefore, it would not be reasonable to run a single heavy duty truck for the three driving modes of local, short and long since the trucks in fact may not be used in this fashion. Therefore, a logical difference in the treatment of the light duty and heavy duty trucks arises in the composite driving cycle and the matching of the nature of the cycle to the particular vehicle. This matching of vehicle and driving mode was discussed in Section II, dealing with the reference vehicle selection and is shown in Table 3.1.

TABLE 3.16

COMPOSITE DRIVING CYCLE FOR LIGHTWEIGHT VEHICLE
10,000 GVW AND UNDER

Annual Miles	F.T.P. 7.46 mi 2,730 mi	11-Lap 2,700 mi	Cruise Portion	Total Miles
	Distribution by % of Distance 10,000			
Accelerations				
1.0 mph/sec				600 mi
1.46 mph/sec	22%			
2.0 mph/sec		16%		432 mi
2.5 mph/sec				
Cruise				
20 mph				
30 mph	60%	15%		2,043 mi
40 mph		42%	1,500 mi	2,634 mi
50 mph		16%	1;870 mi	2,302 mi
60 mph			800 mi	800 mi
70 mph			400 mi	400 mi
Decelerations	18%	11%	0	789 mi
Time at Idle and Deceleration	52 hrs.	18.7 hrs		70.7 hrs.

4. FUEL CONSUMPTION AND WHERE THE ENERGY GOES

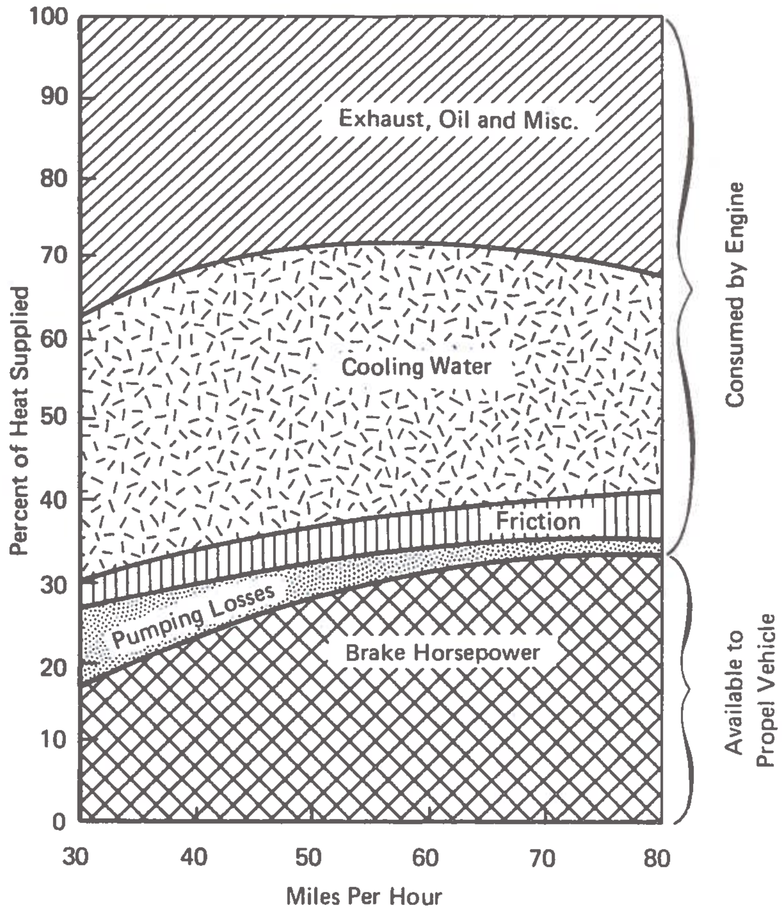
4.1 BREAKDOWN OF WHERE THE ENERGY GOES

The ratio of available energy to useful work performed by a fuel is limited by engine thermodynamic efficiency. The portion of this energy made available to the drive train by the engine is shown in Figure 4.1. The remainder of the energy is partitioned among exhaust gas, cooling water, engine friction and pumping losses. This distribution of energy is also true for the diesel engine shown in Figure 4.2. As can be seen in these figures the distribution of energy is quite different for the gasoline engine and the diesel engine. Engine friction is somewhat higher in the diesel engine due to higher sealing pressures required to maintain the higher mean pressures sustained in the cylinder while pumping losses are reduced since it is a free breathing, unthrottled engine. However the exhaust carries off less heat as a result of greater gas expansion due to increased compression ratio and the ability of the diesel to use more energy out of these expanding gases. For a more complete discussion of the breakdown of energy in the engine refer to the Automobile Fuel Consumption Study[2] and Section 5.2 of this report.

The useful horsepower output of the gasoline engine lies between 19 and 30% of the input fuel energy while the diesel may provide between 20 and 40% of the input energy as useful work. The remainder of the energy is inextricability loss to the exhaust, cooling water, and engine friction. Clearly, the engine is the fundamental energy consumer of the vehicle accounting for at least 60% of the input energy. It is the first and foremost element of the vehicle considered for technological improvements because of its dominance in the partitioning of useful and non-useful energy. A further partitioning of the useful energy in propelling the vehicle is discussed in the following paragraphs.

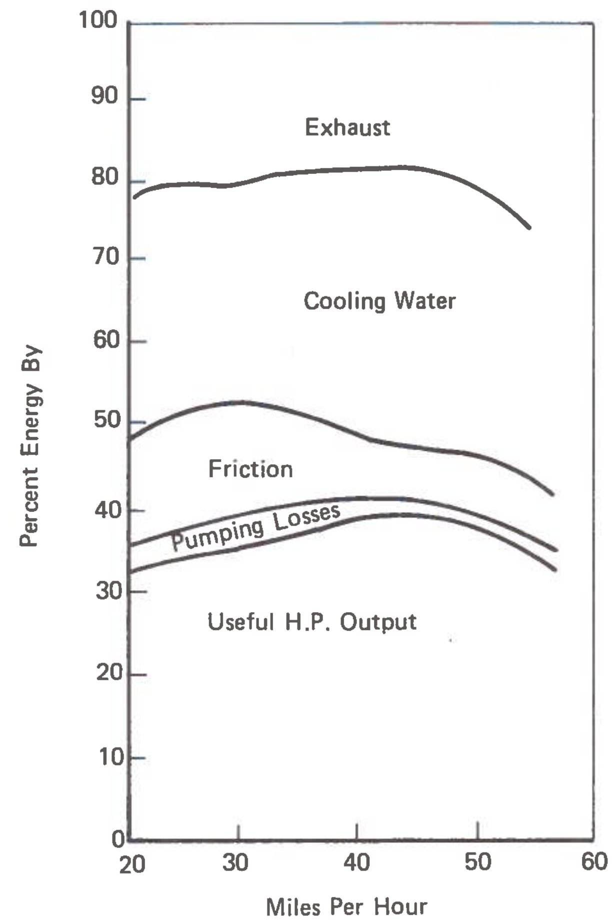
4.2 DRIVE TRAIN AND OTHERS

For the selected referenced vehicles computer simulation was performed at ADL to identify the partitioning of useful work developed by the engine in the subsequent drive train and other vehicle elements. The fuel economy improvements to be gained in changes in elements other than the engine are confined to the portion of the energy that is usefully delivered by the engine, representing about 30% of the input energy. A simulation of vehicles in weight class I, II, VI, and



Based on average performance
of gasoline engines.

FIGURE 4.1 ENERGY DISTRIBUTION IN A 4-STROKE GASOLINE ENGINE



Based on a 4-stroke 672 CID engine
with a 73,280 GVW, 100 sq ft frontal
area tractor-semitrailer, geared to
optimum operation at 55 mph with a
10 speed on manual transmission.

FIGURE 4.2 ENERGY DISTRIBUTION IN A 4-STROKE DIESEL ENGINE (ADL SIMULATION)

VIII was made using the ADL Simulation Program, resulting in data showing the distribution of energy delivered by the engine. The input data is tabulated in Table 4.1. Figures 4.3, 4.4, 4.5 and 4.6 show the distribution of energy delivered by the engine at constant vehicle speeds.

During steady driving substantial portions of the energy go to overcome rolling resistance and aerodynamic drag. Other important power consumption items are the torque converter, rear axle, and transmission.

For accelerations above 1.0 MPH per second vehicle inertia is the primary power consumption element. Second is the torque converter. Rolling resistance and accessories then become three and four while aerodynamic, rear axle, and transmission losses are lowest.

4.3 BASE LINE VEHICLE PERFORMANCE

4.3.1 Fuel Economy – Base Line Vehicles

The fuel economy results of computer simulation at ADL and by Cummins for the reference vehicles over the driving cycles indicated in Section 3 are shown in Table 4.2.

The acceleration performance or gradability set for the vehicles used in the computer simulation runs was maintained at the same level as the baseline reference vehicles. This allowed direct comparison between fuel economy results. The gradability is the measurement of the percent grade for which the vehicle may climb while maintaining a predetermined operating speed. This is the measure of the excess power available for both grades and for acceleration. It is important to recognize that a reasonable gradability requirement was placed on the vehicle so that it was representative of real vehicles used for its weight class. The matching of the engine and transmission for each of the reference vehicles was made in such a fashion that gradability and fuel economy performance characteristics are representative of vehicles sold in the United States as indicated in Section 3.1, Selection of Reference Vehicle.

4.4 FACTORS AFFECTING FUEL CONSUMPTION

4.4.1 Effect of Emissions on Fuel Consumption

As discussed in Section 2.5, emission control is a primary concern in the examination of improvements in truck fuel consumption. The scope of project did not include an in-depth study of the effects of emissions on truck fuel economy.

TABLE 4.1

DATA BASIS SPECIFICATIONS AND ASSUMPTIONS USED FOR SIMULATION OF ENERGY DISTRIBUTION

Configuration	Axle Ratio	Axle Efficiency (%)	Transmission Number of Speeds Type and Ratio	Gross Vehicle Weight	Rolling Resistance Coefficient[1] for Trucks		Front Area Square Feet	Drag Coefficient	Revolution per Mile of Driving Wheel
					C_1	C_2			
Pickup	3.00	0.96	3-auto 2.46 1.46 1.00	6,200#	.012	.00009	48.0	0.60	750
Camper	3.73	0.96	3-auto 2.46 1.46 1.00	10,000#	.012	.00009	60.0	0.65	750
Van	6.80	0.96	4-manual 4.2 2.29 1.19 1.00	22,000#	.0068	.000007	80.0	0.65	523
Tractor-Semi-trailer (XX2)	4.10	0.96	10-manual 8.00 6.30 4.99 3.95 3.2 2.51 1.97 1.56 1.23 1.0	48,860#	.0068	.00007	108.0	0.70	498

1. Rolling Resistance = $C_1 + C_2$ x vehicle M.P.H.

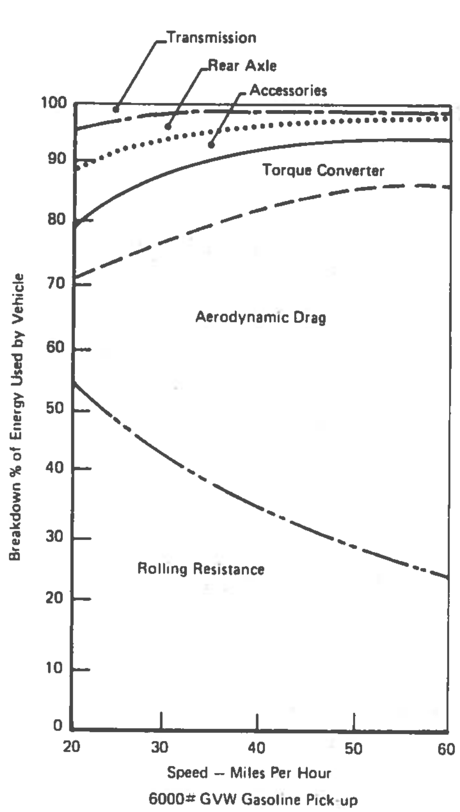


FIGURE 4.3 ENERGY PARTITIONING OF 6000# GVW PICK-UP VEHICLE DURING STEADY CRUISE

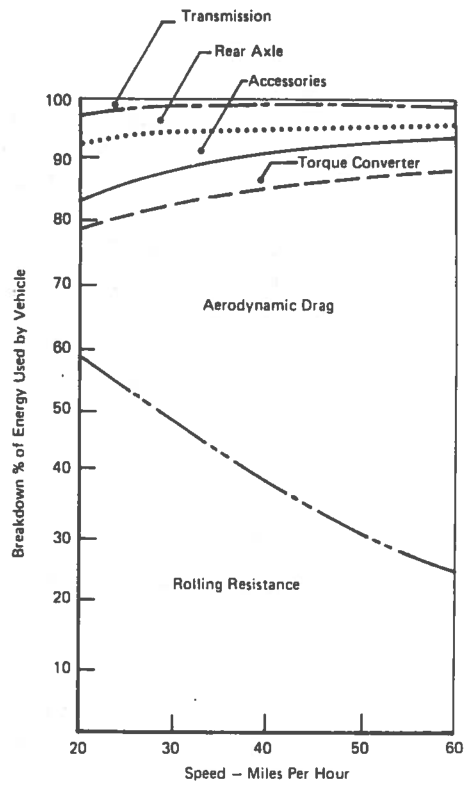


FIGURE 4.4 ENERGY PARTITIONING DURING STEADY CRUISE FOR 10,000# GVW CAMPER VEHICLE

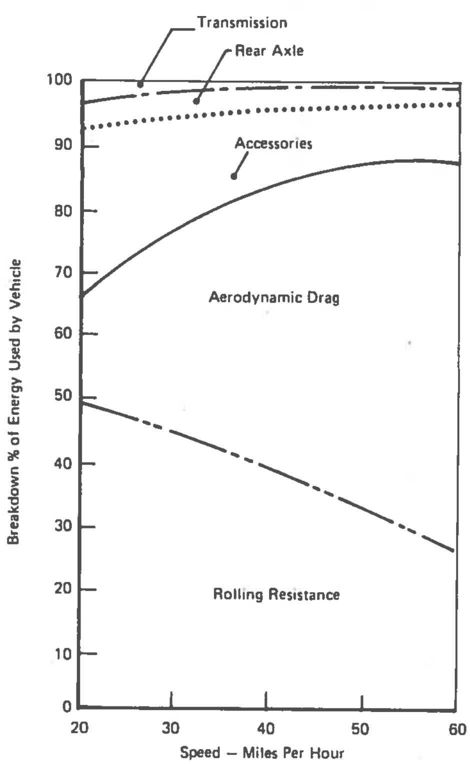


FIGURE 4.5 ENERGY PARTITIONING DURING STEADY CRUISE OF 22,500# GVW GASOLINE VAN TRUCK

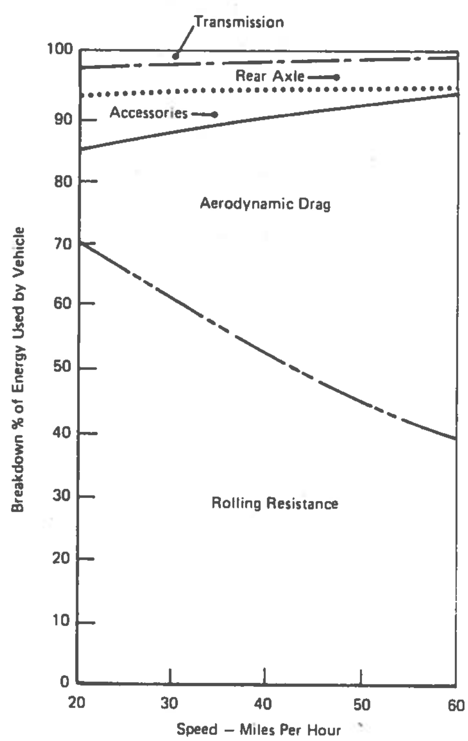


FIGURE 4.6 ENERGY PARTITIONING DURING STEADY CRUISE OF 73,000# GVW TRACTOR–SEMITRAILER

TABLE 4.2

BASELINE FUEL ECONOMY FOR LIGHT DUTY PICK-UP TRUCKS LOADED TO CAPACITY

Pick-up 6000# GVW		Camper 10,000# GVW	
MPH	MPG	MPH	MPG
20	11.2	20	8.0
30	15.5	30	12.3
40	14.5	40	10.5
50	12.2	50	9.1
55	11.4	55	8.4
60	10.5	60	7.0
70	7.8		

Yearly Tank Milieage* 11.7 MPG   Yearly Tank Mileage* 8.8 MPG

BASELINE FUEL ECONOMY FOR MEDIUM AND HEAVY TRUCKS LOADED TO CAPACITY

Fuel Economy in MPG

	Local	Short	Long
Tractor-Semi-trailer 50,000# GVW	–	4.8	4.9
70,000# GVW	4.0	4.0	4.5
Dump Truck	5.0	5.0	–
Van Truck 22,500# GVW	5.1	5.4	–

*See Table 3.16.

A brief summary of present standards and probable future standards will provide the reader with the complexity of the problem.

At present there are two truck emission regulations, one for light duty vehicles 0 to 6,000# GVW and one for heavy duty vehicles. The present and expected emissions are shown in Table 4.3. At the writing of this report the future standards are tentative, though we believe that those given are likely to be implemented. In the future the light duty standards may be extended to trucks weighing 8,000# GVW or even 10,000#.

The difference between the light duty and heavy duty emission standards is quite apparent in this Table 4.3. Light duty vehicles are evaluated on a gram per mile basis penalizing heavier vehicles with larger engines, while the heavy duty emissions tests are based on engine dynamometer tests alone, putting no obvious limitation on the vehicle system as a whole.

These standards are federal standards; California has more stringent standards. The California standards have a substantial impact on fuel consumption improvement techniques, and consideration for meeting these standards was beyond the scope of this study.

To clarify the impact of the emission standards on the heavy duty trucks we have summarized the industry response to the emission requirements in Table 4.4.

TABLE 4.3

TRUCK EMISSION REQUIREMENTS

For 1975

Vehicles 6,000 and Less (grams/mile)		Vehicles Over 6,000 lb (grams/B.H.P. – hr)	
HC	1.5	$HC + NO_x$	16
NO_x	3.1	CO	40
CO	15		

For 1977 and Beyond

Vehicles 10,000 and Less* (grams/mile)		Vehicles Over 10,000 lb (grams/B.H.P. – hr)	
HC	.41	$HC + NO_x$	16
NO_x	(0.4 in 1978)	CO	40
CO	3.4		

*Arthur D. Little, Inc., estimates.

TABLE 4.4

ALTERNATIVES CONSIDERED BY INDUSTRY TO MEET 1975 STANDARDS

Engines

Gasoline Engine — Heavy Duty

Standard	Carburetor	Intake Manifold	Exhaust Manifold	A/F Ratio
CO	Finer control, more constant A/F ratio	Better distribution by evening path lengths	air injection	run leaner than 15.5 — CO nearly eliminated
HC	Finer control, more constant A/F ratio	Improved uniformity so that misfire at lean ratios does not occur	air injection	
NO_x	Finer control, more constant A/F ratio	Exhaust gas recircu-lation EGR		leaner ratio

Diesel Engines — Heavy Duty

Standard	Combustion Chamber	Injection	Exhaust Manifold	Intake Manifold
Smoke	Air swirl or prechamber	Increased rate and advanced	Exhaust catalyst possible	Turbocharging reduces smoke
NO_x	Direct injection emits more NO_x than indirect	Retard injection		Exhaust gas recirculation
HC & CO	Are generally not considered a problem in diesel engines and little, if any, changes are made to accommodate the emission std for these levels.			

Sources: International Harvester Letter to EPA, July 19, 1974 on Emissions.
Ricardo, A Study of the Diesel as a Light-Duty Power Plant, EPA (460), July 1974.

5. TECHNOLOGICAL IMPROVEMENTS IN FUEL ECONOMY

5.1 INTRODUCTION

During the study, the technical and marketing departments of several truck manufacturers were visited. Manufacturers visited were:

Company	Location	Principal Contact	Date
Mack Truck	Allentown, Pa.	L. C. Donnelly	10/25/75
		L. A. Lucchetti	10/25/74
General Motors	Detroit, Mich.	George Hanley	11/2/74
Ford Truck	Dearborn, Mich.	R. H. Shackson	11/1/74
		J.H. Culbertson	
		R.Z. Beauvais	
International Harvester	Ft. Wayne, Ind.	Robert Burton	10/24/74
		R. Eugene Wallace	
Cummins Engine Company	Columbus, Ind.	Mariann Zimmerman	10/24/74
		Don Klokkenga	

Comments regarding innovations were solicited and improvement performance data was obtained. During the manufacturing contacts, additional comments and data obtained by the Dept. of Transportation and Environmental Protection Agency from a wide mailing request were discussed and analyzed.

The material obtained by DOT-EPA was made available in the form of a *Public Docket*. The docket, a library of industry fuel economy for trucks, was in a response to the Energy Supply and Environmental Coordination Act of 1974, Section 10 Fuel Economy Study. A partial list of respondents to the docket is given below.

Partial List of Respondents to Public Docket, Used in This Study

Person	Company	Date
D.A. Jensen	Ford Motor Co.	August 20, 1974
Fred Bowditch	General Motors Corp.	August 23, 1974
R.L. Staadt	International Harvester Corp.	August 6, 1974
John Hampton I.G. Detra	Mack Truck Inc.	August 22, 1974
S.L. Terry	Chrysler Corp.	August 27, 1974
Richard Frank	Caterpillar Tractor Corp.	August 13, 1974
Carl Canfield	Schwitzer	August 14, 1974
W.A. Bresnahan	American Trucking Associations (ATA)	August 16, 1974
Fred G. Favor	Local and Short Haul Carrier National Conference, ATA	August 20, 1974
Charles Laulor	Trucking Equipment Supply Company	August 5, 1974
Charles Selly	Horton Industries, Inc.	August 8, 1974
Douglas Hughes	Heavy & Specialized Carrier Conference, ATA	August 9, 1974
Arthur Huebner	Hyster Company	August 1, 1974
Harvey Weaver	Motor Vehicle Mfg. Association	August 19, 1974

Person	Company	Date
Thomas Young	Engine Manufacturers Association	August 15, 1974
Frank E. Timmons	Rubber Manufacturers Association	August 23, 1974
Murray Aitken	PACCAR, Inc.	August 13, 1974
Stanley Hamilton	National Association of Motor Bus Owners	August 13, 1974

As the study developed it became apparent that a number of innovations useful in one reference vehicle would not improve fuel economy in another. In addition, a number of innovations would not meet the 1980 implementation time frame and could not be considered for the study. A screening was necessary to sort out which innovations could be considered for each vehicle. Table 5.1 is a Summary of the Innovations considered for each vehicle. A number of innovations were not considered further, and in these cases a discussion of the innovation has not been included in this report. These innovations were discussed in Reference 2.

