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# Future Heavy Duty Trucking Engine Requirements

Larry W. Strawhorn and Victor A. Suski  
American Trucking Associations, Inc.

March 1985

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for

**U.S. DEPARTMENT OF ENERGY**  
**Conservation and Renewable Energy**  
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Alexandria, Virginia 22314

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## CONTENTS

	<u>Page</u>
Executive Summary.....	1
1. Introduction	
1.1 Definition of Terms.....	4
1.2 Approach.....	5
2. Task 1, The Role of Heavy Duty Trucks in the Future	
2.1 Background.....	7
2.2 The Interviews.....	10
2.3 Results.....	15
3. Task 2, Fleet Engine Requirements	
3.1 Engine Requirements.....	23
3.2 Vehicle Requirements.....	27
3.3 Cost Factors.....	29
3.4 Other.....	31
4. Task 3, Potential Future Engine Characteristics	
4.1 Background.....	34
4.2 Results.....	35
4.3 Probable Future Engine Characteristics.....	44
4.4 Summary.....	53
4.5 Discussion of Probable Engine Characteristics.....	53
5. Conclusions.....	60
6. References.....	62
7. Glossary.....	70
8. Appendices	
A. Names of Fleets Interviewed.....	87
B. Questionnaire.....	91
C. Results of Fleet Interviews.....	99
D. Bases for Numbers Used in Questionnaire.....	127
E. Effect of EPA Emission Standards.....	135
F. Potential of Aerodynamic Improvements.....	147

## EXECUTIVE SUMMARY

The Engineering Department of the American Trucking Associations Inc., (ATA), undertook a study to compare fleet requirements for future heavy-duty vehicle diesel engines to projected characteristics of those engines in the 1998-2000 time frame. Fleet requirements were developed using current experience and through interviews with executives of major fleets. Projected engine characteristics were obtained by consultation with major engine manufacturers and from the literature.

In order to develop motor carrier requirements for future engines, a picture of the role of heavy duty trucking in the future was developed. Types of vehicles and engine performance, maintenance and cost characteristics were then derived.

It appears that the role of the heavy duty vehicle will diminish over time, while the role for medium duty vehicles will greatly increase. In the Western U.S., heavy duty tractors will be hauling varieties of trailer trains. In the Eastern U.S., "lighter" duty tractors will haul doubles (twin trailers) by night and one of the doubles trailers by day in the local delivery area. This multi-role tractor will appear in local delivery roles throughout the country.

Horsepower levels will not change greatly over today but may increase slightly in the West. Most engine characteristics changes will be good for fleets. Engines will be lighter, more reliable and require less maintenance. However, ATA believes fuel consumption may not be much less than today's engines because of more stringent emission standards. Significant gains in engine fuel economy are possible with uncooled low heat rejection, minimum friction, turbocompounded engines having bottoming cycles. It is unlikely that fleets will be able to cope with the complexity of bottoming cycle systems. Except for this reservation the projected characteristics of future advanced engines match the needs and expectations of fleets.

It is theoretically possible to recover some of the fuel efficiency lost due to more stringent emissions controls by designing an integrated combination vehicle and applying aerodynamic design principles. An 18 mpg combination vehicle is possible, but would require a drastic change in the way motor carriers and especially manufacturers do business.

## 1. INTRODUCTION

The work documented in this report is part of the Department of Energy (DOE) Heavy Duty Transport Technology project and was performed under the supervision of the NASA Lewis Research Center.

This work was undertaken because of the conviction that research on heavy duty diesel engines had to be constrained within some target area, more or less defined by truck fleet preference, or, at the very least, the fleets' ability to digest new technology. It seemed to ATA that developers of advanced heavy duty diesel engines were engaged in exploiting the opportunities presented by new materials and technologies without regard for the concerns of the eventual end user. Indeed, there is no assurance that the truck fleets of tomorrow will exist in either the same form, or numbers, as they do today.

Other large groupings of users such as electrical utilities have structured processes for defining needs. This study attempts to emulate these to a degree, and provide engine researchers with a statement of user need, and/or tolerance level.

The general method employed in this study was to define a picture of the future trucking industry accounting for competitive and socioeconomic factors, defining the role of the heavy duty truck in this future industry, and from that deriving requirements for future engines in terms of numbers, performance, and cost.

A look nominally 15 years into the future, was established through discussions with DOE personnel and is referred to as the 1998-2000 time frame. Some data estimates for 1995 are also included in this nominal period.

The primary source of information for this study was interviews with executives in selected fleets in the motor carrier industry, and with engine manufacturers. This was because these people are assessing and responding to trends in the market place, as they perceive them, long before these trends are noted in the literature; and because, in most of the studies and forecasts seen over a period of several years, no one has asked motor carriers what they think is or is not going to happen.