5.1.1 Improvements Considered in the Study

Diesel Engine

The substitution of diesel engines was considered for both light and medium duty vehicles (weight Class VI considered a medium duty). The diesel was not considered an innovation for the heavy duty class because new trucks in this class are usually equipped with this type of engine. However, improving the fuel economy of diesel engines by turbocharging and lowering engine speed was considered for existing diesel engines in the heavy duty category. The substitution of a diesel engine for a gasoline engine was accomplished by selecting the engine which appeared to offer best brake specific fuel consumption (BSFC) and correct horsepower range.

Improvements in fuel economy by reducing the exhaust back pressure indicated a 0-3% gain. However, this small gain in fuel economy would be offset by increased exhaust noise, at least with conventional exhaust silencer systems therefore this technique was not considered further.

Derated RPM of diesel engines was considered in depth as discussed in Section 5.3.2.

TABLE 5.1

PRELIMINARY SELECTION OF FUEL ECONOMY IMPROVEMENTS AND PROBABLE LEAD TIME FOR PRODUCTION

Possible Within Time Frame

FUEL ECONOMY IMPROVEMENT	PRESENT TO 1980 MODEL YEAR			1981 – 1985 MODEL YEAR			1986 and AFTER MODEL YEAR			FUEL ECONOMY IMPROVEMENTS CONSIDERED		
	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy
ENGINE IMPROVEMENTS												
Diesel Engines												
Diesel Instead of Gas			√	√	√					+	+	–
Turbo-Charge Diesel			√	√	√					+	+	+
Reduced Exhaust Pressure	√	√	√							–	–	–
Derated RPM			√							–	–	+
Spark Ignition Engines												
Lean-Burn Concepts	√	√								+	–	–
Stoichiometric Closed Loop	√									+	–	–
Fuel Injection	√	√								+	–	–
Improved Ignition	√	√								+	–	–
Improved Intake Manifolding	√	√								+	–	–
Turbo-Charging				√	√					+	–	–
Stratified Charge				√	√					+	–	–
Variable Displacement				?	?					–	–	–
Water Injection										–	–	–
Accessories												
Modulating Fan	√	√	√	√	√	√				+	+	+
Constant Speed Drive										–	–	–
Alternate Engines												
Wankel				√	√	?				–	–	–
Gas Turbine							?	?	?	–	–	–
Rankine							?	?	?	–	–	–
Stirling							?	?	?	–	–	–
Improved Lubricants	√	√	√							–	–	–
POWER TRAIN												
Manual Transmission	√	√	√							–	–	–
Semi-Automatic			√							–	–	–
3-5 Speed Automatic w/Lock-Up	√	√	√							+	+	+
										–	+	+
Continuously Variable Transmission			√	√	√					+	–	+
Lower Axle Ratio	√	√	√							+	–	–
Radial Tires	√	√	√							+	+	+
Single Wide Base Tires	√	√	√							–	–	+
Single Drive Rear Axles			√							–	–	+
AERODYNAMICS												
Wind Deflector			√							–	–	+
Vortex Stabilizer			√							–	–	+
Reduced Frontal Area	√	√	√							+	+	–
Smooth Surfaces and Styling	√	√	√							+	+	+
TARE WEIGHT REDUCTION												
Material Substitution	√	√	√							+	+	+

√ Time of earliest incorporation as fuel economy measure
\+ Considered for this study – major improvement
– Not considered for this study either minor improvement, already incorporated, or not applicable to weight class
? Technology not developed far enough to be applicable

Spark Ignited

As indicated in Table 5.1, spark ignited engine innovations were not considered for vehicles in the medium and heavy duty class. This judgment is based on the belief that for the future diesel engines will be chosen over gasoline engines in the heavy duty weight class. Furthermore, diesel engines are growing in acceptance at the low end of the heavy duty weight class. This assessment is supported by projections by Caterpillar Tractor Company[3] which show substantial potential penetration of diesel engines in the Class VI and nearly total penetration in the heavier trucks.

The near term fuel economy gains with the diesel substitution, its longer life, and growing acceptance by truck owners for the medium-heavy duty class make it the most realistic engine innovation choice in the 1980 time frame for the medium and heavy trucks.

While attendant possible advantages of multi-fuel capability for the stratified charge may seriously challenge the diesel's growing popularity in the medium and heavy duty weight classes, the questions of manufacturability and hence availability must be considered. At present, we know of no manufacturer seriously considering the stratified charge for heavy duty applications. If this is indeed the case, it is unlikely that stratified charge engines will substantially penetrate the heavy duty market within the five-year time frame because of development and production lead times.

As indicated above, the stratified charge engine does have some significant advantages over gasoline and diesel engines. The Texaco engine[4] is a stratified charge engine capable of using a variety of fuels including members of the diesel class of middle distillates. The multi-fuel capability has received attention from the Army because of material logistic considerations. However, engine production lead time is a severe constraint, as at present only a few prototype engines have been made. The multi-fuel capacity permits a wider latitude of refining procedures and optimization. Because of the reduced octane and/or cetane capability of such a stratified charge engine, refiners may deliver acceptable stock at reduced refinery energy cost and at increased refinery output. While consideration of the effects of the balance of refinery output and vehicle fuel is not within the scope of the study we feel that in the future the multi-fuel stratified charge engine will have merit on a total energy system basis.

A number of innovations were judged as having a minor or negative effect on fuel economy or as having a development time outside of the Study Time Frame of 1980-1981. These innovations, not considered further, are assembled in Table 5.2 along with brief explanations as to why they were discarded.

TABLE 5.2

POSSIBLE IMPROVEMENTS NOT CONSIDERED FURTHER

Improvement	Reason for Exclusion
Variable Displacement	Concept development not within time frame.
Water Injection	In itself has not been shown to improve fuel economy. As a knock limiter it may be used in conjunction with turbocharging, advanced timing or increased compression ratio.
Wankel	Not within time frame of this study for trucks. Has not shown fuel economy, durability necessary for use in trucks.
Rankine	Not within time frame of study, and has not shown improvement in fuel economy.
Stirling	Promising fuel economy potential however not within study time frame.

Accessories

The modulated cooling fan was considered for all the vehicles while the constant speed drive (see Section 4.3.5.3 of Reference 2) was not considered further.

Alternative Engines

While the time frame for the introduction of the alternative engine concepts shown here is beyond the time allowable for consideration in this study, a brief review of the Gas Turbine Concept is given in Section 5.5. Of all the alternative concepts, the Gas Turbine is most likely to penetrate the heavy truck market first, because of its durability, potential for low maintenance cost, and specific power advantages.

Improved Lubricants

Studies[5] indicate a reduction in motoring friction by the use of additives to the motor oil. Recent studies[6] indicate that such additives may reduce engine friction by 8 to 12% giving a 2-4% improvement in fuel economy. We feel that the use of improved lubricants for reduced friction and increased engine life will have a growing place in the truck market. This area deserves further investigation.

Power Train — Aerodynamics — Weight Reduction

In the areas of power train, aerodynamics and weight reduction innovations, a complete discussion follows in Sections 5.7, 5.8, and 5.9 respectively.

5.1.2 Summary of Percent Improvement in Fuel Economy by Individual Improvements

Light Duty Class I and II

A detailed review of the literature and discussions with manufacturers has led to the finding that innovations applicable to automobiles are equally applicable to light duty trucks weight classes I and II. The findings of the Automobile Fuel Consumption Study (Reference 2) have been updated and applied directly to the two light duty vehicles and the results are given in Table 5.3

TABLE 5.3

SUMMARY OF PERCENT IMPROVEMENT IN FUEL ECONOMY (MPG) BY INNOVATION FOR LIGHT DUTY TRUCKS

WEIGHT CLASS 1 AND 2

Innovation	Light Duty Annual Mix % (Representing Personal, Not Business Usage)
Engine	
Substitute Diesel	20-35
Lean Burn	10-15
Closed Loop Stoichiometric	10-15
Turbocharge (gasoline)	5-10
Stratified Charge	15-25
Cooling System	2-3
Power Train	
Transmission	
4 speed auto and lockup	7-15
Continuously Variable Ratio Transmission	12-30
Radial Tires	2-3
Aerodynamics — 10% reduction in drag	1-2
10% Weight Reduction of Vehicle in Unloaded Condition	2-3

Medium and Heavy Duty Trucks

The percentage improvements for individual innovations applied to the van (medium duty weight class) and the three heavy duty trucks are summarized in Tables 5.4 – 5.5. They are a result of the analysis discussed in Section III using both the ADL Simulation Program and the Cummins Vehicle Mission Simulator. However, as noted by italics in the Summary table and as discussed in the individual sections describing the innovations certain innovations could not be simulated due to the lack of representative data, and in these cases the developer or manufacturers experimental data on fuel savings were used.

TABLE 5.4

SUMMARY OF PERCENT IMPROVEMENT IN FUEL ECONOMY (MPG) BY INNOVATION FOR WEIGHT CLASS VI

	Van Truck Type Duty Cycle	
	Local (%)	Short (%)
• Gas Engine		
Reduce Aero Drag	2	2
Substitute Radial Tires	6	9
Modulated Fan Control	3	4
• Substituted Diesel	60	55
4 Speed Auto. Trans. and Lock-up	(0-10)	(0-10)

90% of the fuel consumed by this class (VI) vehicle is in local service

( ) denotes ADL estimated since computer simulation could not be made.

TABLE 5.5

SUMMARY OF PERCENT IMPROVEMENT IN FUEL ECONOMY (MPG) BY INNOVATION FOR HEAVY DUTY TRUCKS OF WEIGHT CLASS VIII

	Truck Type					
	Dump Truck Duty Cycle		Tractor-Trailer 50,000 lb GVW Duty Cycle		Tractor-Trailer 70,000 lb GVW Duty Cycle	
	Local (%)	Short (%)	Short (%)	Long (%)	Short (%)	Long (%)
Reduce Aero Drag	1	1	1	3	1	2
Substitute Radial Tires	9	6	6	6	9	8
Derate Engine Speed	-0-	1	1	2	6	4
Modulated Fan	3	4	5	5	5	4
Tag Axle	2	2	2	2	2	2
Turbocharge	(1)	(3)	(3)	(4)	3	4
CVRT*	(10-15)		(10-15)	–	(10-15)	–

( ) denotes ADL estimate since computer simulation could not be made

*Continuously Variable Ratio Transmission (CVRT)

5.2 DIESEL SUBSTITUTION FOR SPARK IGNITED ENGINE

Fuel utilization by the diesel engine and the gasoline engine can best be understood by examining how the fuel energy is used to develop useful work. Consider the *indicated work* as the work of the expanding hot gases on the piston in the engine and the piston work delivered to the engine drive line, as the *brake thermal work*. The indicated power available in the cylinder to do work is reduced by mechanical inefficiencies to the level of the brake power delivered as useful work output.

The indicated thermal efficiency of a gasoline engine and a diesel engine are nearly totally a function of the compression ratio which is the ratio of the volume of the combustion chamber at the bottom of the stroke divided by the volume occupied by the gases at the top of the stroke. Based on indicated thermal efficiency it can be shown that at equal compression ratios a diesel engine is somewhat less efficient than a gasoline engine. This is due to the higher temperatures and pressures achieved by the gasoline engine for such a compression ratio. However, gasoline engines rarely have compression ratios greater than 10:1 while diesel engines operate at compression ratios between 14 and 24:1. In the gasoline engine the lower compression ratio is necessary to prevent uncontrolled combustion prior to initiation by a spark. Whereas in the diesel engine the high compression ratio is used to heat the intake air to a level at which the injected fuel will self ignite. This means that the high temperatures and pressures achieved during the compression stroke in a diesel are sufficient to ignite the fuel/air mixture ratio without the aid of a spark. This fundamental difference in compression ratios between the spark ignition and compression ignition engine contributes to limit gasoline engine thermal efficiency to approximately 30 to 35% of the energy in the fuel while the diesel engine may have thermal efficiencies in excess of 42%.

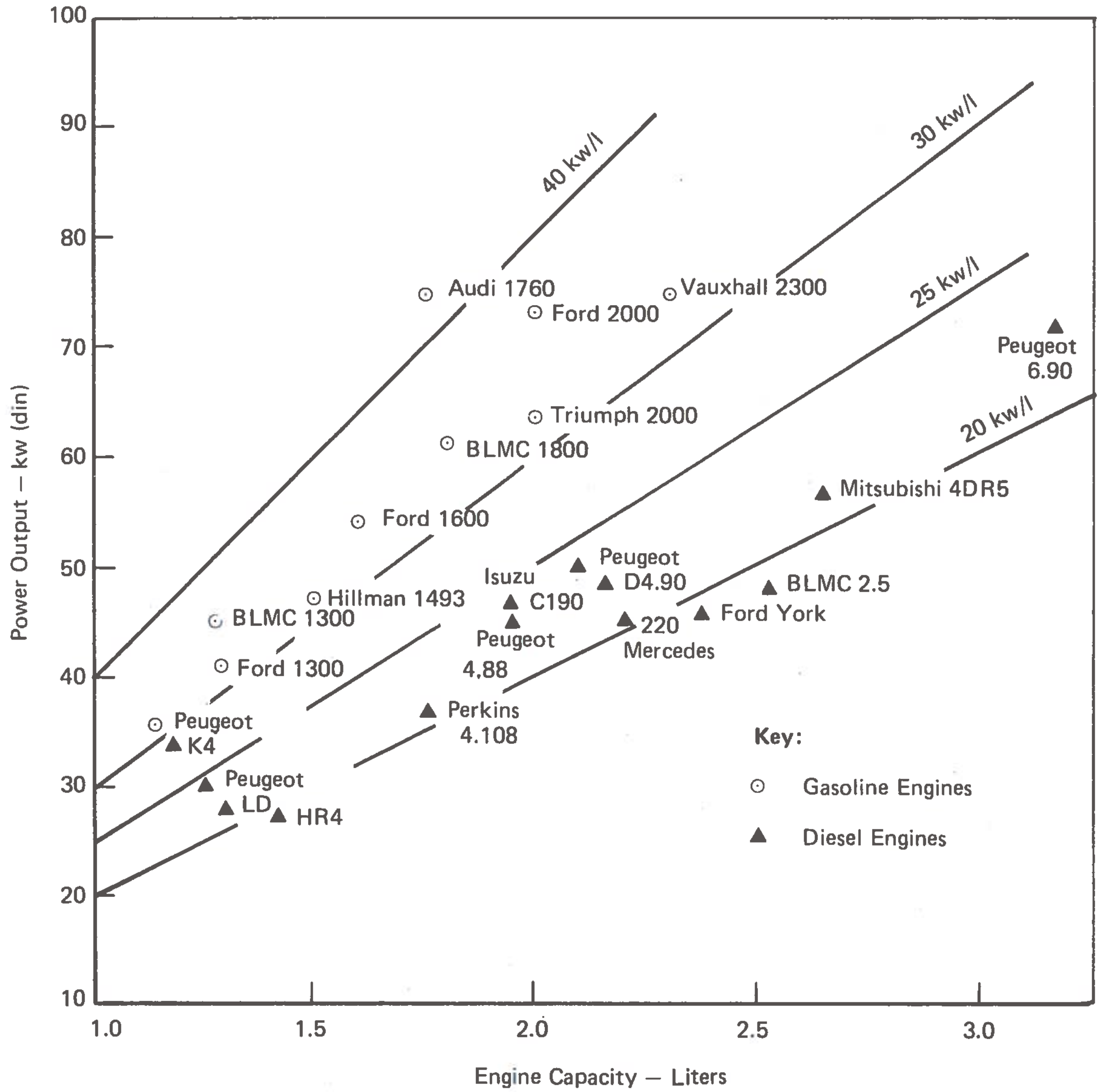
The amount of energy consumed in moving the piston in the cylinder absorbs a portion of the work delivered by the expanding gases during the expansion stroke. The sliding friction of the piston in the cylinder creates mechanical friction losses which detract from the amount of work the engine is able to usefully deliver. At any given piston speed a gasoline engine will have anywhere between 10% and 50% less frictional loss (see Figure 4.2) than a comparable diesel engine. Another form of power loss is due to the energy necessary to draw fresh air into a cylinder for the combustion process. In a diesel engine air is drawn freely into the cylinder without restriction. In a conventional gasoline engine the quantity of air ingested is limited by the carburetor throttle plate. This means that during the intake stroke of a gasoline engine the piston must draw air through a quantity limiting restriction. This creates pressure losses above those of a diesel engine which subtract from the gasoline engine useful work output. This situation is aggravated at light loads as during engine idling or low speed urban driving when the gasoline engine is most heavily throttled.

A major limitation on the use of diesel arises from the lower specific power of the diesel engine versus the gasoline engine. Specific power is the engine output power per pound of engine, and is a measure of the potential performance. Since a higher specific power means more power per pound and a smaller engine, a higher accelerating potential is achievable. The diesel has lower specific power than a gasoline engine for two reasons. First, because of higher peak pressures on a liter to liter displacement capacity comparison, a diesel engine weighs more than a gasoline engine. This is seen in the following figure (Figure 5.1) taken from the Ricardo Report to EPA.[7] Second, on a liter to liter comparison, the energy density of the fuel/air mixture charge is lower in a diesel engine than a gasoline engine. This is because nearly all the air drawn into a gasoline engine can be mixed with fuel for combustion; where as in the diesel excess air is maintained to prevent smoke. This is due to the nature of the combustion process, in which the diesel engine relies on mixing of the fuel in the combustion chamber during combustion. In the gasoline engine the fuel is premixed with air. During the combustion process there must be a plentiful supply of oxygen and sufficient time for complete combustion, otherwise incomplete combustion occurs and carbon particles are formed which appear as black smoke in the exhaust. Legislated limits on smoke production by a diesel engine limit the energy density of injected fuel in the cylinder. To avoid smoke production the diesel injection system must be limited to a fuel density level guaranteeing complete combustion of particles so that black smoke is avoided. This represents the limit on the specific power in a diesel engine resulting in an overall lower power-to-pound and power-to-volume ratio for a diesel engine as compared to gasoline engines. It must be kept in mind that turbocharging or supercharging will permit reducing the diesel engine size which will partially offset weight increase.

On a per horsepower basis, a diesel engine is heavier and larger than a comparable power gasoline engine. This means that a one-for-one exchange of a gasoline engine for a comparable powered diesel engine cannot be arbitrarily made without accommodating the larger volume, heavier weight engine with some changes in the engine compartment design.

Another possible major limitation toward the use of diesel engines is the production capacity of diesel manufacturers. Presently diesel engine production is not able to keep up with the growing demand for diesels in the heavier duty weight class, and production capacity is being increased in an attempt to meet the demand.

A diesel powered truck is more expensive than a comparably sized gasoline truck. The engine itself is made to closer tolerances to prevent variation in compression ratio and is equipped with a direct fuel injection system which is more costly than comparable carburetion and ignition systems used on gas engines. The engine is heavier and is generally designed for greater durability.



Moneghan, M.L., et al., "A Study of the Diesel as a Light-Duty Power Plant," EPA-460/3-74-011, July 1974.

FIGURE 5.1 POWER/LITER OF SOME CURRENT GASOLINE AND DIESEL ENGINES

These factors also affect the cost of the truck itself which is generally more durable and heavier in order to match the increased life and size of the diesel engine. Recommended retail prices for substitution of a present diesel into the higher weight class VI pickup and delivery service are approximately $4000 to $6000. Comparable figures for other diesel substitutions show the following.

Type Vehicle	% Cost Increase in Diesel Substitution
Cab over-tractor 30,000# GVW	27%
Fuel delivery truck 33,560# GVW	22%

As discussed in Section 2, the light duty truck is used primarily for personal service. Its duty and design are so nearly the same as the auto that it was felt that improvements would have nearly the same impact on the light duty truck as they did in the automobile. The accuracy of this assumption can be seen in the comparison following (Figures 4.3 and 4.4), showing the partitioning of energy in propelling a light duty truck compared with a car, which shows the larger similarity between automotive and pickup truck fuel usage.

Table 5.6 shows the effect of substituting a diesel in 4 different cars. These figures represent the kind of fuel economy improvement that could be expected from a diesel substitution into a light weight truck with the emissions meeting the interim 1977 standards* for automobiles rather than pick-ups.

The percent improvement in fuel economy lies between 20 and 30% for the F.T.P. and 20% to 40% for steady driving. The figures are necessarily conservative since emission constraints for the light duty automobile have been applied. It must be recognized that the light duty truck weighs 35 to 45% more than the standard automobile, that a 10 to 15% increase in fuel consumption would result from this increase in weight, and that an estimated comparable emission increase would occur. (See Table 5.7.)

These estimates are based on figures developed by Ricardo Engineers, Ltd. in the Automobile Study. The design is based on a prechamber 326 CID diesel engine rated at 150 HP at 4000 RPM.

*Level set January 15, 1975.

TABLE 5.6

EFFECT ON FUEL ECONOMY OF DIESEL SUBSTITUTION IN 4 CASES

		Miles per Gallon per Automobile							
	Fuel Type	F.T.P.	30	40	50	60	70 MPH	MPG Composite Cycle	% Improvement in Fuel Economy for Annual Mix
Case 1 Standard	Gas	11.0	19.0	19.8	18.6	16.5	14.6	16.5	15
	Diesel	14.3	22.5	22	20.3	18.2	15.9	18.9	
Case 2 Standard	Gas	10.4	18.6	18.5	17.3	15.4	14.0	15.4	27
	Diesel	14.4	23.6	23.1	21.2	18.9	16.5	19.6	
Case 3 Compact	Gas	17.4	27.9	27.1	23.8	20.7	17.8	22.7	26
	Diesel	21.8	32.1	29.8	26.6	23.2	20.0	28.6	
Case 4 Compact	Gas	13.8	21.7	20.4	19.4	16.9	13.5	17.8	33
	Diesel	20.5	32.6	29.2	26.0	22.6	19.5	23.7	
								Average	25%

Source: Arthur D. Little, Inc., estimates, based on Reference 2, op. cit.

TABLE 5.7

EMISSION STANDARDS & ESTIMATED LEVELS IN GRAMS/MILE

	Pick-Up and Auto Standard		Level of Diesel in 4200# Car	Estimated Level in 6000# Truck
	1975-1976	Future*		
HC	1.5	.41	.4	.5
CO	15	3.4	3.5	5.0
NO_x	3.1	2.0*	2.25	3.0

*ADL Estimate

The fuel economy gains shown in Table 5.8 for the medium duty vehicles were derived from simulations of vehicles with diesel (turbocharged and derated) engines substituted for gasoline engines. Under current standards NO_x and HC levels are combined (NO_x + HC) and specified on a per horsepower hour basis for heavy duty diesel engines. This gives the manufacturer a wide latitude of design freedom permitting higher levels of NO_x emissions while meeting the HC and NO_x level since the diesel has extremely low levels of HC. The results of the computer analysis for the substitution of the diesel in the weight class VI are shown in Table 5.8.

TABLE 5.8

FUEL ECONOMY IMPROVEMENT FOR DIESEL SUBSTITUTION INTO A MEDIUM DUTY TRUCK

Medium Duty Vehicle 19,501# – 26,000# GVW Weight Class

	Local Driving	Short Haul
Baseline Gas	5.2 mpg	5.4 mpg
Diesel Substitution	7.9 mpg	8.0 mpg
Resultant Improvement	51.9 %	48 %

Source: Cummins Simulation performed for ADL.

As indicated in Table 3.2 earlier, the diesel accounts for over 90% of the fuel consumed by heavy duty vehicles. The diesel itself cannot be considered as an innovation in the heavy duty weight class.

5.3 DIESEL ENGINE IMPROVEMENTS

5.3.1 Turbocharging

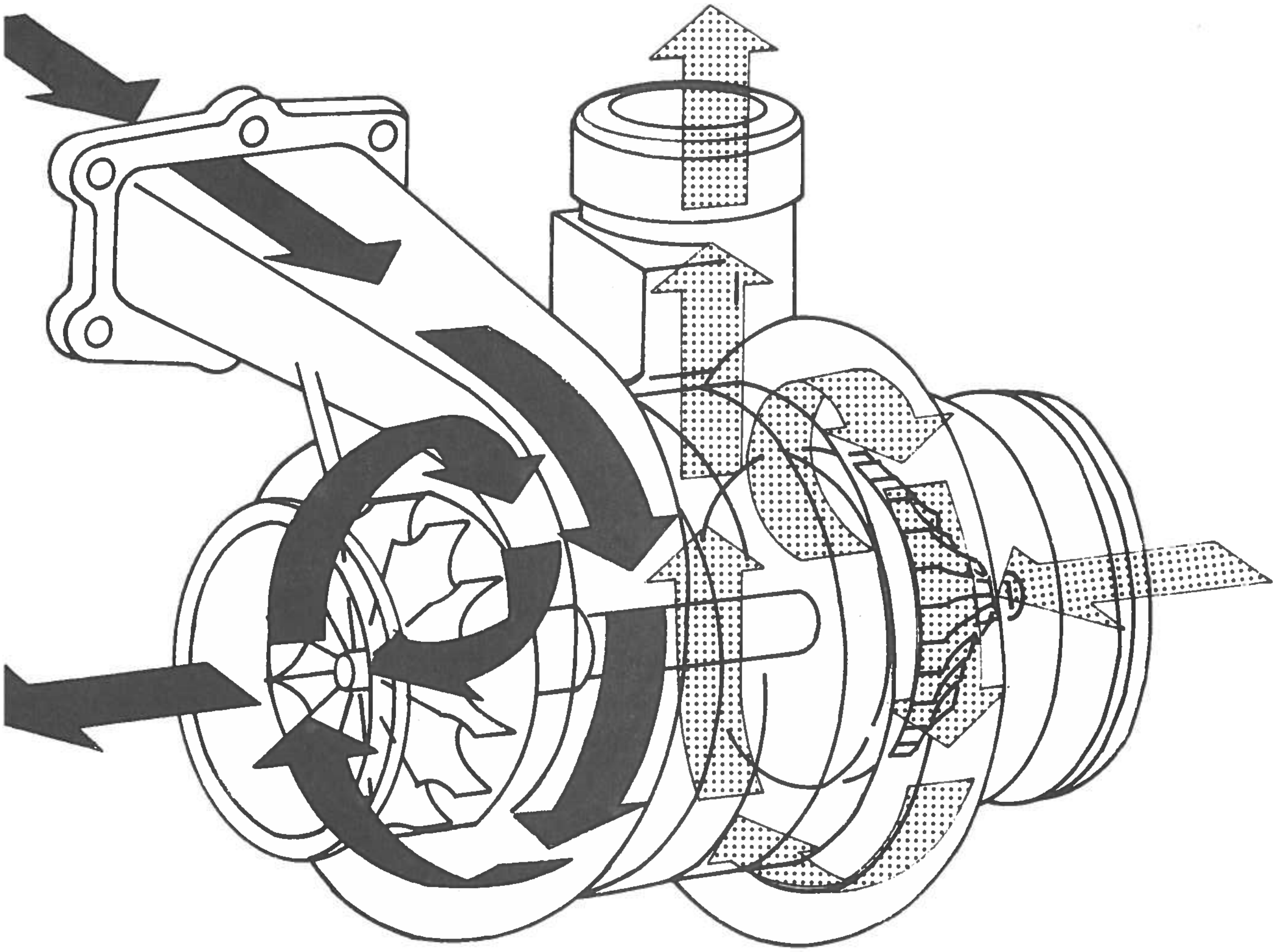
The turbocharger is a device added to an engine which utilizes exhaust gas energy to operate a compressor supplying air to the engine. A diagram of the turbocharger is shown in Figure 5.2. The turbocharger introduces more air to the combustion chamber than would normally enter, reducing smoke due to unburned fuel, and at the same time, if combined with increased fuel, will increase specific power. This in turn permits operation of the engine at lower speeds reducing friction and improving efficiency.

The turbocharger has become popular recently, because of its positive effect on emission as well as improving fuel economy and increasing power capability. The higher air delivery and temperatures insure more complete combustion and eliminate the practice of overfueling in order to raise the engine horsepower. As seen in Figure 5.3, the smoke produced by the diesel when turbocharged is substantially reduced.

The turbocharger is not recommended for use on diesel engines not specifically designed to handle the higher cylinder pressures and temperatures. The higher pressures occur because more air is introduced to the cylinder than in a freely breathing engine; this means that more mass is compressed into the same volume and the pressures and temperatures are raised; unless specifically designed to handle the higher average pressures, the diesel would have a shorter life than would be acceptable.

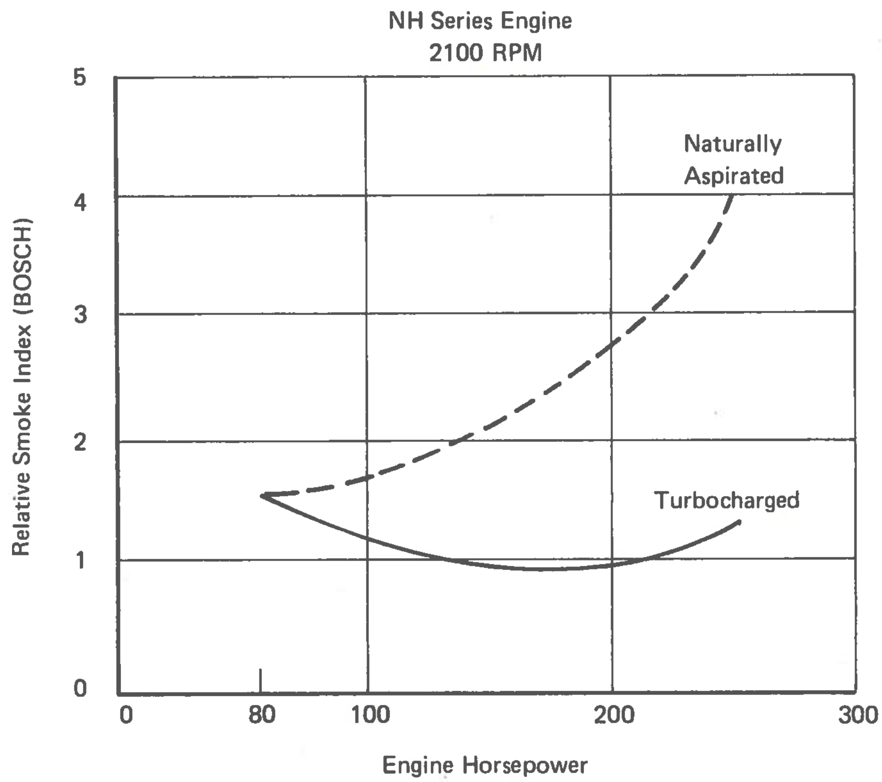
At this time a very high percentage of the diesel power plants sold have turbochargers. This percentage is increasing and will continue to increase in the coming years. Three major manufacturers are expanding capacity now. The number of new diesel engines built is increasing at an average annual rate of ten to fifteen percent,[8] and the number turbocharged is increasing at a rate of fifteen to twenty percent annually. There is a substantial retrofit market of heavy duty, 4-cycle diesel truck engines not originally turbocharged, but this will tend to decline by 1980.

During the study manufacturers' comments were sought by the Department of Transportation with regard to turbochargers. Responses to the requests are summarized in Table 5.9.



The inlet air is drawn in on the right and delivered out the top while the exhaust turbine is on the left of the common shaft.

FIGURE 5.2 TURBOCHARGER SCHEMATIC



Source: Taken from Cummins literature on engines.

FIGURE 5.3 EFFECT OF TURBOCHARGING ON SMOKE FROM DIESEL

TABLE 5.9

SUMMARY OF MANUFACTURERS ESTIMATE OF FUEL ECONOMY IMPROVEMENT FOR A TURBOCHARGED DIESEL OVER A NATURALLY ASPIRATED DIESEL

Manufacturer	% Improvement
Cummins	4-5
International Harvester	up to 10
Schwitzer	up to 10

The typical figure from Cummins is a result of an over-the-road simulation of a variety of trucks under a variety of conditions, it reflects the fact that except for a few engines the turbocharger does not give as large an improvement in urban driving where load on the engine is reduced. This reduced load also reduces the energy in the exhaust gas and thus the boost power available from the turbocharger. However, the Mack Maxidyne engines have the turbocharger performance tailored to provide more boost at the lower end, and show a larger gain in fuel economy as compared to naturally aspirated engines. However, this is not true for all makes of engines and it is generally felt that turbocharging is not as effective at low end loads and speeds.

The results of the over-the-road simulation of the improvement gained by turbocharging are shown in Table 5.10.

TABLE 5.10

% IMPROVEMENT IN FUEL ECONOMY BY TURBOCHARGING

	70,000# GVW Tractor Trailer		
	Local	Short	Long
Turbocharged Diesel	0	2.5%	4.2%

A turbocharger may be included as original equipment on a newly purchased vehicle or it may be purchased separately as a retrofit kit to modify existing vehicles. Manufacturer's data indicate that a typical turbocharger retrofit kit will cost approximately $800-1000. In addition, there will be approximately $300 labor costs to install the turbocharger. Incremental initial costs for a turbocharge option included on a new vehicle are $1100.* The additional maintenance costs for a turbocharged engine over the life of the vehicle are predicted at $200. In a number of cases the addition of the turbocharger increases the low speed engine torque reducing the number of transmission gears necessary. In a system design such as this, the cost applied to the turbocharger should reflect reduced costs on other system elements.

Air to air intercooling has recently been used in certain engines to further increase engine performance with turbochargers. Without intercooling the compressed inlet gases, at an elevated temperature due to the compression process, enter the combustion chamber at densities below that which could be achieved if the compressed gases were cooled. The Figure 5.4 below is a schematic of a turbocharger and intercooler presently available.

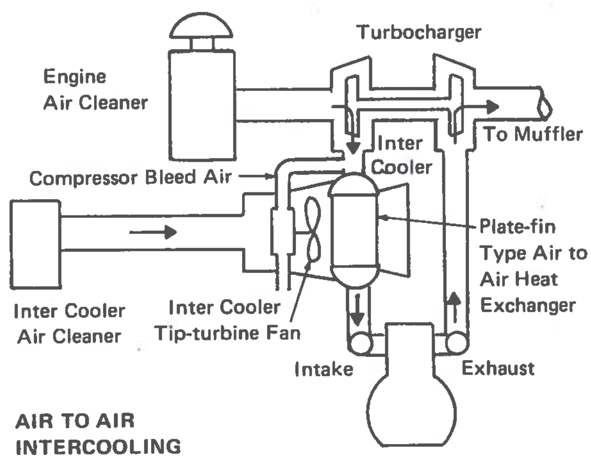


FIGURE 5.4 INDUCTION SYSTEM SCHEMATIC FOR A TURBOCHARGED, INTERCOOLED DIESEL ENGINE

Indications are that intercooling is a cost effective means of extending the horsepower of a given engine which would permit the use of a smaller engine. The engine of course has to be designed to offset the higher combustion chamber pressures.

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* Data from manufacturer reflects engine modifications for higher pressures in addition to installation of turbocharger.

5.3.2 Diesel Engine – Reduced Engine RPM Rating

The fuel flow to a diesel is modulated by an engine speed governor. The power signal generated in the linkage connected to the accelerator pedal is used by the governor to provide fuel to the cylinders. The governor limits the fuel flow to a predetermined maximum based on the engine RPM.

Many truck diesel engines are presently designed for normal full load maximum RPM of 2100, which corresponds to the point at which the governors start to limit fuel. This is about 10-20% above the engine speed for best fuel efficiency. Under highway cruise conditions, many drivers use the engine governor as a vehicle speed control device. This is accomplished by maintaining the maximum pedal setting and allowing the governor to restrict fuel flow to match road-load and aerodynamic forces on the vehicle.

The intent of reducing engine speed is to force the driver to operate the engine closer to its point of best fuel efficiency rather than at point of maximum RPM. At least one heavy duty engine manufacturer has recognized this and is reducing product line engine speed ratings. There is no incremental increase in initial cost accruing from the derating of an engine. The difficulty with reducing governor setting alone is that some additional shifting will be required with attendant additional wear on the drive train components.

Route simulation data from the Cummins Engine Company[9] shows that for a slight increase (0.7%) in trip time, fuel savings of as much as 6% can result from engine deratings.

Using the Cummins VMS_T, ADL substituted engines specifically designed to run at 1950 RPM at rated power for conventional 2100 RPM diesel engines. The tractor-trailer of the 50,000# GVW type and the 70,000# GVW type with derated engine speed are shown in the following table (Table 5.11).

TABLE 5.11

EFFECT OF DIESEL ENGINE RPM DERATING BY SUBSTITUTING A 1950 RPM ENGINE WITH HORSEPOWER EQUAL TO A 2100 RPM ENGINE

	Duty	% Improvement in Fuel Economy	% Trip Time Increase
Tractor-Trailer	Short	.8	0
#50,000 GVW	Long	2.4	6.2
Tractor-Trailer	Short	.4	0
#70,000 GVW	Long	4.4	4.6

NOTE: In both cases a 1950 RPM engine rated for the same horsepower as the reference vehicle engine at 2100 RPM were used.

5.4 SPARK IGNITED ENGINE IMPROVEMENTS

The improvements in spark ignited (SI) engines are applied to the light duty class only as discussed in Section 5.1.

A comprehensive discussion of the innovations considered for this class is provided in the previous study on automobiles.[2] The reader is referred to this discussion for background. The following material is a summary and update on the findings of the earlier report.

In general there are two areas in which an engine may be improved, in the indicated thermal efficiency and in the friction losses. Table 5.12 summarizes the innovations considered for a spark ignition engine.

TABLE 5.12

GENERAL APPROACHES TO IMPROVING THERMAL EFFICIENCY AND REDUCING FRICTIONAL HORSEPOWER IN SPARK IGNITION ENGINES

Improvements Aimed at an Increase in Indicated Thermal Efficiency

Increase Compression Ratio

- Leaded fuel
- Stratified charge engine

Optimize Air/Fuel Ratio

- Lean burn
- Stratified charge (FCP)
- Dual-chamber stratified charge
- Stoichiometric A/F with loop-controlled system and catalyst and improved carburetor

Ignition Optimization

- Optimize spark advance
- High energy spark
- Sustained ignition
- Wider spark gap

Improved Air/Fuel Cylinder-to-Cylinder Distribution and Reduced Cycle-to-Cycle Variation

- Improved manifold design
- Increase intake air turbulence

Improvements Aimed at a Decrease in Frictional Horsepower

Increase Air Capacity

- Improved exhaust and intake manifolding
- Turbo-or-supercharged

Decrease Mechanical Friction

- Piston ring modification
- Lower engine speed requirement by a wider range of gearing in the transmission
- Improved lubricants

Decrease Pumping Losses

- Turbocharged or supercharged engines
- Operate engine under less throttled conditions by proper engine and transmission matching, e.g., greater range of gearing or continuously variable transmissions

5.4.1 Air/Fuel Delivery System

The innovations which are under development may be viewed on a spectrum of increasing control over mixture preparation, as shown in Table 5.13.

TABLE 5.13

FUEL SAVINGS OVER CONVENTIONAL ENGINE

Lean-Burn Carburetor, Improved Manifold	Port Fuel Injection	Stratified Charge
10-15%	5-15%	15-25%

- Higher compression ratio ⟶
- Higher cost ⟶
- Better control over mixture preparation ⟶
- Leaner mixtures feasible ⟶

The lean-burn concept (delivering about 10-15% less fuel to each cylinder than could be consumed by the available air) offers substantial benefits in both emission control and fuel economy, but often requires sophisticated and costly mixture preparation hardware. Fuel savings can accrue not only from eliminating the earlier "bootstrap" emission controls (restoring compression ratio and spark advance) but also from reducing the flame temperature and thus the heat transfer losses and dissociation losses.

Selected lean-burn systems are presented in Table 5.14 along with reported economy gains.

The limitations to running air/fuel mixtures leaner than about 18/1 in order to further reduce emissions are (a) reduced power, (b) excessive hydrocarbon emissions because of misfire, and (c) excessive combustion duration. Methods being investigated to speed up the heat release rate include spark intensification, turbulence generating devices, and multiple spark plugs.

The estimate of initial incremental cost resulting from the incorporation of the lean burn concept was based on costs given in Table 4.16 of Reference 2.

As the lean burn concepts are still in the development stage, durability and reliability figures have not yet been exactly established. Estimates of the projected incremental maintenance and replacement costs have been included in cost analysis (Section 6.0).

TABLE 5.14

SELECTED LEAN-BURN SYSTEMS

Systems	Method of Mixture Preparation	Air to Fuel Ratio	Fuel Economy Gain (FTP)	Reference
Autotronics	Version I Ultrasonic atomization Single-plane manifold	18.5/1	15%	2
	Version II Both of the above, plus: 10:1 Compression ratio Valve turbulator	20/1	20%	10
Dresserator	Variable venturi, "choked" flow carburetor, Single plane manifold	19.5/1 to 18.5/1	12%	11
Chrysler Clean Air Package	Improved induction manifold "Sophisticated" carburetor "Special" intake valves Electronic spark advance	19.5/1 to 18.5/1	10-15%	12

5.4.2 Port Injection

In order to reduce costs, conventional SI engines provide a fuel metering at a central point (carburetor) and then rely on the manifold for evaporation and uniform distribution to all cylinders. The penalties for relinquishing mixture preparation responsibility to the manifold are as follows (see Figure 5.5). During transient engine duty, the manifold is sluggish in responding to the vehicle's fuel needs:

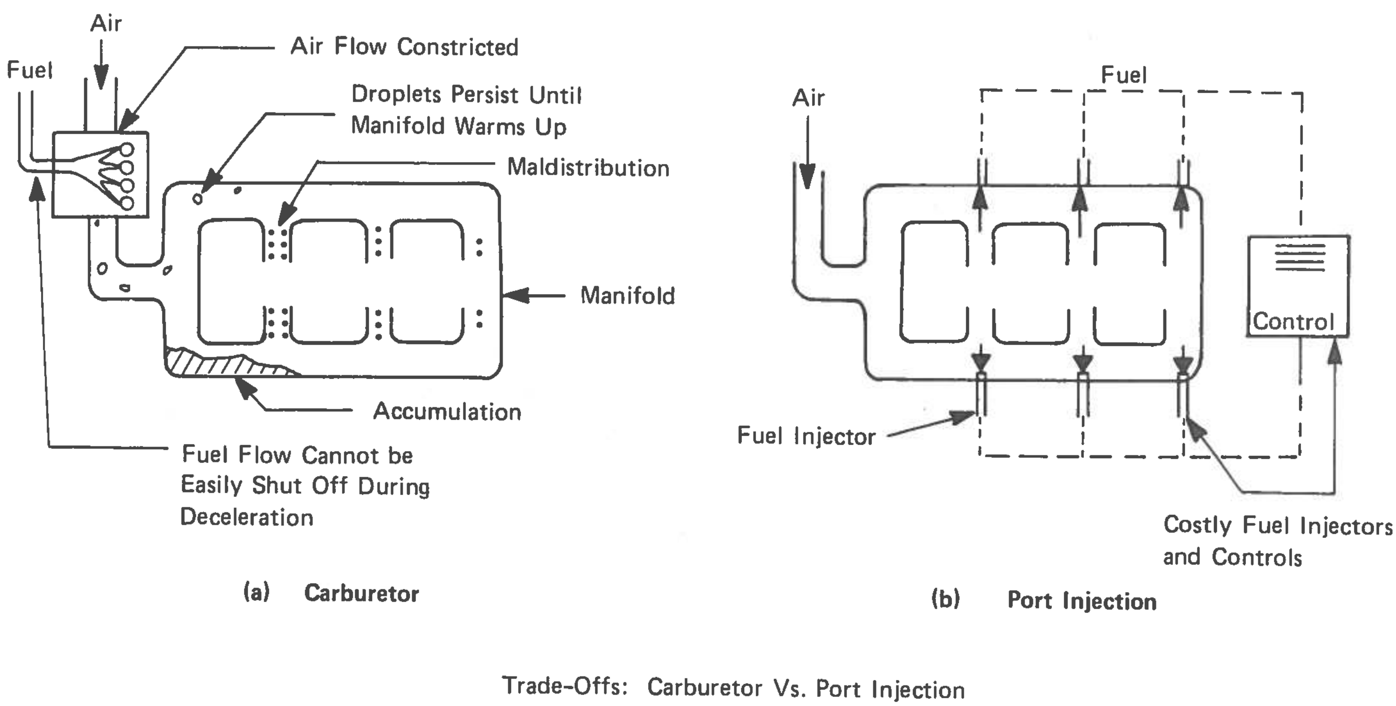


FIGURE 5.5 COMPARISON OF CARBURETED MANIFOLD AND FUEL INJECTED MANIFOLD

- Fuel accumulates on the manifold wall, introducing a phase lag in throttle control which is overcome by enrichment of the mixture for acceleration purposes.