### 1.1 Definition of Terms

It is essential to clearly understand the terms used in this report. Few outside the transportation and trucking industries will be familiar with these terms, and indeed there is an ambiguity about some of them, even to people within the trucking industry. These terms, as used in this report, are defined in the glossary. Silhouettes of the various vehicle configurations referred to are also shown in the glossary.



## 1.2 Approach

There are three tasks involved in this effort. The first is to define, insofar as possible, the role heavy duty motor transport is expected to play fifteen years hence. The term heavy duty is meant to cover those classes of tractors using engines from 270 to 350 hp - nominally classes 7 and 8.

The second task is to derive from the anticipated heavy vehicle role(s) the particular engine performance, maintenance and cost characteristics required by fleets.

The third task is to extrapolate current engine research trends and compare their probable future characteristics to the requirements developed in Task 2. Such engine performance parameters as brake specific fuel consumption (BSFC), specific weight, durability and cost are investigated.

Task 1 was accomplished by interviewing executives in the trucking industry. From these interviews came conclusions regarding what the future industry would be like, what number of heavy duty trucks would probably be required, and what were the roles that would likely be filled by heavy duty trucks.

Task 2 was accomplished by taking various engine performance parameters, surfaced during the interviews, and assigning a range of values to them, in consultation with fleet executives. This

necessitated defining what current trucking industry experience is with these parameters. In addition, with some parameters the engine cannot be studied separately from the chassis, so total vehicle factors were dealt with. Finally, the desired values for vehicle performance parameters were projected fifteen years hence.

For Task 3, the approach was to interview the major heavy duty diesel engine manufacturers and obtain their projections for future engine performance characteristics. Current literature was also reviewed. These projections were then compared to the engine requirements developed in Task 2.

## 2. TASK 1

### The Role of Heavy Duty Trucks in the Future

#### 2.1 Background

The motor carrier industry is in a state of drastic change brought about by the Motor Carrier Act of 1980. The nature of the industry is changing and because of this real and perceived equipment needs will be different in the future.

The motor carrier industry, prior to the Motor Carrier Act of 1980, comprised approximately 16,000 fleets regulated by the Interstate Commerce Commission (ICC). Today there are close to 30,000 fleets having ICC authority.<sup>1</sup>

In 1983, 2,227 class 1 and 2 (revenues of over \$1,000,000) regulated carriers generated over \$38 billion in revenue, ran over 13 billion miles, and operated 139,051 tractors. (1)<sup>2</sup>

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<sup>1</sup> In order to legally carry commodities regulated by the ICC a carrier must receive operating authority from the ICC. Since 1980, thousands of carriers, including one truck operators, have received operating authority.

<sup>2</sup> Numbers in parenthesis refer to references at the end of this paper.

The industry has been closely regulated by the Interstate Commerce Commission since 1935. The ICC regulated the trucking industry as a "national utility" controlling entry, markets served, commodities carried, routes used, tariffs and other factors. The objective of such regulation was a healthy, stable industry with adequate return on capital.

Carriers became divided into categories based on the nature of the customers they served. Common carriers have an obligation to serve all who tender freight. Contract carriers haul only for a particular shipper(s). Private carriers could haul only their own freight, e.g. Safeway Stores. Safeway could send a truck from a major distribution center to a destination warehouse or retail outlet, and then had to return empty because they had no authority, nor could it be gotten, to carry other than their own freight.

Because carriers, in many cases, would travel only certain routes, transporting the same commodities to and fro, equipment optimized for a particular route/freight combination was purchased. This made for very efficient equipment - but with thousands of carriers doing this - a lot of variety in equipment.

It was, and is, normal to haul coast to coast and from North to South, often times with two drivers and stopping only for food, fuel, rest and repairs. Some companies contend this can still be done with doubles and compete with piggyback movements.

The vehicle doing this hauling is the well known "18 wheeler" - the 5 axle tractor semitrailer. This tractor can be fitted with a variety of drive trains and suspensions and can be configured to haul over 100,000 lbs. gross combination weight (itself, plus trailers, plus cargo). The maximum legal weight in most places is, however, 80,000 lbs.

In a typical operation the carrier hauls "line haul" from terminal to terminal - say New York to Cleveland - and then the freight is off loaded and run across the loading dock to class 4-6 city delivery trucks, which deliver in the local area served by the Cleveland terminal. (Class 4-6 covers 14,001 to 26,000 lbs. gross vehicle weight).

Perhaps the most fundamental factor affecting motor carrier equipment is that it is designed more by legislators than by a process of considering optimum transportation efficiency. The size, weight and axle spacing of vehicles is defined by road, bridge and political constraints translated into statute. The locations where more productive vehicles can be used depend more on local political considerations than moving a given amount of freight economically.