- Until the manifold warms up (during cold start), evaporation is so slow that spark ignition cannot occur without enrichment.

In addition, during normal operation, performance is compromised:

- Because of less than ideal intake manifold design the A/F ratio must be enriched to prevent misfire in the "leanest" cylinder.[13]

- Air flow is restricted by the carburetor reducing volumetric efficiency.
- During deceleration, fuel is delivered to the engine through the idling circuit at a time when the engine is acting as a brake.

All of these inefficiencies can be ameliorated by placing a metered fuel spray at the intake port of each cylinder, thereby distributing fuel through fuel lines rather than through the manifold. These systems reduce the maldistribution to the cylinders which allows leaner running.

Port-injection systems have been available for at least 20 years, but the increased costs of pumps, controls, and injectors have so far justified their use for high performance engines such as aircraft engines, and luxury sports autos and some four-cylinder engine vehicles.

The fuel consumption benefit of substituting a port-injection system for a carburetor is in the 0-10% range. The saving depends on the amount of transient duty and on the sophistication of the carburetor/manifold, as shown by Freeman and Stalman.[14] Their engine "B" (which was out of adjustment) showed up to 30% BSFC improvement; however, their engine "D" showed no improvement at all. Likewise, the carburetor vs injector comparison tests of Bendix[15] reproduced in Table 5.15 gave a 2-5% BSFC edge to the injector, but this configuration doubled (NO_x + HC) emissions. Bendix injector configurations which lowered NO_x up to 63% actually increased BSFC by 15-40% (these tests were performed before the oil shortage).

TABLE 5.15

COMPARISON OF BENDIX FUEL INJECTED ECONOMY WITH CARBURETED ENGINE

Engine Conditions		Carbureted Engine			Electronic Fuel Injection			Fuel Economy Improvement (%)
		# Fuel/	G/bhp-hr		# Fuel/	G/bhp-hr		
RPM	Torque FT-lb	HP-HR	HC + NO_x	CO	HP-HR	HC + NO_x	CO	
1200	45	.893	6.2	12	.841	18	10.7	5.8
1200	100	.535	7.7	7	.531	15.8	5.1	.7
2000	70	.649	13.7	7.6	.614	10.0	7.3	5.3
2000	180	.432	16.4	5.2	.432	8.6	6.4	0
640	35	1.250	2.7	15	1.114	8.1	13	10.8

Note: The engine under test is a 429CID gas engine with a CR of 10.5:1.

For the \$175 ± 50 added retail price, port injectors give up to a 10% fuel savings, and are most effective when applied to a driving cycle with numerous transients (e.g., postal work or delivery van).

5.4.3 Stratified Charge Systems

By arranging the fuel-air mixture to be locally rich in the vicinity of the spark plug, quite lean overall mixture ratios can be burned with attendant fuel savings. In addition, since the engine load (open chamber) can be controlled by fuel rates rather than by throttling, air pumping losses are reduced. However, the mixture cannot be stratified without sophisticated fuel preparation arrangements which eliminate the wasteful fuel distribution of normal carburetor/manifold systems. Thus, stratified charge systems lie on a spectrum of increased control over fuel/air mixture preparation, as shown before in Section 5.4.1.

Stratified charge systems available or under development are listed in Table 5.16. The open chamber, direct injection systems offer less wall-quenching heat losses, elimination of possible flow loss from prechamber to main chamber, and if so designed multi-fuel capability all at higher cost. The fuel economy gains are projected to be approximately 20%.

TABLE 5.16

STRATIFIED CHARGE SYSTEMS

System	Chamber Configuration	Mixture Preparation	Fuel Consumption Improvement	Reference
Honda CVCC	Prechamber	Separate carburetor Venturi Auxiliary air inlet valve	15%	16
Texaco "Controlled-Combustion"	Open chamber	Direct ignition	25%	17
Ford "Programmed-Combustion"	Open chamber	Direct ignition	–	–

The major cost increment for the stratified charge system to the initial purchaser would result from the injection or dual carburetion-manifold systems. At the present time, we estimate that the injection system, including the added expense for the complexity of the cylinder head and the intake valve mechanism, would cost from \$300 to \$500. Furthermore, other costs might occur in that there would be an increase in heat rejected to the water jacket due to the somewhat larger surface area within the combustion chamber. This might, in turn, require some increase in the cooling system capacity. We have also included the possible added cost for the spark plug modifications required by this approach. An estimate of these added incremental maintenance costs is included in the cost analysis in Section 6.

5.4.4 Turbocharged Gasoline Engine

The turbocharger is an engine supercharger driven by a turbine in the engine exhaust. Turbocharging increases the ability of the engine to deliver power by increasing the quantity of air available for combustion. If applied properly, it will also provide an increase in fuel economy.

Unlike the turbocharger for the diesel engine, the turbocharged gasoline engine must be carefully controlled to prevent knocking. The added charge increases the effective gasoline engine compression ratio, which may lead to harmful pre-ignition or knock at high loads. A control system used to bypass part of the compressed inlet air at higher engine loads must be used. The major advantage of the turbocharger, as discussed in Reference 2, is that a smaller engine developing an equivalent horsepower may be used, reducing fuel consumption.

Since there is considerable experience in manufacturing turbochargers for diesels, there is reason to believe that the technical problems in applying this concept to a gasoline engine are of a medium to low risk. In addition, the requirements for the turbocharger in a gasoline engine are less severe because the boost pressures are considerably lower. This in turn allows modifications to be made in the construction of the turbochargers. The opinions of the turbocharger manufacturing industry are that the cost of turbocharging a small engine, including the benefits gained by producing a smaller engine and possibly the elimination of a catalytic converter, are worth the effort. Offsetting these gains are possible costs because higher engine output on a continuous basis would require more expensive exhaust valves for durability. Also, if the carburetor is downstream to the turbocharger, it could be more complex, thus reducing the reliability of the carburetor and increasing its maintenance. Offsetting these disadvantages would be the weight saving resulting from the use of a smaller engine and subsequent lighter chassis components. It should be recognized, however, that the production of turbocharged gasoline engine could not be undertaken immediately. Generally, such a gasoline engine would have to be of new design. Gasoline engines designed to take a turbocharger would be much smaller and lighter. As presently designed, current smaller engines could not be simply turbocharged to significantly increase their horsepower ratings. Components (bearings, etc.) of such an engine would have to be redesigned to be able to withstand higher working pressures.

Table 5.17 shows the effect of turbocharging on fuel economy as measured by the 13 mode Federal test procedure.[18]

TABLE 5.17

PERCENT IMPROVEMENT IN FUEL ECONOMY BY TURBOCHARGING A GASOLINE ENGINE FOR LIGHT DUTY SERVICE

Local	Short	Long
15-25%	15-25%	10-15%

Data estimated from: Schwerket & Johnson, "A Turbocharged Spark Ignition Engine with Low Exhaust Emissions and Improved Fuel Economy," SAE 730633.

Estimates of the increased maintenance costs are included in the cost analysis. For this study we have used the best judgment in evaluating projected costs given to us by a number of sources and are using the range of $150 to $250 for the initial added cost of the turbocharged system over a 1974 vehicle.

5.5 REGENERATIVE GAS TURBINE

The regenerative gas turbine at its current stage of development offers no fuel consumption advantage over the diesel for Class VII and VIII vehicles, but has shown up to 10% lower BSFC than the spark ignition engine, as shown in Table 5.18.

TABLE 5.18

POWER PLANT COMPARISON[19]
(200 HP at the wheels)

	Spark Ignition	Diesel	Gas Turbine
Engine HP	256	220	200
Powertrain Weight	900 lb	1,250 lb	800 lb
Fuel Consumption lb/bhp-hr	0.50	0.40	0.45-.51
Relative Cost	1.0	1.6	2.0

21. Mortimer, J., "Small Gas Turbines — Will They Succeed?", Engineer, September (1972).

The market for a 350 HP truck engine which could meet the proposed standards prompted Ford, General Motors, British Leyland, Fiat, and Mitsubishi to develop gas turbine power plants to compete with the diesel. Table 5.19 lists manufacturers developing gas turbines. Ford's gas-turbine powered vehicles were tested in 1971, but because of low fuel economy relative to the diesel, and technical problems related to compressor blade life, the program has been delayed. To illustrate the fuel consumption problem, a Russian dump truck fitted with a 1,200 HP gas turbine gave 0.62 BSFC compared to 0.41 BSFC for the diesel.[20]

TABLE 5.19

GAS TURBINES FOR TRUCKS AND BUSES

Manufacturer	Size	State of Development
Ford	300-520 HP	Development
General Motors	280-375 HP	Field Trials (Greyhound & Truck Co.'s)
British Leyland	350-400 HP	Development
Chrysler	130 HP	Development
Fiat	–	Development
Mitsubishi	–	Development
Caterpillar	600 HP	Development
Garrett Airesearch	200 HP	Production (APU for Aircraft)

The advantage of the smaller regenerative gas turbine for the SI engine is questionable for school buses, delivery vans, and other Class III-VI vehicles. Although the engine would be smaller, lighter, and cleaner (4 g/mi NO_x, 1.4 g/mi CO, and 0.15 g/mi HC for a 225 HP engine in a 4,500 lb car), the fuel consumption is comparable to SI engines (10 mpg)[21] or at most 10% improved.[22] Two factors limit the performance of the 150-200 HP class gas turbine:

- Maximum turbine inlet temperature (theoretical efficiency) limited by turbine blade failure. Efforts are under way by Ford/ Westinghouse[23] to develop ceramic gas turbine blades which, if operated at 2500°F, would offer 30% fuel economy improvement over the SI engine and 10% over the diesel.

- The gas turbine loses efficiency rapidly below 25% power (about six times more fuel required at idle than for an SI engine) yet low power modes are an essential part of the duty cycle for buses and light trucks.

Other problems have been encountered with the design of the regenerative gas turbine. Recently disclosed regenerator problems with leaching and compressor seal leakage suggest that a great deal of additional work is required in the development of a truck gas turbine.

5.6 OPTIMIZED COOLING SYSTEM

Two areas of significant power consumption are found in the cooling system. The energy consumed by the fan to cool the engine coolant, and the energy required to push the coolant through the engine.

The system is designed for low initial cost and the most severe condition expected by the vehicle manufacturer (low vehicle speed, high engine power at relatively high ambient air temperatures). This dual requirement generally results in the adoption of a continuously driven cooling fan with significant excess capacity under most operating conditions. This excess capacity also translates into wasted power. To eliminate this power waste, various approaches from air actuated dry clutch systems, viscous drive systems, through completely variable speed hydraulic drive systems have been engineered and marketed.

The Department of Transportation initiated a series of field evaluations of various types of demand fan drive systems on heavy duty over-the-road vehicles. Twenty five units have been placed in the field for such evaluation utilizing both the simple on/off dry clutch type, see Figure 5.6, and the fully modulated fan drive system. Results of these tests indicate that, through a typical year of operation, total "on" time is 5% of the engine hours or less. Of this experienced "on" time, only half occurs when the engine is operating above 1,600 rpm, a level at which significant power would be absorbed by the fan. These tests, conducted for purposes of verifying noise control approaches, are wholly appropriate to the question of fuel economy. The indications are clear that 97-98% of the time the 20-30 fan horsepower presently being consumed could be saved. Thus with a typical large truck we could see power and hence fuel savings of 10% at full engine load. Present operators of fan clutches are indicating 5-10% fuel economy improvements without fuel system changes as evidenced by submissions to the study group from International Harvester, Horton Industries, Inc., Rockford Clutch Division of Borg-Warner and Schwitzer Division of Wallace-Murray Corporation. Other inputs from fleet operators indicate similar results of up to 10% improvements in fuel economy without optimization of the cooling system but simply through retrofitting of such fan drive systems.

We have made a number of computer simulations in an attempt to estimate the potential fuel savings possible due to improvements in the efficiency of the fan. In these simulations we have turned the fan off completely and noted the fuel consumption of the vehicle over a given course. We have also made corresponding simulations where the fan was operating normally.

We have found fuel savings predicted by these simulations to be 3 to 5 percent as reported in Table 5.20.

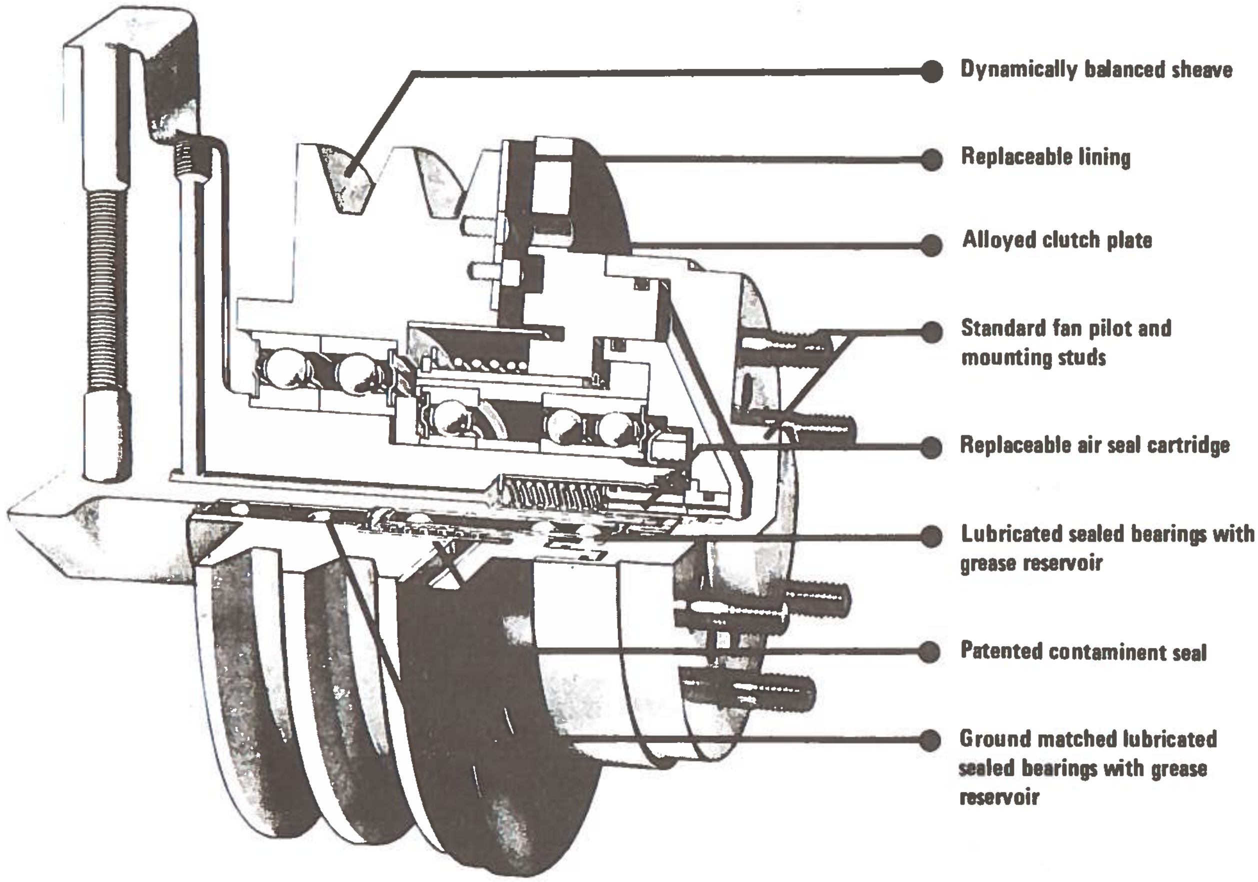


FIGURE 5.6 PNEUMATIC COOLING FAN CLUTCH

TABLE 5.20

SIMULATED EFFECT OF FAN CLUTCH DRIVE ON TRUCK FUEL CONSUMPTION
(percent fuel economy improvement)

Light Duty	Van		Dump		Tractor-Trailer (50,000 lbs)		Tractor-Trailer (70,000 lbs)	
Annual Mix	Local	Short	Local	Short	Short	Long	Short	Long
3.0	3	4	3.4	3.5	4.8	4.5	5.2	4

Establishing an accurate estimate of the cost for the addition of a thermostatically controlled fan clutch depends on the projection of expected cost for a more fully developed, reliable system. The initial incremental cost used in this study is $150 to $250. Assuming that the projected durability and reliability will be comparable to that of the existing cooling system, no additional maintenance or repair costs have been included in the cost analysis.

The manufacturing costs associated with the estimate for the improved cooling system design include the cost for providing the required air flow with minimum fan tip speed, fan shrouds to minimize space between fan tip and shroud and optimized radiator-to-fan engine clearance; the cost of a new truck should be unchanged. Substitution of blocking thermostats instead of radiator shutters* should result in cost savings of approximately $130 and a reduction in weight of 20 pounds. Addition of temperature controlled fan drives should increase the weight by some 10 pounds and increase the cost by some $200.

For the lighter weight vehicles which are used most often in a local stop and go driving mode, the fuel savings associated with a temperature actuated fan would be somewhat diminished. This is primarily due to the fact that under stop and go conditions there would be a greatly reduced natural air flow through the radiator core. Hence the fan would have a higher duty cycle and the fuel savings would be reduced.

Specific performance data on the energy consumption by the water pump for the heavy duty trucks were not available; however industry estimates put the horsepower at about 10 HP at 2,100 rpm, for a 290 horsepower diesel. The power necessary to move the coolant in a diesel engine is attributable to the fact that the

*In many cases radiator shutters are presently employed to close the air passage to the radiator when the diesel water temperature is below the optimum temperature for good operation.

diesel is prone to localized hot spots in the combustion chamber which reduce the engine life. High rates of cooling water flow are used to assure good heat transfer and hence reduction in localized hot spots. This results in higher water pump horsepower and commensurate fuel consumption.

While we know of no work under way on reducing water pump horsepower demands in diesel engines, we suggest that a small gain in fuel economy could be linked with an optimized cooling system which reduces water coolant pump horsepower.

5.7 DRIVE TRAIN IMPROVEMENTS

5.7.1 Improved Transmissions

A gain in fuel economy is possible by properly adjusting engine speed and torque to meet road horsepower demand. This is the role of the transmission. Improving transmissions to guarantee the best matching of engine conditions with horsepower demand will improve fuel economy. In addition, the skills involved in proper operation of transmissions of large trucks add to driver fatigue.

Two new transmissions available for heavy duty vehicles as production units are: automatic four and five speed transmissions with lock-up and continuously variable ratio transmission (CVRT). The second development is relatively new and provides an infinite number of gear ratios within a range.

The four and five speed transmissions allow a low final drive ratio, reducing the engine speed during cruise conditions, while a downshift into a lower gear ratio can provide acceptable acceleration performance for passing and merging with freeway traffic, hill climbing, etc. In addition to the lower speed ratio for boosting cruise fuel economy, the fuel consumption can be further reduced under urban driving conditions by a torque converter lock-up to eliminate converter slip losses. These four and five speed automatic transmissions find application in the light duty Pickup Truck for all driving modes and in the medium and heavy duty trucks for local pick-up and delivery. A typical four speed automatic transmission with lockup is shown in Figure 5.7 following. The four speed automatic has also been considered for use in the local heavy duty truck service, but not for the short and long duty, since it will not offer a fuel economy improvement over the ten speed manual.

The continuously variable ratio transmission (CVRT) is one which offers any desired gear ratio between the upper and lower limits of its ratio range and is capable of changing ratio smoothly in a continuous sweep from one end of its ratio range to the other. The two principal types of continuously variable transmissions are the traction type and hydraulic (hydrostatic or hydro-mechanical).

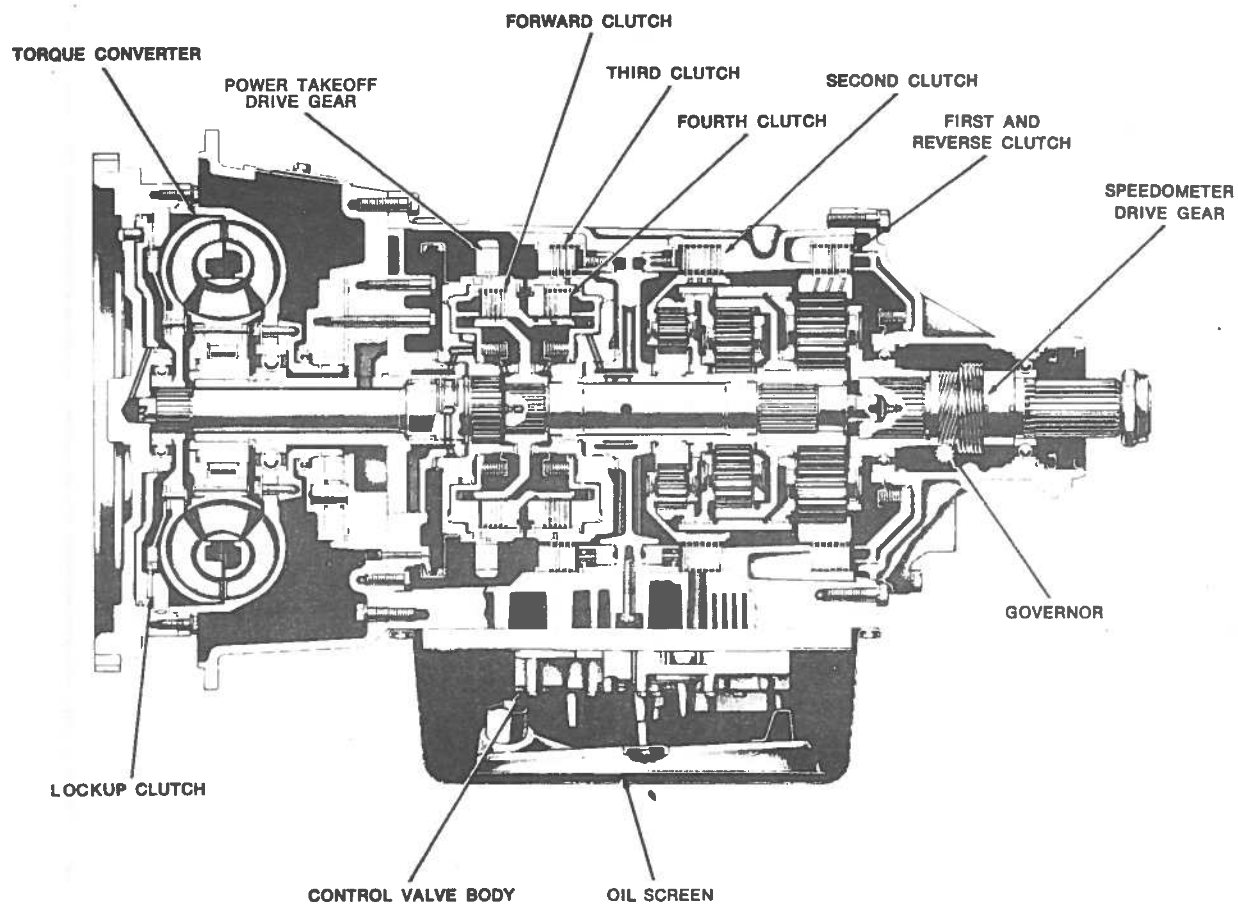


FIGURE 5.7 ALLISON MT 640 FOUR-SPEED AUTOMATIC TRUCK TRANSMISSION WITH LOCK-UP TORQUE CONVERTER

At present there are no production traction type transmissions available for trucks. Tracor Inc. has been developing a Traction Drive CVRT to the automotive market and a comprehensive discussion of the Tracor development is given in Reference 2. There is, however, a production hydrostatic/hydromechanical constantly variable transmission available offered by Cummins-Sunstrand. The transmission is available for heavy trucks and is designed for short haul usage. Figure 5.8 presents a diagram of the transmission.

Within the time frame of 1980 a constantly variable transmission may become available for the light truck (see Sections 4.3.4.10, and 4.3.4.11 of Reference 2) and is being considered for further examination. A summary of the transmission improvements considered by truck type and driving mode is given in Table 5.21.

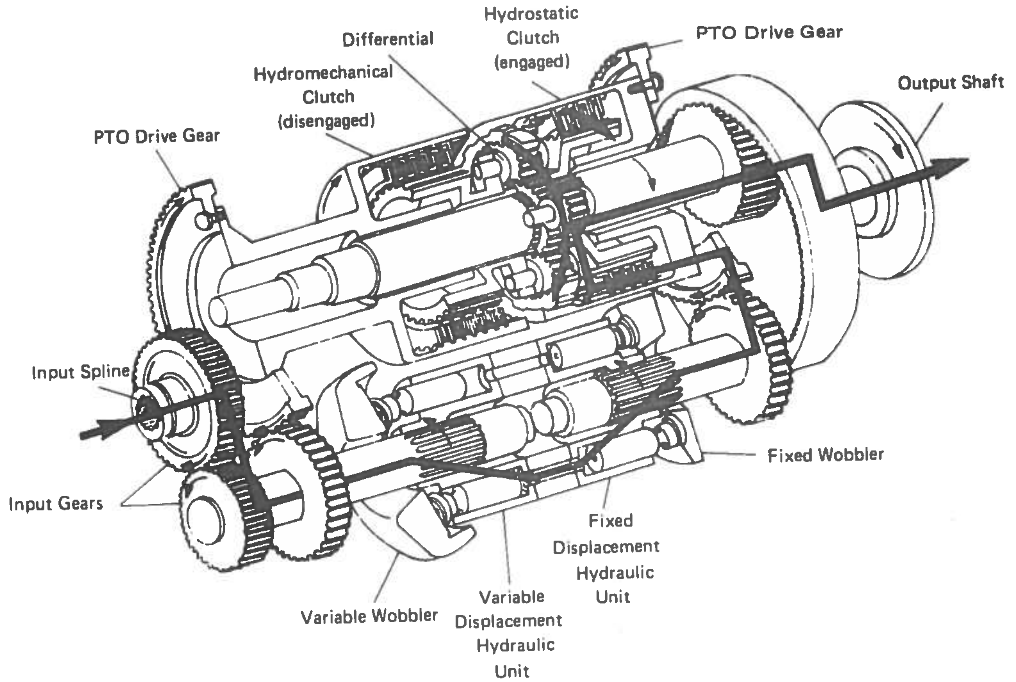
TABLE 5.21

TRUCK TYPES TO WHICH TRANSMISSION IMPROVEMENTS WERE MADE
(X denotes areas considered for transmission improvement)

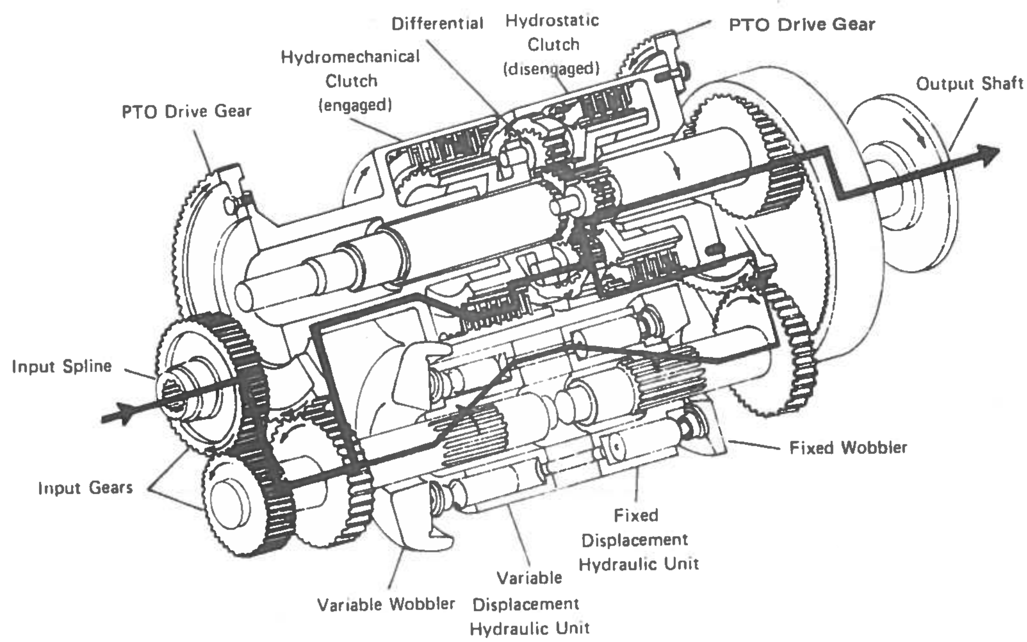
	Truck Types					
	Light	Medium		Heavy		
Improvement	Annual Mix	Local	Short	Local	Short	Long
4 or 5-speed auto with lockup	X	X	X	X		
CVRT	X			X	X	
Baseline Transmission	3-speed automatic	4-speed manual		10-speed manual		

The four speed transmission with lockup considered for the automobile can be applied directly to the pickup trucks. While it is recognized that the torque converter (see Reference 2, Section 4.3.4.2) of a pickup truck is a heavier duty device than in an automobile, we have used the automotive results directly, because of a lack of other data. Torque converter data was not available and in our estimate the automotive analysis is reasonably representative for pickup truck use.

Reported below (Table 5.22) are the results of the automotive study for the four speed automatic with lockup. These improvements reflect the gain in fuel economy by the addition of a gear and a lockup torque converter over a conventional three speed automatic transmission.



Start-Up Mode (hydrostatic)
During start up the hydrostatic clutch is engaged and the hydromechanical clutch is disengaged. As engine speed and power increase, the control system causes the stroke of the variable displacement hydraulic unit to increase. This hydraulically drives the fixed displacement unit. The fixed unit output speed and torque are transmitted through the hydrostatic clutch to the output gearing and shaft.



Full Speed Mode (hydromechanical)
As the variable unit reaches maximum displacement the power flow is changed from the hydrostatic to the hydromechanical clutch. This begins to change the engine power flow from hydraulic to mechanical. At 60% of geared truck speed the displacement of the hydraulic units is zero and all engine power is transmitted mechanically. Above 60% the control system begins to supplement the mechanical power with hydraulic power from the hydraulic units. This continues until maximum operating speed is obtained.

FIGURE 5.8 TRANSMISSION DIAGRAM

TABLE 5.22

SUMMARY OF PERCENT OF FUEL ECONOMY IMPROVEMENT BY TRANSMISSION CHANGE ON LIGHTWEIGHT TRUCKS*

Transmission	Percent Improvement for the Following Conditions					
	FTP	30 mph	40 mph	50 mph	60 mph	Annual Mix
4-speed and lockup	7-13	12-18	11-20	13-24	11-26	10-15

* Section 4.4.2, reference 2.

The use of four speed automatic transmissions in the medium and heavy duty weight classes is limited to local and short haul. In both cases the automatic will replace a manual transmission of equal number of gears or greater and cannot compete in fuel economy based on mechanical considerations alone. Improvements that the automatic transmission offers arise in stop and go traffic when many shifts are required. In a manual transmission, engine overspeeding during shifts is nearly impossible to avoid, causing unnecessary fuel consumption. Tests[24] at the GM proving grounds show a 10% improvement in fuel economy for an automatic four speed with lockup in a 20,000 lb van.

Similar tests of a heavy-duty trailer semi-tractor of 71,138 lbs weight indicate no improvement under the driving conditions used in the Trans-Expo Demonstration. The tractor trailers were driven at slightly higher speeds than the vans with fewer stops. The manual transmission, a ten speed, had a clear mechanical advantage over the five speed automatic transmission to which it was compared, though the fuel consumption was nearly equal. Other test data in medium and heavy duty trucks with and without automatic transmission is not available, and until more extensive tests are performed we will have to hold our judgment on the value of automatic transmission for medium and heavy duty trucks. However, it is clear that these applications will be limited to those vehicles used in local and short haul, accentuating the effect of driver performance. It is likely that under stop and go conditions the large truck will show an improvement with an automatic transmission as driver fatigue or inexperience limits the effectiveness of a 5 to 10 speed transmission.

To obtain an upper limit measure of the fuel economy gains available from an efficient continuously variable ratio transmission (CVRT), computer simulation runs made on the light duty reference vehicles were taken from the Automotive Study. In the simulation, the transmission ratios were selected to allow the engine to operate at all times at its most efficient point (lowest BSFC) for the instantaneous power level demanded. It was assumed that the transmission could change ratio instantaneously during transient vehicle operation and that its ratio range was infinite. (In actual practice the ratio range is restricted to about 9:1 which requires torque converter at very low vehicle speeds.) The results of the computer simulation are summarized below (Table 5.23) for the light duty trucks.

TABLE 5.23

SUMMARY OF PERCENT OF FUEL ECONOMY IMPROVEMENT BY TRANSMISSION CHANGE TO CVRT ON LIGHT DUTY TRUCKS

	Percent Improvement			
	FDC	30 mph	50 mph	Annual Mix
CVRT	12-26	19-20	22-41	15-30

These must be considered as upper limits and do not reflect actual transmission efficiency at part load, which could well offset savings made in fuel economy.

At present there is no continuously variable ratio transmission (CVRT) available for the medium duty truck. There are, however, hydromechanical transmissions earmarked for the heavy trucks. We believe these transmissions will ultimately penetrate the medium duty market if they are successful in the heavy duty class. It is certain that design changes of the heavy truck CVRT will be necessary for their use in the medium truck though the technology is directly applicable. The reason the manufacturers have chosen the heavy duty truck for the CVRT is that a substantial amount of driving for certain specific applications like cement mixer trucks, garbage trucks, etc., is in the local and short driving where CVRT use has its greatest benefit, and heavy duty truck owners may better afford the added cost of a CVRT. Until the CVRT is explored more actively for application in the medium duty class, we will refrain from predicting its impact and turn our attention to the CVRT in the heavy truck.

As reported in the Appendix of Reference 2, Orshansky Transmission Corporation is developing a hydromechanical CVRT for heavy truck use. The Orshansky Transmission is a hydromechanical torque splitting transmission potentially yielding very similar results to the Cummins-Sunstrand mentioned earlier.

The continuously variable transmission offers the same driver aid advantages in the heavy trucks as does the automatic transmissions with lockup. The CVRT and automatic limits overspeeding of the engine which may occur when manual transmissions are not properly used. In addition the CVRT adjusts the transmission ratio as a function of speed and load to minimize engine speed, and lower fuel consumption.

The CVRT in the light duty truck offers an advantage over the existing transmission primarily because it substantially increases the number of ratios available. In the heavy duty truck the present ten speed manual transmission can be operated so as to run the engine at minimum speed and hence best economy. Under conditions when the truck is fully loaded, higher engine speeds are required in order to deliver the necessary horsepower, particularly when accelerating in the local and short haul situation. On return trips when the truck is unloaded lower engine speeds will provide the necessary power but unless drivers compensate accordingly savings will not be realized. The CVRT in the heavy truck responds to the change in load and automatically reduces the engine speed. Specific performance data on each transmission was not available so that computer simulations were not made. However, road tests with Cummins-Sunstrand transmission[25] indicated that a fuel savings of 10-15% may be expected for local and short haul use, while little improvement for the long haul will result.

A summary of the improvements in fuel consumption resulting from transmission changes are given below in Table 5.24.

TABLE 5.24

SUMMARY OF FUEL ECONOMY IMPROVEMENT BY TRANSMISSION CHANGE

	Percent Improvement in Fuel Consumption					
Truck Type	**Light I, II**	**Medium VI**		**Heavy III**		
Duty Cycle	**Annual Mix**	**Local**	**Short**	**Local**	**Short**	**Long**
4 or 5 speed automatic with lockup	10-15	0-10		Small		
CVRT	15-30				10-15	

5.7.2 Rear Axle Ratio

The vehicle drive ratio in any selected gear is the product of the mechanical advantage provided by the transmission and the rear axle. As such, the rear axle ratio plays a significant roll in determining vehicle fuel economy. Reductions in the numerical rear axle ratios force the engine to operate at lower speeds and at higher brake mean effective pressures, usually resulting in fuel savings.

To assess the effect of axle ratio changes on fuel economy, comparative computations were made using a 10% numerical ratio reduction. For light duty vehicles, usually sold with specific axle ratios selected by the manufacturer, the effect is shown in Table 5.25. For heavier vehicles, the rear axle is generally customer selected. The effect on fuel consumption is greatly affected by the vehicle operating schedule and is most effective where speeds can be maintained.

TABLE 5.25

EFFECT OF A 10% REDUCTION IN REAR AXLE RATIO ON FUEL ECONOMY OF LIGHT TRUCKS*

Percent Fuel Economy Improvement (mi/gal)				
FTP %	30 mph %	50 mph %	70 mph %	Annual Mix %
1	3.5	4	4	2.5

The high emphasis placed on acceleration transients by the Federal Test Procedure (FTP) resulted in only a 1% improvement in fuel economy.

In heavy vehicle operation, a balance should be struck between reduced axle ratio and engine speed and degrading of performance or gradeability to optimize the overall effect on fuel economy, vehicle driveability and maintainability. Usually a lower numerically rated rear axle ratio will require additional shifting with subsequent increased wear on drive train components.

On the initial purchase of a vehicle, if the operator specifies a lower axle ratio then there would be no incremental cost increase. In addition, there would be no discernible incremental change in maintenance and repair costs, providing the vehicle has been powered and geared properly to meet the particular route grade requirements.

5.7.3 Radial Tire Substitution

The force required to overcome tire rolling resistance becomes a significant portion of the vehicle requirement under constant speed level road conditions. For tractor-semi trailer vehicles this ranges from 70% at 20 mph to 40% at 60 mph when aerodynamic drag becomes significant. Most tires, currently used on trucks are of the bias ply type; that is, the reinforcing carcass plies are overlapped at an angle. As a tire of this type flexes under rolling conditions, the angular plies are forced to work against each other in a shear type of action that opposes tire rolling and creates internal heat buildup. At this writing, the most effective way to reduce these effects is to use a tire constructed with reinforcing plies running radially (at right angles to the tread). In this construction form, the plies are able to work together during rotation thus reducing internal friction and consuming less energy.

A third factor which needs further examination is the total life including retreading. Industry figures vary from both extremes, ranging from better to worse than bias tires for retreading. For want of accurate retread figures, we have estimated that bias ply and radials can both be retreaded twice and each retread yields about 85% of the life of the original tread it replaces.

At present the cost of a radial tire is greater than that of a bias ply tire. More U.S. manufacturers are becoming equipped to manufacture radial ply, which should reduce the cost somewhat. At present radials are more expensive to manufacture and may never be available widely at the same price as a bias ply tire. At present the cost increment on the initial purchase is as given below in Table 5.26.

TABLE 5.26

APPROXIMATE % INCREASE IN PRICE OF A RADIAL OVER A BIAS PLY

Light Duty	Medium and Heavy Duty
80-90%	20-30%

In general the performance characteristics are reported in terms of a tire rolling resistance coefficient, in pounds of rolling resistance per 1,000 pounds of normal load. Conservative estimates place the reduction in rolling resistance coefficient for a radial tire at 15% but this reflects the improvement from a wide variety of radials. One particular type of radial tire shows a consistent 30% improvement[26] over the rolling resistance of bias ply tires, which we believe reflects a true picture of the radial tire potential. In our initial examination of radial tires we used a 15% reduced rolling resistance coefficient in the computer simulations. Experience suggests that a 30% coefficient reduction will double the percentage fuel saving potential. Based on computer simulations for the 15% reduction in coefficient of rolling resistance, the following estimates of fuel economy improvements for radial tires have been made, and are given in Table 5.27.

There is a good deal of controversy with regard to the tire life tradeoff when radial tires are substituted for bias ply. We have summarized our findings on the tire life of radials as compared to bias plies for trucks in Table 5.28 following. This table is not a complete consensus opinion of the listed sources, but is our best summary of the present thinking on the substitution of radial tires for bias ply.

TABLE 5.27

ESTIMATED PERCENT IMPROVEMENT IN FUEL ECONOMY BY SUBSTITUTION OF RADIAL TIRES

Truck	Type of Driving Cycle: Annual Mix	Local	Short	Long
Pickup	4.5%	–	–	–
Van (22,500#)	–	0	1.4	–
Dump (62,000#)	–	8.4	6.0	–
Tractor-Trailer (50,000#)	–	–	6.2	6.2
Tractor-Trailer (70,000#)	–	–	8.8	8.4

TABLE 5.28

SUMMARY OF TIRE LIFE ESTIMATES IN MILES

		Pick-Up	Medium and Heavy Duty: Driven Tires	Non-Driven Tires
Initial Tire Life	Radial	40,000	45,000	200,000
	Bias-Ply	22,000	56,000	180,000
Retreads	Radial	Retreading is not normally done by private owner	2	2
	Bias-Ply		2	2
Total Life	Radial	40,000	≈125,000	≈500,000
	Bias-Ply	22,000	≈125,000	450,000

Sources: Private Communications with: 2/13/75
Rod Nerney, Nerney Motors, Attleboro, Massachusetts
Mike Murphy, Ryder Truck, Jacksonville, Florida
Ignatz Gusakov, Calspan, Buffalo, New York
Jan Neilson, Michelin, Cambridge, Massachusetts
Robert Snyder, Uniroyal, Detroit, Michigan

It should be pointed out that the radial truck tire has a maximum original tread of 16/32″ while comparable bias ply tires have a 26/32″ tread. It is said that the radial tire is limited to this tread depth because of heat buildup in the carcass. Advances in tire technology may permit deeper tread patterns in radials lengthening their lifetime further.

Another factor with regard to tire tread and lifetime, is that the lug pattern (cross bar, or deep tread) bias ply tire may run into more restrictive use because of federal noise legislation. If noise legislation limits the use of lug pattern, deep tread tires, then radial ply tires will gain a tremendous advantage in tire life over bias ply tires.

5.7.4 Single Driven Rear Axles

In vehicle weight class VIII a large number of trucks are equipped with driven tandem rear axles. These axles require an interaxle differential to accommodate rotational differences between axles, in addition to the dual axle differentials. The added drive train components reduce driveline efficiency by 2 to 4%. A single driven rear axle with a non-driven "tag" axle following will reduce driveline losses and improve fuel economy as summarized in Table 5.29.

TABLE 5.29

PERCENT IMPROVEMENT IN FUEL ECONOMY FROM A TAG AXLE

	Driving Cycle		
Truck Type	Local	Short	Long
Dump Truck	2.3	2.3	–
Tractor Trailer 50,000#	–	2.2	2.3
Tractor Trailer 70,000#	–	2.2	2.4

This fuel economy gain can be accompanied by some problems in rear axle life and vehicle tractive effort.

In their driveline analysis work International Harvester examined the reliability of a single rear axle and a tandem rear axle under identical torque histories. A single axle carrying all of the torque (normally split between tandem rear axles) may have only 1/10 the predicted life in miles of a tandem driven rear axle system. This limits the usefulness of the single driven rear axle to those missions where torque requirements are low.

Secondly, a single driven tandem rear axle has less tractive capability than a dual driven rear axle, because half the rear end load is carried by a non-driven axle. If both axles are driven, the total weight carried by the two rear axles is available thus doubling the tractive capability.