The second most important factor affecting vehicles and engines is fuel. The price of fuel is a critical factor because it is fundamental to calculations of return on investment and other calculations involving tradeoffs in operating costs. In addition, fuel quality is a concern because poor quality fuel wears out engines faster, and increases harmful emissions.

## 2.2 The Interviews

The interviews with key motor carrier executives were the means used for completion of Task 1. Individuals interviewed held a variety of positions: Maintenance Director, Vice President for Maintenance, Vice President for Marketing, Vice President for Research, Director of Engineering and Company President. The great majority of individuals held positions in maintenance because this report deals with equipment issues, yet at the same time the individuals were sufficiently high in the company hierarchy to have a sense of marketing and financial concerns.

The interview process was in effect the Delphi method. The Delphi method is an iterative survey technique designed to derive a consensus from a panel of persons knowledgeable about a given question. It was developed at the RAND Corporation in the early 1950's to obtain consensus among homogeneous, expert panels. While its use has been extended beyond that of a forecasting tool, it has been used in this study in its original, narrower form. Results of the interviews (Appendix C) were provided to the interviewees for feedback.

The fleets to be interviewed were selected by taking a list of the top 100 fleets in the country, in terms of revenue, and identifying those which belonged to the American Trucking Associations' Technical Advisory Group (TAG) and The Maintenance Council (TMC).

The TAG is comprised of executives from 30 of the top common carrier, private carrier, contract carrier, tank carrier and rental fleets. TAG meets quarterly to review policy implications of equipment regulations and standards and provides guidance on these matters to the ATA Engineering Department. The Maintenance Council is comprised of executives and maintenance managers from approximately 400 fleets of all descriptions, and some 600 product support personnel from original equipment manufacturers, engine manufacturers and companies which supply motor carriers and original equipment manufacturers. Their interest is the improvement of equipment and its maintenance. The noteworthy characteristic of both TAG and TMC is that their interests are industry wide.

Most of the fleets contacted were in the general freight carrier category. General freight carriers have had to report financial and operating data to the ICC for the past 30 years, so there is an historical record for these carriers. The reporting is done only by class I and class II carriers (those with revenues of \$1 million and above) and in 1983 there were 2227 reports filed. That total included 617 (28%) general freight carriers who owned 94,433 tractors in 1983. (1) Specialized carriers were 58% of the total, but the largest subcategory (liquid petroleum carriers) is only 4% of the total. Thirty-one general freight carriers, five specialized carriers, two contract carriers and one auto hauler were interviewed. Two truck rental and leasing companies were interviewed to gain insight into the needs of private carriers - many of

whom lease equipment, and who because of trying to make their private fleets into profit centers, are beginning to face the same concerns as carriers of general freight.

Household goods carriers and fleets which employed owner operators exclusively were not approached. Household goods carriers were not approached because their clients are basically individuals, not shippers in the sense of companies which supply the retail business or other industries (although this is changing too). Hence, their needs will always be dictated by different factors than those affecting the rest of the industry. Insofar as equipment is concerned their requirements will be atypical as long as they rely on owner-operator teams, driving tractors with top-of-the-line options and amenities. Even so, being constrained by the same size and weight limits as general freight carriers, their engine needs would not be all that different from those discussed in Task 2.

Fleets using owner-operators, exclusively, were not contacted because they do not usually purchase vehicles and so their influence on equipment design is minimal. Owner-operators were not approached because, being small purchasers, they do not have as much influence as volume buyers. Although there are probably over 100,000 of them, their influence on what equipment will be available 15 years hence is not in proportion to their numbers.



The truck operators interviewed own approximately 86,000 tractors. Accepting estimates of a heavy truck population of 1,500,000 in 1982<sup>3</sup>, the 40 fleets interviewed accounted for 5% of the total heavy vehicle population and 84% of the class I and II general freight carrier owned tractors. They accounted for approximately 64% of the highway miles driven by the class I and II general freight carriers and 50% of the total ton-miles generated by these fleets. The ton-miles they generated in 1983 were approximately 7% of the estimated total commercial vehicle ton-miles.

The fleets contacted are those that set the pace for the industry, and those with whom vehicle and equipment manufacturers consult regarding future vehicle developments. These fleets have an influence on future equipment far greater than their numbers would imply, extending well into the future, as well as across the industry in a given time frame. If it is assumed that the actual life of a heavy duty tractor is 10 years, with engine rebuilds, and that the large, influential fleets trade in equipment on a five or seven year cycle, then many thousands of the small fleets which have, and are coming into existence, will be purchasing these as used vehicles. It is obvious that the vehicle purchased in 1998, by a major fleet, (which influenced the vehicle's design somewhat over the preceeding years), will still be running for some small fleet

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<sup>3</sup> Estimates of heavy truck population and why we accept 1,500,000 as the number are explained in Appendix D.

into the year 2008 or later. Should the fleets contacted coordinate so that they all bought new tractors in the same year their purchases would amount to over 70% of the class 8 tractors sold in 1983.