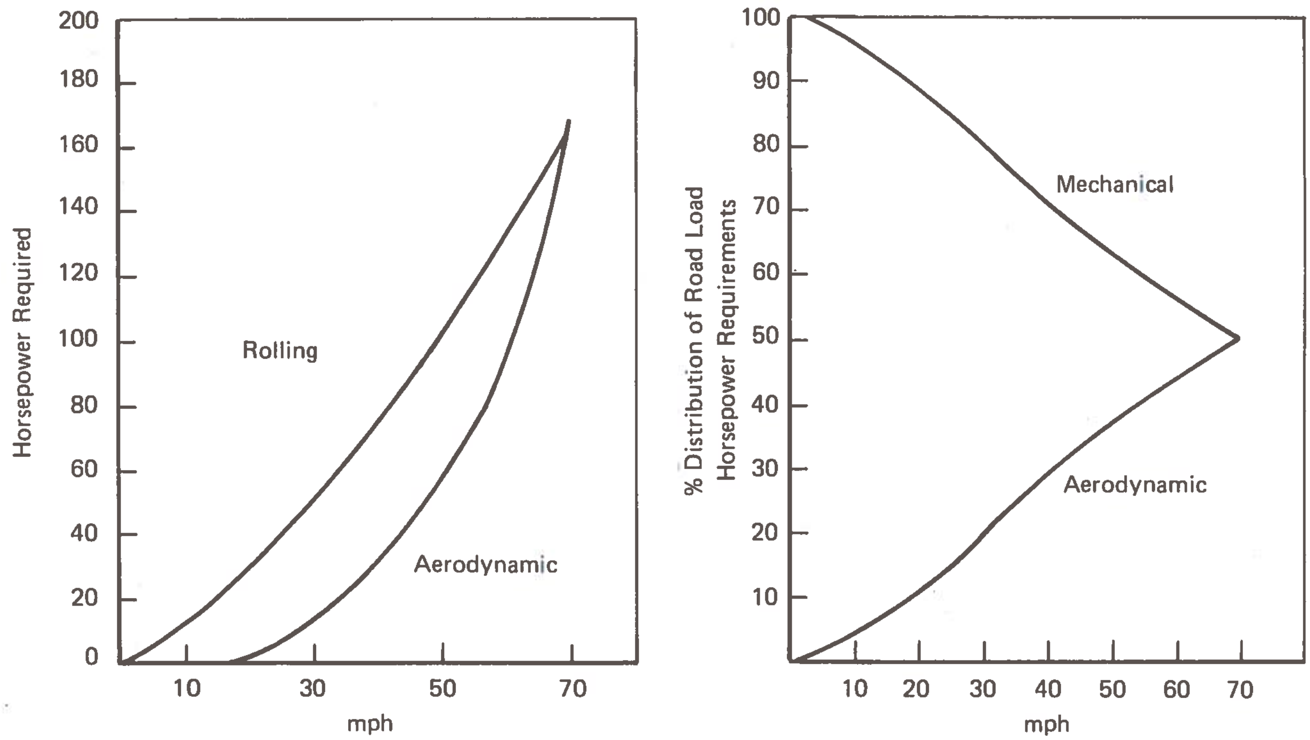
In certain cases, when tractive effort demands and rear axle torque capacity can be met by single driven rear axle the additional savings in initial cost makes it an attractive concept. An initial cost savings of $2,000[27] can be expected in some instances when single driven rear axles are installed instead of dual driven tandem axles.

5.8 TRUCK AERODYNAMICS

Resistance due to aerodynamic drag plays an important role in truck fuel consumption. Along with rolling resistance due to the tire energy consumption the aerodynamic drag accounts for nearly all of the energy consumed for constant speed driving. As seen in the following figure (Figure 5.9) aerodynamic resistance requires horsepower nearly equal to the rolling resistance at 65 miles an hour for a 73,000 pound, 100 square foot frontal area truck. At normal over the road speeds of 55 miles per hour aerodynamic resistance may account for 72 out of the 190 horsepower to meet level road requirements. This is approximately 38% of the road load requirement. When compared to the road load horsepower requirement for a four door sedan, as shown in Figure 5.10, it can be seen that aerodynamic resistance in the very large trucks plays a somewhat reduced role in horsepower requirements because of the higher load factors on the truck tires as discussed in Section 5.7.3. The equivalence point for the four door sedan is at about 58 miles per hour and for the truck the aerodynamic and rolling resistance becomes equal at about 65 miles per hour.

Section 4.3.7 of Reference 2 contains a discussion of aerodynamics in automobiles. This section provides a background of the impact of aerodynamics on automotive fuel consumption and a means by which aerodynamic drag may be reduced. It concluded that by moderate styling changes, a 10% reduction in aerodynamic drag and a 10% reduction in the frontal area would reduce fuel consumption by about 4% at 70 miles per hour.

These results can be applied directly to the light weight pickup trucks because of the similarity in use and design. The similarity results from the fact that the partitioning of the energy for the pickup truck and the automobile are the same as regards to road load. Therefore, the same percentage improvement in drag coefficient will give the same percentage improvement in fuel economy over the same driving cycle. As with automobile styling changes, add-on devices may be expected to give a 10% reduction in aerodynamic drag. Fairing of sides and lowering of the vehicle front profile alone will reduce aerodynamic drag. For the



Source: GMC Truck Selection Data 10–8–73

FIGURE 5.9 LEVEL ROAD HORSEPOWER REQUIREMENTS OF A 73,000 LB GVW 100 SQ. FT. FRONTAL AREA TRUCK

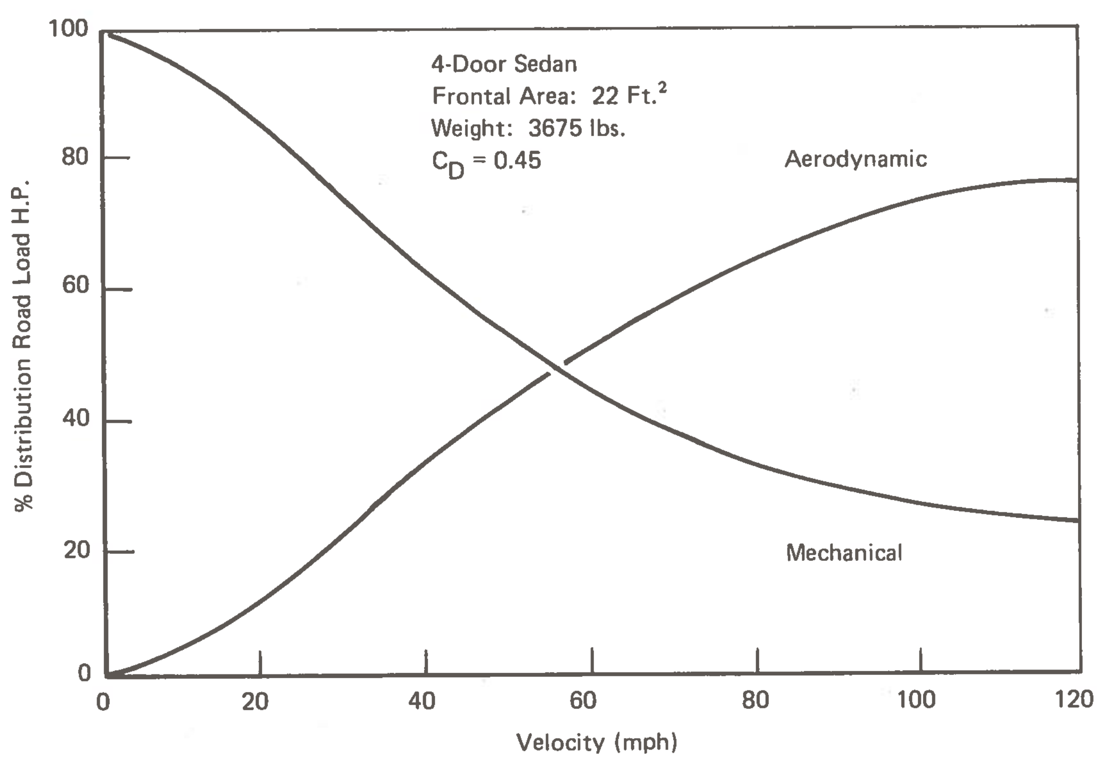


FIGURE 5.10 ROAD LOAD HORSEPOWER DEMAND AS A FUNCTION OF SPEED

light duty pickup there will be no incremental first cost attributed to the styling changes resulting in drag reduction, if the changes are incorporated at major body styling changes. Therefore, this improvement will be cost effective regardless of the fuel cost.

For the purposes of this study, pickup trucks and automobiles differ little from an aerodynamic standpoint. However, there are differences which should be recognized. Pickup trucks have a sharp transition at the rear of the cab where increased turbulence could be expected and hence more drag. Tailoring the air flow at this point could reduce the drag slightly. Particularly if a camper body or cargo enclosure is installed, both of which would add substantially to the frontal area and aerodynamic drag. Also the height of the truck from the road is usually greater than an automobile creating a different road effect. Both of these aspects will make the truck differ from the automobile; however, no significant work has been done on these elements, so we only comment on their possible relevancy.

Heavy duty truck aerodynamic improvements are significantly different from the automobile or the pickup truck. For the heavy duty truck, cargo load capacity is a primary design consideration. With regulations on length, height, and width, the truck manufacturer and trucker have adopted the philosophy of building the truck as large as possible to maximize cargo carrying capacity. Aerodynamic improvements by frontal area reduction is not generally a viable means of reducing truck aerodynamic. In some instances, when certain cargo can be tailored to a different storage arrangement, frontal area reductions may be possible. However, this is limited to a specific truck application and not as a universal tool for reducing truck aerodynamic drag. Most studies on truck aerodynamics recognize this fact and have examined other means of reducing the vehicle aerodynamic resistance. These studies generally concentrate on the transition between the cab and the body of the van.

At the transition between cab of the tractor and semi-trailer (for larger trucks) substantial induced air motion takes place resulting in increased aerodynamic resistance. Several devices have been developed which reduce this turbulence and therefore vehicle resistance. These have been reported in the literature and investigated during this study. Nearly all the material has concentrated on the tractor-trailer combination, the distinction being that the tractor-trailer has two independent elements and the van has an integrated cab and body. In some instances, the add-on devices while tailored to the tractor-trailer may be useful for the van-truck although at present the literature makes no mention of this approach.

Means of reducing the aerodynamic resistance for tractor-trailers include a variety of modifications. The first of these is a simple rounding of the sharp edges of the trailer. Secondly, a fairly common wind deflector for cab top mounting shown (Figure 5.11) has been shown to reduce aerodynamic drag by 11-14 percent in zero wind conditions at 55 mph depending on the particular design of the deflector.[28] As can be seen in this sketch, the wind displaced by the tractor-trailer would normally swirl in the space between the cab and the trailer creating vortices and increased drag on the vehicle. The wind deflector minimizes the effect of the difference in the height and separation between the cab and the trailer.

An additional device compatible with the wind deflector is a vortex stabilizer shown in Figure 5.12. This device is intended to minimize the vortices formed by cross wind or induced vortices from vehicle motion that would form in a horizontal plane unaffected by the wind deflector. In tests on the vortex stabilizer and wind deflector a combined drag reduction of about 21% was found for a tractor-trailer combination.

More complicated concepts include a collapsible fairing which essentially encloses the entire space between the tractor and trailer at speeds over about 40 mph. The fairing automatically deploys when a certain vehicle speed is reached, and driver activation is not required. The deployment is a passive system in which the wind forces are used to extend the transitional housing between the cab and the trailer. At speeds below the deployment speed the housing is retracted permitting complete mobility between the cab and the trailer for maneuvering. Indications are that up to 20% reduction in aerodynamic drag may be achieved with such a system.

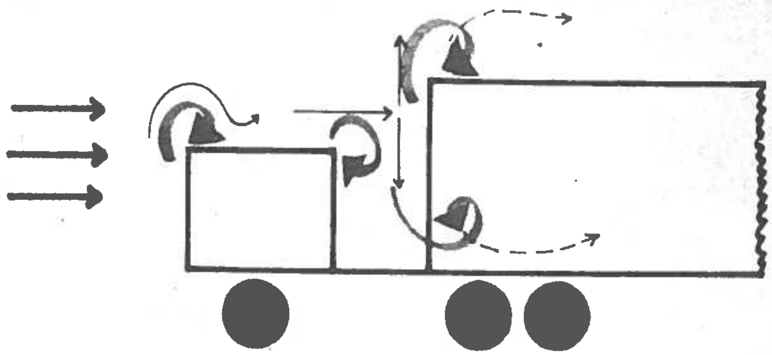
Air vanes applied to the front of the trailer are reported by some manufacturers of these devices to reduce vehicle drag by 30-40 percent. No test data was obtained that confirmed these values. Tests at California Institute of Technology, Merril Wind Tunnel Facility, have indicated that vanes used to direct the air flow over the trailer corners preventing separation and reducing turbulence can indeed reduce aerodynamic resistance. However, the results of these studies have been obtained by wind tunnel tests while results reported for devices described in previous paragraphs have been verified on over the road fuel consumption tests.[28]

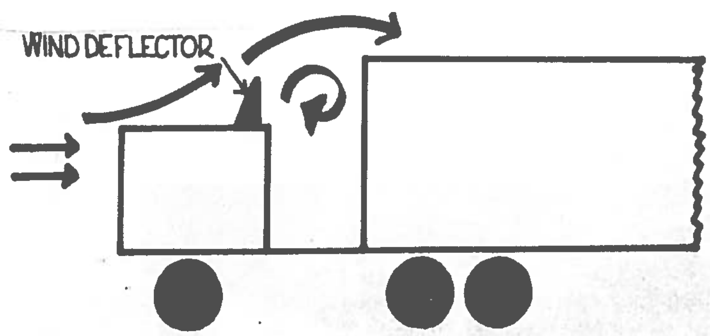
The summary of the reduction in aerodynamic drag is shown in Table 5.30.

TABLE 5.30

AERODYNAMIC DRAG REDUCTION – WIND TUNNEL DATA

Add-On Device	Aerodynamic Drag Reduction
Cab mounted wind deflector	29
Vortex stabilizer	30
Deflector and stabilizer	30
Collapsible fairing	29

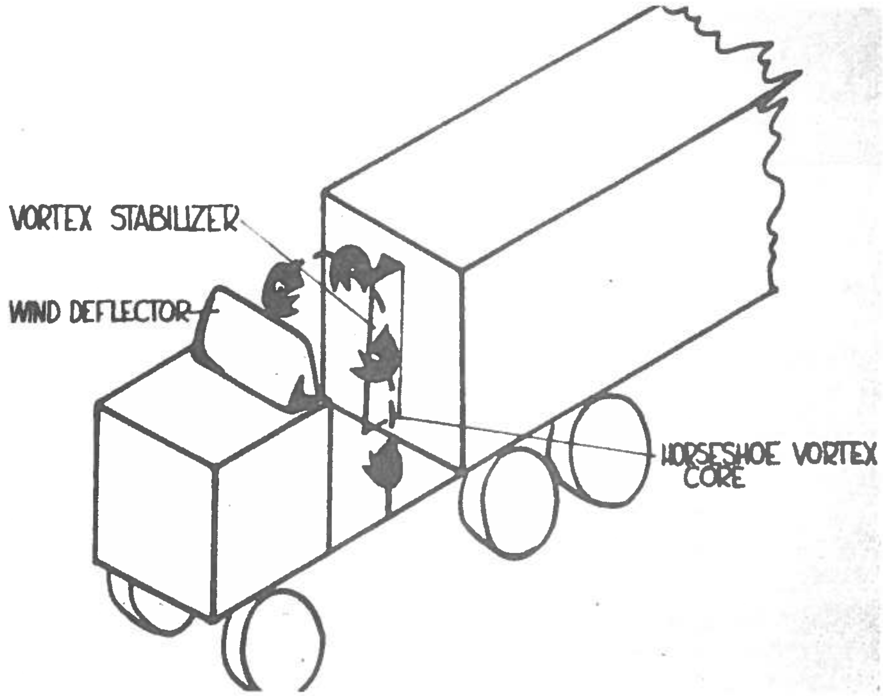


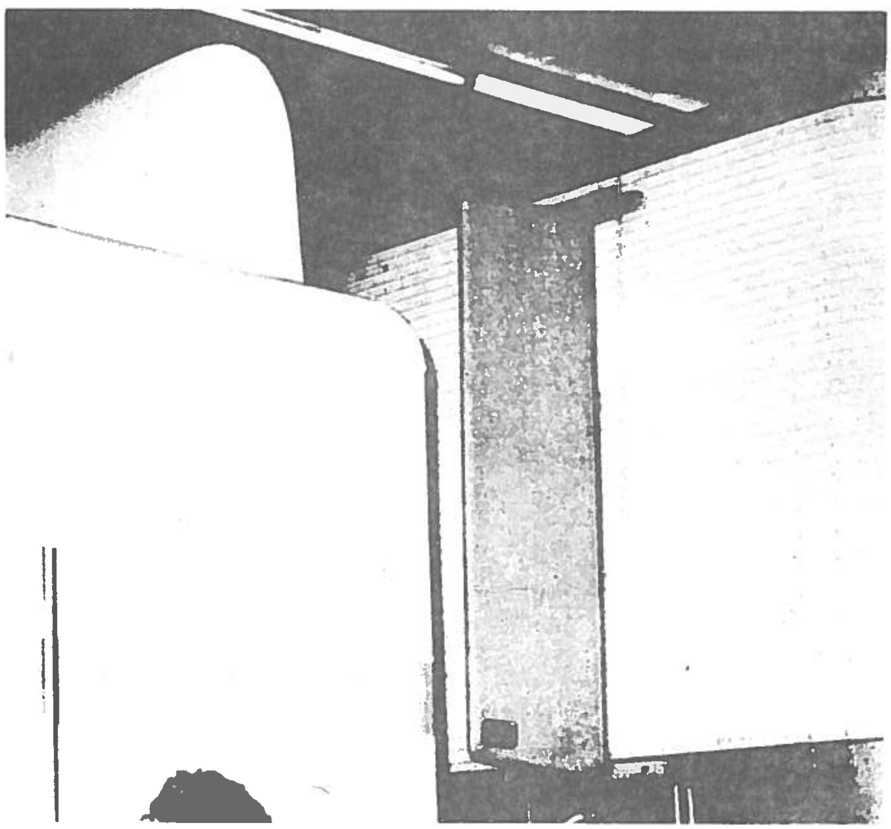


This is how vortexes are formed as a rig travels through the air. The vortexes, which resemble "dust devils," create much more air drag on a rig that isn't "streamlined," particularly in the gap between the tractor and trailer.

Source: Circular from Airshield Division of Rudkin Wiley Corporation.

FIGURE 5.11 TYPICAL AIR FLOW TRACTOR SEMI-TRAILER PATTERNS WITH AND WITHOUT WIND DEFLECTORS





Source: Rudkin Wiley Corporation

FIGURE 5.12 EXAMPLE OF WIND DEFLECTOR AND VORTEX STABILIZER

While these wind tunnel test results indicate large reductions in aerodynamic drag resistance, we feel it is realistic that the average aerodynamic drag may be reduced by 10% for line-haul heavy trucks. Furthermore, indications are that conventional cab-behind-engine tractor designs have less drag than cab over engine types. For purposes of this study it was judged that only the wind deflector could be widely used. For computer simulation purposes a 10 percent reduction in drag coefficient was the value used to represent the utilization of the wind deflector. The results are reported in Table 5.31.

TABLE 5.31

PERCENT IMPROVEMENT IN FUEL ECONOMY WITH A 10 PERCENT REDUCTION IN AERODYNAMIC DRAG – OBTAINED BY USE OF WIND DEFLECTOR

	Duty Cycle		
Truck Type	Local	Short	Long
Dump Truck	1.2	1.8	–
Tractor-Trailer 50,000# GVW	–	1.7	3.0
Tractor-Trailer 70,000# GVW	–	1.2	2.2
Van*	.3*	1.2*	–

*Assuming a wind deflector is devised for the van type truck.

The incremental initial costs for the wind deflectors range from $200 to $350 for vehicle Classes VI, VII, and VIII. If it is assumed that the durability of these devices matches that of the vehicle, there would be no increased maintenance costs associated with the addition of the stationary air shields, when they are properly installed to prevent vibrations.

5.9 WEIGHT OPTIMIZATION AND THE EFFECT ON FUEL ECONOMY

There are two distinct aspects to consider when dealing with the impact of weight and size on the optimization of fuel economy.

The first aspect is the effect on fuel economy by increased productivity either by increased cargo payload weight or volume. The present limits to weights and sizes are legislated. Therefore, a maximized vehicle configuration as a fuel economy technique is not an alternative that manufacturers or fleet owners are presently free to spontaneously adopt. Therefore, we have not considered this first aspect as part of the scope to evaluate technological change resulting in improved fuel economy. Also the change of legislated limits (for instance from 73,280 to 80,000 as of January 6, 1975) of actual weights and sizes will not be dealt with. For those readers who are interested in this aspect, they should refer to pages 81-87 of Reference 1.

The second aspects related to the effects of decreasing vehicle weight in order to increase payload while remaining within the GVW limits. In other words how can the ratio of the weight of payload to the regulated weight be increased, thereby maximizing the product moved per unit of fuel consumed?

A sample of 217 trips by Class VII and VIII vehicles between Chicago and Kansas City[30] has shown that the following linear expression approximates the relationship between fuel consumption and gross combination weight:

$$GPM = .139 + .00290\ GCW$$

where GPM is expressed in gallons per mile and GCW is in tons. Assuming an average tare weight at 13 tons, this can be rewritten as:

$$GPM = .177 + .0029\ P \qquad (1)$$

where P is the payload in tons. The average truck fuel productivity (FP) is the ton-miles of payload handled per gallon of fuel used, or

$$FP = \frac{P}{GPM}$$

From Expression (1), we obtain

$$FP = \frac{P}{.0029P + .177} \qquad (2)$$

Payload weights (P) are presently distributed in some fashion over the interval

$$0 \leqslant P \leqslant GCW_L - TW$$

where TW is the tare weight and GCW_L is the allowed limit on gross combination weight.

Assuming the ratio of the average payload $\bar{P}$ to the limit payload P_L is a constant (note that $P_L = GCW_L - TW$):

$$\frac{\bar{P}}{P_L} = a$$

Statistics on heavy trucks[31] show that at present, $\bar{P} \approx 13.5$ tons and $P_L \approx 23.5$ tons, so that

$$a \approx .57$$

Using the above assumption and Equation 2, we can estimate the change in average fuel productivity resulting from a reduction in tare weight thus increasing the payload capacity. First we must write the expression for $\overline{P}$ as a function of percent reduction, b, in tare weight:

$$\overline{P} = a\ [GCW_L - (1-b)\,TW] \qquad (3)$$

Using values of 36.5 tons for GCW_L and 13.0 tons for TW (typical of existing vehicles), we can solve for $\overline{P}$ as a function of b. The resulting average payload can then be substituted into Equation 2 using $\overline{P}$ for P to obtain the new fuel productivity. This is shown in Table 5.32.

TABLE 5.32

CHANGE IN FUEL PRODUCTIVITY AS A FUNCTION OF DECREASES IN TARE WEIGHT (OVERALL WEIGHT LIMIT HELD CONSTANT)

B Percent Decrease in Tare Weight	$\overline{P}$ Mean Payload (tons)	FP Fuel Productivity (ton-mi/gal)	Percent Increase in FP
0	13.5	62.5	–
10	14.2	65.5	4.8
25	15.4	69.4	11.0

The reduction in tare weight to accomplish the improvement in fuel productivity pays dividends regardless of how fully loaded the truck is. However, the methods used to accomplish the weight reduction are costly and this added cost must be paid back by increased payload income since the fuel savings alone would not pay for the improvement.

Some typical examples of how weight may be reduced and payload increased by use of aluminum in trucks and trailers are:

Engine/Transmission
- Transmission cases
- Engine fly wheel housing
- Engine front trunnion and rear supports
- Engine timing gear covers
- Exhaust mounting brackets

Tractor Chassis Parts
- Fuel tanks
- Front axle
- Battery boxes and covers (also plastic)
- Front cross members
- Bumpers
- Front and rear spring brackets
- Rear axle carrier housings
- Steering gear housing
- Wheel hubs and discs
- Air reservoirs

Body Parts
- Cab doors
- Radiator grills and complete assemblies

6. COST ANALYSIS

6.1 GENERAL DISCUSSION ON BASELINE COST VERSUS FUEL ECONOMY IMPROVEMENT

Tables 5.3, 5.4, 5.5, Section 5.0, show the percentages of fuel economy (% miles per gallon) improvement that were derived from the computer simulation analysis. These percentages of fuel economy improvement were used to determine the total fuel saved during the normal useful life of this vehicle, using the parameters for the payback period as shown in Table 6.1.

Estimates were made from the incremental initial cost of the improvement and the commensurate added (or decreased) repair and replacement costs. These were then compared with the savings accrued in gallons of fuel and a break-even $ per gallon of fuel was calculated.

6.2 INDIVIDUAL IMPROVEMENTS

The individual improvements have been evaluated on the basis of the minimum break-even cost of fuel per gallon. The break-even fuel cost is the cost of fuel per gallon necessary to pay back the total incremental cost of the improvement based on the number of gallons of fuel saved. The incremental cost of the improvement includes additional initial costs, repairs and replacements due to the use of the individual improvement. The cost is amortized over a period of time which depends upon the type of vehicle and the type of owner and its service. Average use factors and periods to pay back the initial cost were developed for each vehicle type. From Section 5.0, Tables 5.4, 5.5, 5.6 plus Tables 6.2-6.13 and Figures 6.1-6.6 the cost of improvement is given and the minimum break-even fuel cost is shown.

6.3 SYNTHESIZED VEHICLES

A combination (synthesized vehicle) of improvements was made using the results from the preceding series of individual improvement break-even costs. In general, a design improvement was chosen when it could improve fuel economy at a break-even cost of $.70 per gallon or less. The synthesized reference vehicles along with the individual improvements are summarized in the following figures 6.1 – 6.6. The figures derived from the fuel economy improvement tables of Section 5 are also summarized in the following tables.

The cost figures for the synthesized vehicles, developed in a manner similar to those for the individual improvements are given as backup.

TABLE 6.1

PAYBACK PERIOD BASELINE PARAMETERS

Vehicle	Payback Period in Years	Baseline Average Vehicle Miles Per Year	Total Payback Period in Miles	Baseline Average Vehicle Miles Per Gallon	Baseline Vehicle Total Gallons Consumed in Payback Mileage Period
I – II					
Light Duty	3	16,600	50,000	10.25	4,900
VI					
Medium Duty –					
Van					
Local	5	10,000	50,000	5.1	9,800
Short	5	10,000	50,000	5.4	9,300
VIII					
Dump Truck					
Local	5	20,000	100,000	5.0	20,000
Short	5	50,000	250,000	5.0	50,000
VIII					
50,000# GVW					
Short	5	50,000	250,000	4.8	52,000
Long	5	100,000	500,000	4.9	102,000
VIII					
70,000# GVW					
Short	5	50,000	250,000	4.0	62,000
Long	5	100,000	500,000	4.5	110,000

Source: ADL estimates based on discussions with industry. Shorter payback periods are used by some truck fleets.

TABLE 6.2

PERCENT IMPROVEMENT IN FUEL ECONOMY WITH OPTIMUM COMBINATION OF OPTIONS

Class	Driving Cycle	Specific Options	% Gain in Fuel Economy (MPG)
I & II	Annual Mix When used as a personal vehicle	• Improved S.I. Engine or Diesel Substitution • 4-sp Auto Trans • Radial Tires • Modulated Fan • Reduced Weight	25-40
VI	Local	• Diesel Engine Substitution • Modulated Fan • 4-sp Auto Trans • Radial Tires	70-80
VIII	Local	• Derated RPM • Modulated Fan • CVRT	15-20
VIII	Short	• Radial Tires • Derated RPM • Modulated Fan • CVRT • Reduced Aero Drag	20-30
VIII	Long	• Radial Tires • Derated RPM • Modulated Fan • Tag Axle • Reduced Aero Drag • Turbocharging	18-23

TABLE 6.3

INDIVIDUAL ENGINE IMPROVEMENTS FOR LIGHT-DUTY TRUCKS*

	Lean Burn	Stratified Charge	Closed Loop Stoichiometric	Turbocharged Gasoline	Light-weight Diesel
Incremental Initial Cost $	100	500	300	200	600
Incremental Maintenance Replacement Cost $	100	300	400	300	0
Total Incremental Cost $	200	800	700	500	600
Fuel Econ. Improvement % (Miles/Gal)	12.5	20	12.5	7.5	27.5
Fuel Reduction % (Gallons)	11.1	16.7	11.1	7.0	21.6
Gallons Saved	541	815	541	342	1054
Minimum Breakeven $/Gal.	0.37	0.98	1.30	1.46	0.57

*The base line gasoline powered vehicle has a payback of 50,000 miles and uses 4,900 gallons of fuel.

TABLE 6.4

MODULATED FAN CONTROL & IMPROVED COOLING SYSTEM DESIGN

	I & II	VI Van		VIII Dump Truck		VIII 50,000# GVW		VIII 70,000# GVW	
		Local	Short	Local	Short	Short	Long	Short	Long
Miles, Driven Ave. Gal. Used	50,000 4,900	50,000 9,800	50,000 9,300	100,000 20,000	250,000 50,000	250,000 52,000	500,000 102,000	250,000 62,000	500,000 110,000
Incremental Initial Cost $	50	200	200	200	200	200	200	200	200
Incremental Maintenance Replacement Cost $	–	0	0	0	0	0	200	0	200
Total Incremental Cost $	50	200	200	200	200	200	400	200	400
Fuel Econ. Improve (MPG) %	3	3.5	4	3.4	3.5	4.8	4.5	5.2	4
Fuel Reduction %	2.9	3.4	3.8	3.3	3.4	4.6	4.3	4.9	3.8
Gallons Saved	141	334	352	660	1,700	2,400	4,388	3,062	4,222
Minimum Breakeven $/Gal.	.35	.60	.57	.30	.12	.08	.09	.07	.10

TABLE 6.5

AUTOMATIC 4-SPEED TRANSMISSION WITH
TORQUE CONVERTER LOCK-UP

	I & II	VI Van		VIII Dump Truck		VIII 50,000# GVW		VIII 70,000# GVW	
		Local	Short	Local	Short	Short	Long	Short	Long
Miles, Driven Ave. Gal. Used	50,000 4,900	50,000 9,800	50,000 9,300		N O T	C O N S I D	E R E D		
Incremental Initial Cost $	75	100	100						
Incremental Maintenance Replacement Cost $	0	0	0						
Total Incremental Cost $	75	100	100						
Fuel Econ. Improve (MPG) %	11.	5.	5.						
Fuel Reduction %	10.	4.76	4.76						
Gallons Saved	488	467	441						
Minimum Breakeven $/Gal.	.15	.22	.23						

TABLE 6.6

CONTINUOUSLY VARIABLE RATIO TRANSMISSION (CVRT)

	I & II	VI Van		VIII Dump Truck		VIII 50,000# GVW		VIII 70,000# GVW	
		Local	Short	Local	Short	Short	Long	Short	Long
Miles, Driven Ave. Gal. Used	50,000 4,900	NOT CONSIDERED		100,000 20,000	250,000 50,000	250,000 52,000	500,000 102,000	250,000 62,000	500,000 110,000
Incremental Initial Cost $	200			1,500	1,500	1,500	NA	1,500	NA
Incremental Maintenance Replacement Cost $	0			0	0	0	–	0	–
Total Incremental Cost $	200			1,500	1,500	1,500	–	1,500	–
Fuel Econ. Improve (MPG) %	21			17.5	17.5	12.5	–	12.5	–
Fuel Reduction %	17.			11.	11.	11.	–	11.	–
Gallons Saved	829			2,200	5,500	5,730	–	6,875	–
Minimum Breakeven $/Gal.	.24			.68	.27	.26	–	.22	–

TABLE 6.7

AERODYNAMIC DRAG IMPROVEMENT

	I & II	VI Van		VIII Dump Truck		VIII 50,000# GVW		VIII 70,000# GVW	
		Local	Short	Local	Short	Short	Long	Short	Long
Miles, Driven Ave. Gal. Used	50,000 4,900	50,000 9,800	50,000 9,300	100,000 20,000	250,000 50,000	250,000 52,000	500,000 102,000	250,000 62,000	500,000 110,000
Incremental Initial Cost $	0	275	275	300	300	300	300	300	300
Incremental Maintenance Replacement Cost $	0	0	0	0	0	0	0	0	0
Total Incremental Cost $	0	275	275	300	300	300	300	300	300
Fuel Econ. Improve (MPG) %	1.3	0.3	2.2	1.2	1.8	1.7	3	1.2	2.2
Fuel Reduction %	1.2	2.9	2.15	1.18	.99	2.9	2.9	1.18	2.15
Gallons Saved	58	284	199	236	495	1,510	2,960	737	2,389
Minimum Breakeven $/Gal.	0	.96	1.38	1.27	0.60	0.20	0.10	0.40	0.12

SUBSTITUTION OF RADIAL TIRES FOR BIAS PLY TIRES

	I & II	VI Van		VIII Dump Truck		VIII 50,000# GVW		VIII 70,000# GVW	
		Local	Short	Local	Short	Short	Long	Short	Long
Miles, Driven Ave. Gal. Used	50,000 4,900	50,000 9,800	50,000 9,300	100,000 20,000	250,000 50,000	250,000 52,000	500,000 102,000	250,000 62,000	500,000 110,000
Incremental Initial Cost $	200	150	150	250	250	350	350	450	450
Incremental Maintenance Replacement Cost $	-200	—	—	-100	+200	+200	+400	200	400
Total Incremental Cost $	0	150	150	150	450	550	750	650	850
Fuel Econ. Improve (MPG) %	4.5	6.0	8.6	8.4	6.0	6.2	6.2	8.8	8.4
Fuel Reduction %	4.8	5.6	7.9	7.9	5.7	5.7	5.7	7.9	7.7
Gallons Saved	235	550	735	1,580	2,850	3,000	5,800	5,000	8,600
Minimum Breakeven $/Gal.	0.0	0.28	0.20	0.10	0.16	0.20	0.14	0.13	0.09

TABLE 6.9

WEIGHT SAVING

	I & II	VI Van		VIII Dump Truck		VIII 50,000# GVW		VIII 70,000# GVW	
		Local	Short	Local	Short	Short	Long	Short	Long
Miles, Driven Ave. Gal. Used	50,000 4,900	50,000 9,800	50,000 9,300	100,000 20,000	250,000 50,000	250,000 52,000	500,000 102,000	250,000 62,000	500,000 110,000
Incremental Initial Cost $	100	NOT CONSIDERED – SEE TEXT							
Incremental Maintenance Replacement Cost $	0								
Total Incremental Cost $	100								
Fuel Econ. Improve (MPG) %	2.8								
Fuel Reduction %	2.6								
Gallons Saved	126								
Minimum Breakeven $/Gal.	.79								

TABLE 6.10

SUBSTITUTE DIESEL ENGINE FOR GASOLINE ENGINE

	I & II	VI Van		VIII Dump Truck		VIII 50,000# GVW		VIII 70,000# GVW	
		Local	Short	Local	Short	Short	Long	Short	Long
Miles, Driven Ave. Gal. Used	50,000 4,900	50,000 9,800	50,000 9,300	100,000 20,000	250,000 50,000	250,000 52,000	500,000 102,000	250,000 62,000	500,000 110,000
Incremental Initial Cost $	600	2,500	2,500		NOT	CONSIDERED			
Incremental Maintenance Replacement Cost $	0	0	0						
Total Incremental Cost $	600	2,500	2,500		NOT	CONSIDERED			
Fuel Econ. Improve (MPG) %	27.5	67	48		ALREADY USED AS STANDARD ENGINE				
Fuel Reduction %	21.6	40	32.4						
Gallons Saved	1,054	3,933	3,000						
Minimum Breakeven $/Gal.	.57	.63	.83						

Note that the durability of the diesel engine is generally superior to the spark-ignited engine.

TABLE 6.11

TURBOCHARGER INSTALLED AS ORIGINAL EQUIPMENT ON ENGINE
(DIESEL OR GASOLINE)

	I & II	VI Van		VIII Dump Truck		VIII 50,000# GVW		VIII 70,000# GVW	
		Local	Short	Local	Short	Short	Long	Short	Long
Miles, Years Ave. Gal. Used	50,000 4,900	50,000 9,800	50,000 9,300	100,000 20,000	250,000 50,000	250,000 52,000	500,000 102,000	250,000 62,000	500,000 110,000
Incremental Initial Cost $	200	NOT CONSIDERED		300	300	1,150	1,150	1,150	1,150
Incremental Maintenance Replacement Cost $	300			200	200	200	200	200	200
Total Incremental Cost $	500			500	500	1,350	1,350	1,350	1,350
Fuel Econ. Improve (MPG) %	7.5			1.	2.5	2.5	4	2.5	4.2
Fuel Reduction %	7			1.0	2.4	2.4	3.8	2.4	4.
Gallons Saved	342			198	1,200	1,250	3,877	1,500	4,444
Minimum Breakeven $/Gal.	1.46			2.53	.42	1.08	.35	.90	.31

TABLE 6.12

COMBINED IMPROVEMENTS
LIGHT-DUTY WEIGHT CLASS

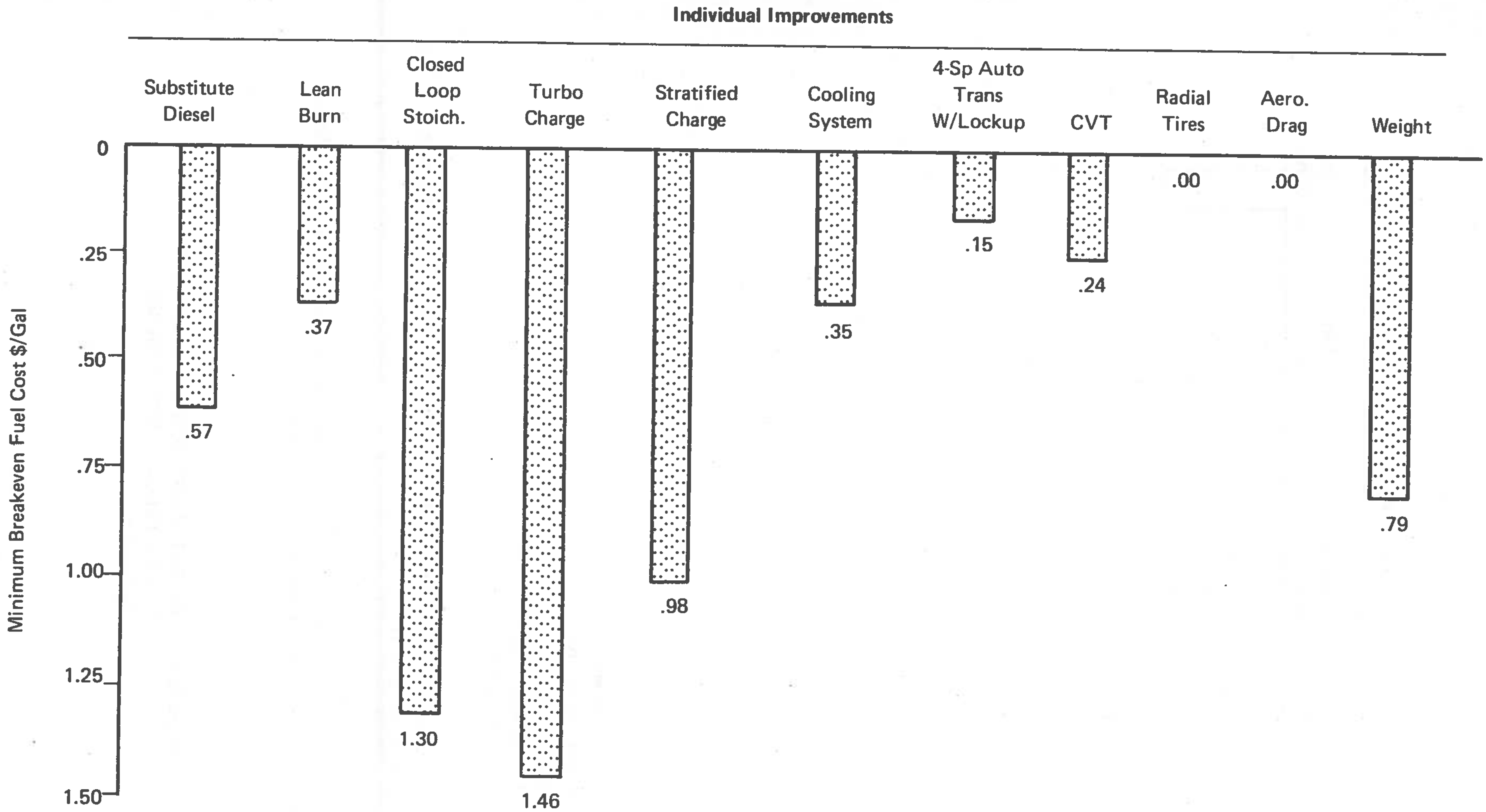
Combined Improvements	Diesel Substitution 4-sp Auto Trans Radial Tires Modulated Fan Reduced Weight	Closed Loop Stoichiometric 4-sp Auto Trans Radial Tires Modulated Fan Reduced Weight	Stratified Charge 4-sp Auto Trans Radial Tires Modulated Fan Reduced Weight	Lean Burn 4-sp Auto Trans Radial Tires Modulated Fan Reduced Weight
Total Incremental Life Cost $	625	725	825	225
% Reduction in Fuel Consumption	40	29	35	25
Savings in Gallons	1950	1415	1710	1220
Break Even Fuel Cost $/Gal.	.32	.51	.48	.18

Baseline vehicle = 3 years ownership/50,000 miles.

TABLE 6.13

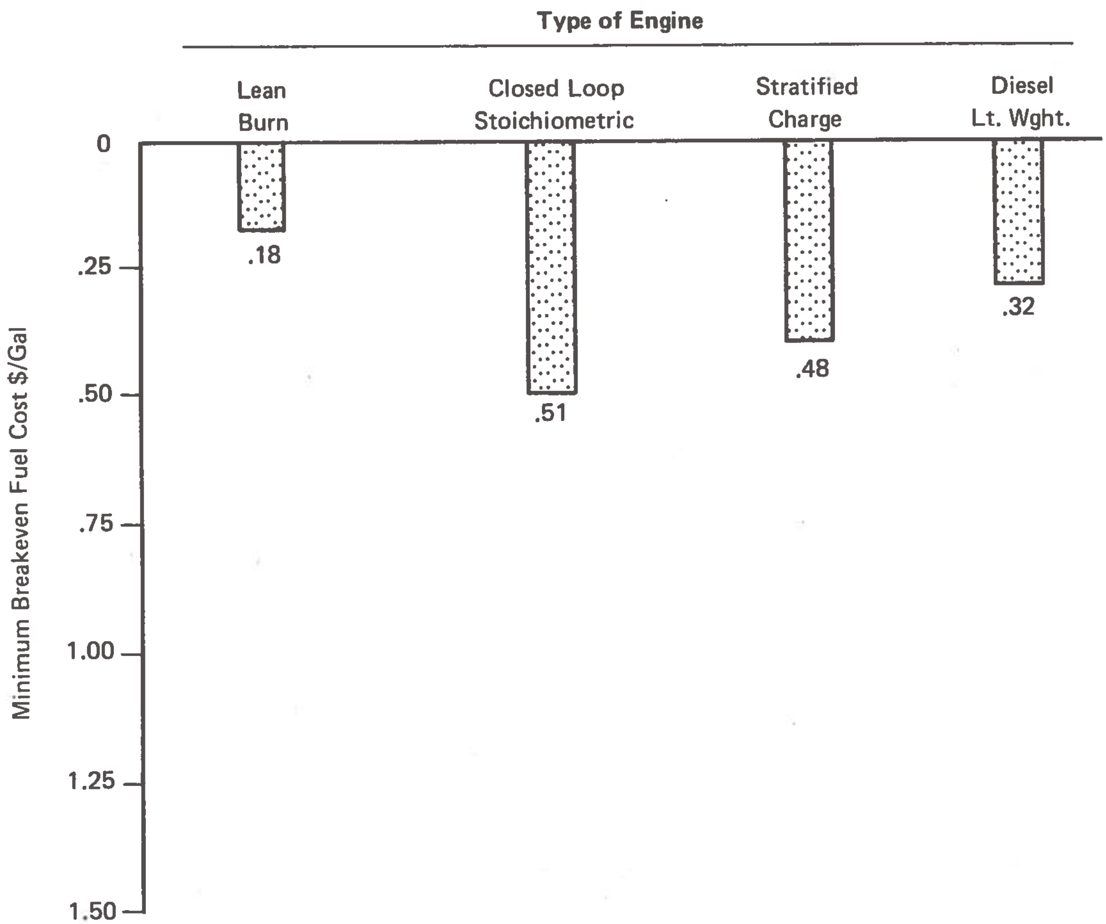
COMBINED IMPROVEMENTS
HEAVY-DUTY TRUCKS

Vehicle Class	VI Van	VIII Dump	VIII 50,000#	VIII 70,000#
Combined Improvements	Diesel Substitution Modulated Fan 4-sp Auto Trans and Radial Tires	Derated RPM Modulated Fan CVRT Radial Tires	Derated RPM Modulated Fan Aerodynamic Drag Reduction CVRT Radial Tires	Derated RPM Modulated Fan Aerodynamic Drag Reduction Turbocharging Radial Tires
Total Incremental Life Cost $	3000	1860	3,200	3,450
% Reduction in Fuel Consumption	42	18	20	22
Savings in Gallons	4200	3700	10,500	20,300
Break Even Fuel Cost $/Gals.	.70	.49	.30	.17



Based on:
1. Annual Driving Cycle when used as a personal vehicle is a Mixture of 35% Urban (F.T.P.) 65% Steady State 30-70 MPH
2. 3 Years = 50,000 Miles of Use (First Owner)
3. Cost is at 0% Discount Rate
4. Minimum Breakeven Fuel Cost is Cost per Gallon that will Generate Sufficient Savings to Offset All Incremental Cost for the Improvement

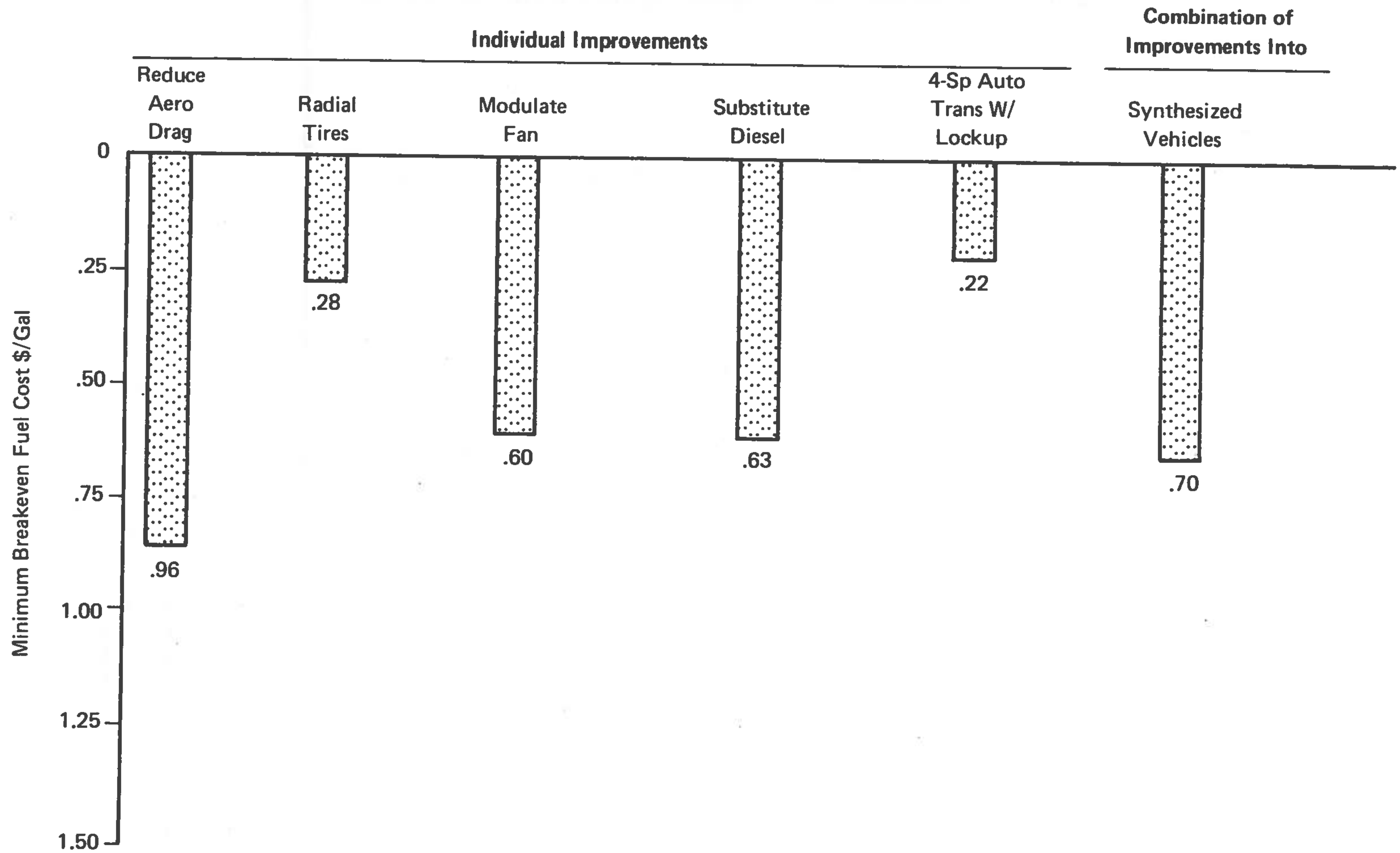
FIGURE 6.1 WEIGHT CLASS I AND II – LIGHT DUTY PICK-UP TRUCK



Includes: Cooling System
4-Speed Auto Trans.
Radial Tires
Aerodynamic Drag Reduction
Weight Reduction

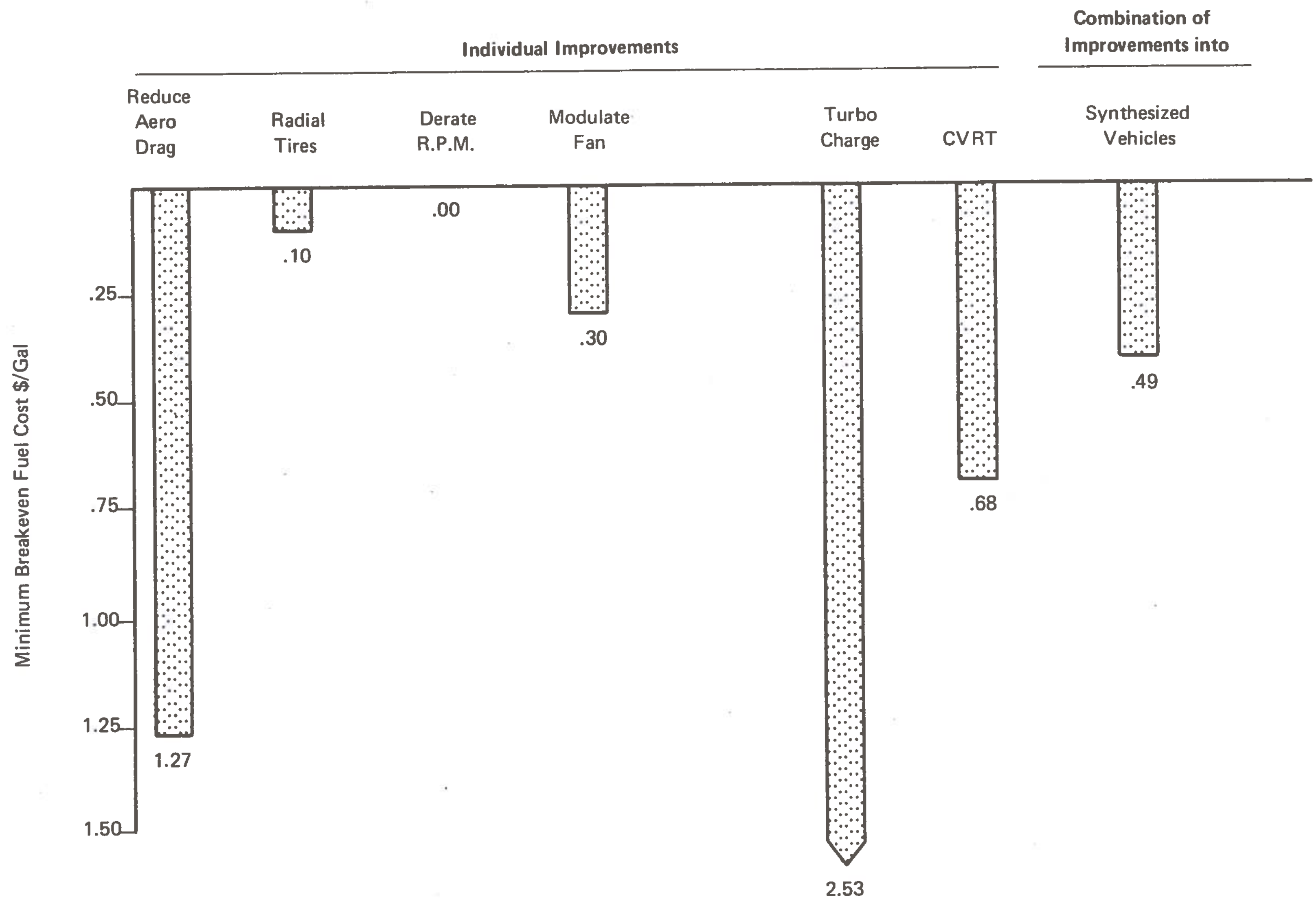
Based on:
1. Annual Driving Cycle when used as a Personal Vehicle is a Mixture of 35% Urban (F.T.P.), Steady State 30-70 MPH
2. 3 Years = 50,000 Miles of Use (First Owner)
3. Cost is at 0% Discount Rate
4. Minimum Breakeven Fuel Cost is Cost per Gallon that will Generate Sufficient Savings to Offset all Incremental Cost for the Improvement

FIGURE 6.2 WEIGHT CLASS I AND II – LIGHT DUTY PICK UP TRUCK – SYNTHESIZED VEHICLES



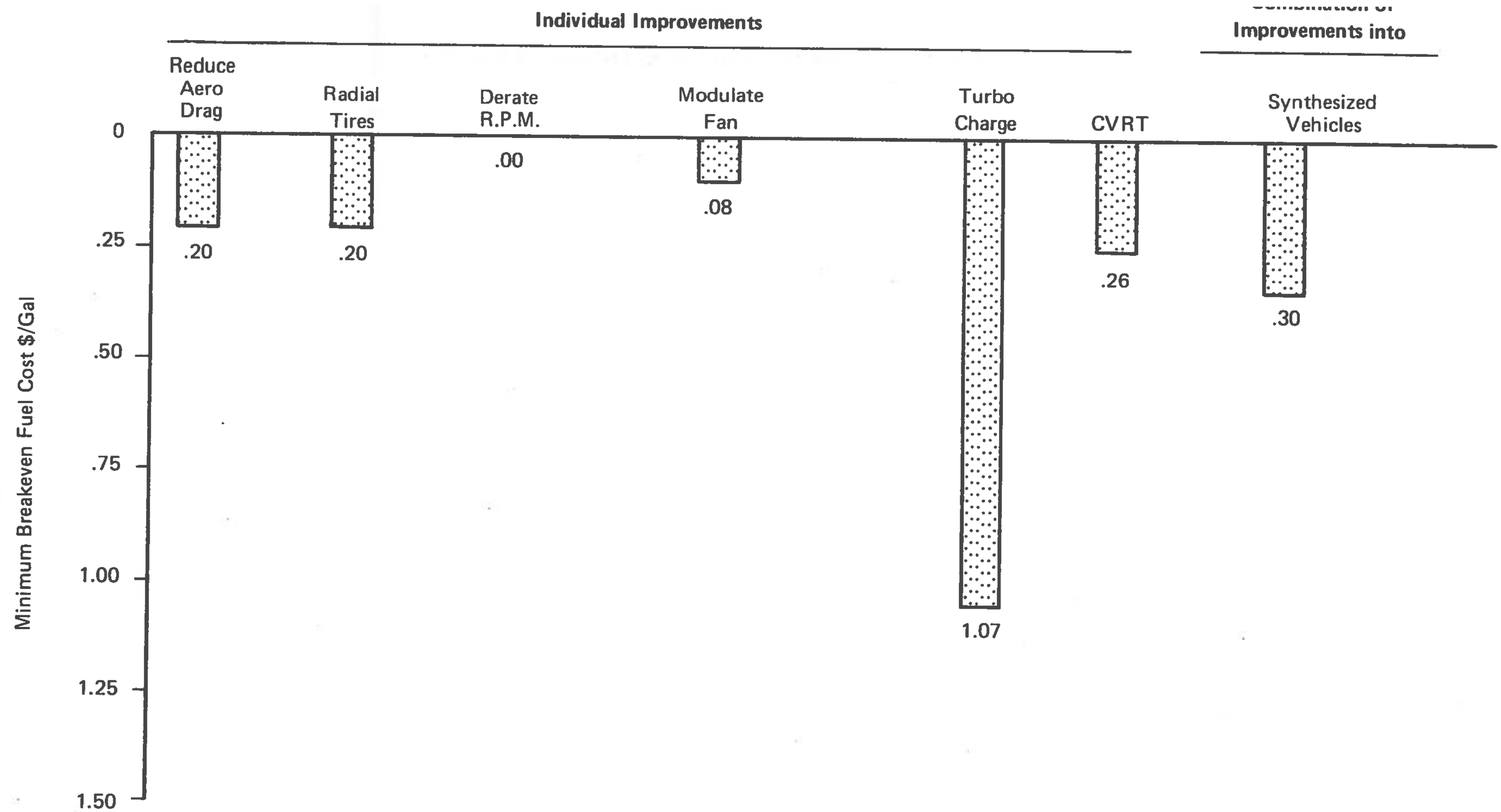
Based on: 1. Local-Duty Cycle is Comparable to 100% FTP for Light Duty Vehicles
2. 5 Years = 50,000 Miles of Use (First Owner)
3. Cost is at 0% Discount Rate
4. Minimum Breakeven Fuel Cost is Cost per Gallon that will Generate Sufficient Savings to Offset all Incremental Cost for the Improvement

FIGURE 6.3 WEIGHT CLASS VI – VAN TYPE – LOCAL-DUTY CYCLE



Based on: 1. Local-Duty Cycle is Comparable to 100% FTP For Light-Duty Vehicles
2. 5 years = 100,000 Miles of Use (First Owner)
3. Cost is at 0% Discount Rate
4. Minimum Breakeven Fuel Cost is Cost per Gallon that will Generate Sufficient Savings to Offset all Incremental Cost for the Improvement

FIGURE 6.4 WEIGHT CLASS VIII – DUMP TRUCK – LOCAL-DUTY CYCLE



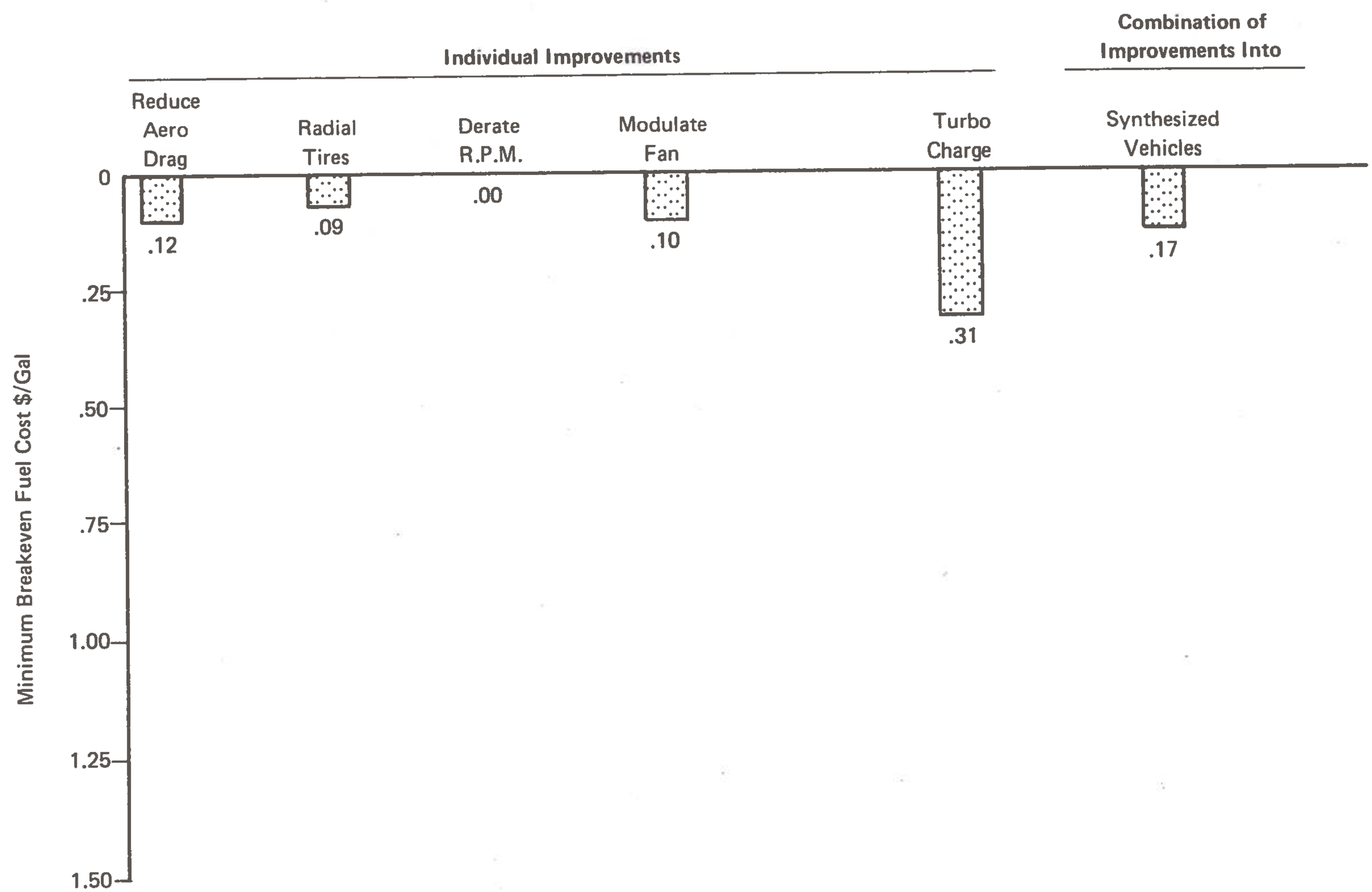
Based on: 1. Short Trip Duty Cycle is Round Trip from Base Returning at Night with a Mixture of Urban, Suburban and Highway Driving Between Cities

2. 5 Years = 250,000 Miles of Use (First Owner)

3. Cost is at 0% Discount Rate

4. Minimum Breakeven Fuel Cost is Cost per Gallon that will Generate Sufficient Savings to Offset all Incremental Cost for the Improvement

FIGURE 6.5 WEIGHT CLASS VIII – 50,000 LBS TRACTOR TRAILER – SHORT TRIP DUTY CYCLE



Based on: 1. Long Trip Duty Cycle-One Way-Line Haul High Speed Freight Delivery
2. 5 Years = 500,000 Miles of Use (First Owner)
3. Cost is at 0% Discount Rate
4. Minimum Breakeven Fuel Cost is Cost per Gallon that will Generate Sufficient Savings to Offset all Incremental Cost for the Improvement

FIGURE 6.6 WEIGHT CLASS VIII – 70,000 LBS TRACTOR TRAILER – LONG-DUTY CYCLE

APPENDIX

REPORT OF INVENTIONS

After a diligent review of the work performed under this contract, no new innovation, discovery, improvement, or invention was made.

REFERENCES

1. "Study of Potential for Motor Vehicle Fuel Economy Improvement, Truck and Bus Panel Report," Report No. 7 by U.S. Dept. of Trans. and U.S. Env. Prot. Agency, January 10, 1975.

2. Hurter, D.A., *et. al,* "A Study of Technological Improvements in Automobile Fuel Consumption," DOT-TSC-057-74-40 – Volume I, II, III, and IV, December 1974.

3. Alberte "In Medium-Duty Trucks Rising Fuel Costs Spur Mid-Range Diesel Sales," Diesel and Gas Turbine Progress, June 1974.

4. Alperstein, Schafer, Villforth, "Texaco's Stratified Charge Engine; Multi-Fuel, Efficient, Clean, and Practical" SAE 740563, May 1974.

5. Reference 2, Volume IIIA, p. 197-213.

6. Private communication with David Gresty, Climax Molybdenum Company. 2/73

7. Monaghan, M.L., *et al.* "A Study of the Diesel as a Light-Duty Power Plant" EPA-460/3-74-011, July 1974.

8. Schwitzer Division, Wallace-Murray Corp. Docket Submission, August 14, 1974.

9. Data from Cummins Publication "Truckers Guide to Fuel Savings." 1974

10. JPL Presentation at DOT, 18 October 1974.

11. Envir. News 3 October 1974.

12. Automotive Industries, November 74 p 25 ff.

13. Phone interview November 1974 with AMBAC: Alex Hossack.

14. Freeman, J.H. and Stalman, R.C. SAE Paper 650863.

15. Gala, V.B. "Bendix Control of NO_x Emissions from Mobile Sources," April 72 Report to EPA No. 6213.

16. Bascunana, J.L. 66th APCA Meeting (1973) Paper No. 74.

REFERENCES (Continued)

17. Mitchell, E., and Alpestain, M., Cumbustion Science and Technology *8* p 39 (1973).

18. Schwerket & Johnson, "A Turbocharged Spark Ignition Engine with Low Exhaust Emissions and Improved Fuel Economy," SAE 730633.

19. Mortimer, J., "Small Gas Turbines – Will They Succeed?", Engineer, September (1972).

20. Shteynberg, A.S., *et al.*, "Gas Turbine Engine of a Dump Truck," AD 747608.

21. Nagey, T.F., *et al.*, ASME Paper (1973).

22. *Op. Cit.* Mortimer, J.

23. Lenoe, E.M., "Ceramics for Turbines," AAPS Conference (1974).

24. Report of Trans-Expo Demonstration. Conducted at GM Proving Grounds, U.S. Auto Club Supervised. September 1972.

25. Cummins published data in "Partners in Trucking" Marketing Division, Cummins Engine Co., Columbus, Indiana.

26. Private communication with Don Klokkenga of Cummins Engine Company, Inc. 2/75

27. Private communications with M. Murphy, Ryder Truck, Jacksonville, Florida. 2/75

28. Montoya, L.C., Sterns, L.L., NASA-TM-56028, "Aerodynamic Drag Reduction Tests on a Full Scale Tractor-Trailer Combination with Several Add-On Devices," December 1974.

29. *Op. Cit.* Montoya

30. Commercial Car Journal, September 1973.

31. Fax, G.E., and Kaye, M.C., "Truck Noise III-D, The Economics of Quieting the Freightliner Cab-Over-Engine Diesel Truck," DOT-TST-75-22, October 1974, pages 7-12.

32. *Op. Cit.* Fax.