The list of fleets with whom interviews were held is contained in Appendix A. Note that 42 fleets are listed in Appendix A, but only 39 were interviewed because one fleet, ANR Freight System, includes three additional fleets. In the 39 interviews, a total of 45 individuals participated. One of the ground rules for the interviews was that there would be no linking of comments to an individual or company.

The next step, after determining who to interview, was to design a questionnaire which would proceed logically from the question of total freight movement to details about engines, with a few questions along the way to cover additional areas of interest. It was decided to provide the individuals being interviewed with a point of departure or reference for the questions involving statistics. Hence, numbers were presented in the questions, not to validate those numbers, but to provide a reference to which the subject could relate the answer. The questions used, and how they were formulated are discussed in Appendix B. There were, as mentioned above, several questions which digressed from the engine area. They pertained to future legislation, highways, the kind of tractor anticipated to be available in the future, and current research and possible outcomes in engines.

The results of the interviews are given in Appendix C. Two general conclusions about the interviews must be noted: The first is that the fleets contacted are forward looking and innovative; and most make a practice of experimenting with new equipment as a matter of course.

The second is that there would be an almost unanimous embrace of new fuel saving equipment if the pay back was there. (18-24 months pay back period was the most often quoted).

### 2.3 Results

From these interviews the ATA Engineering Department drew the following conclusions:

2.3.1 The roles filled by heavy duty truck-tractors are likely to be the following:

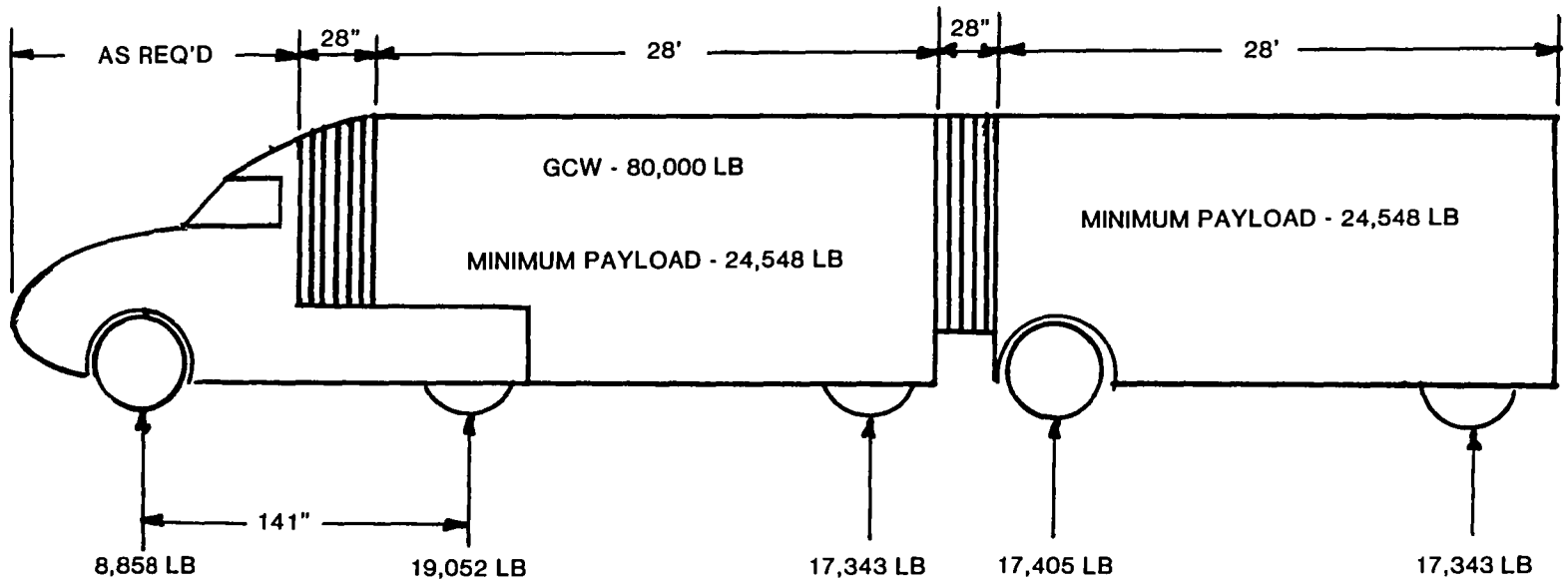
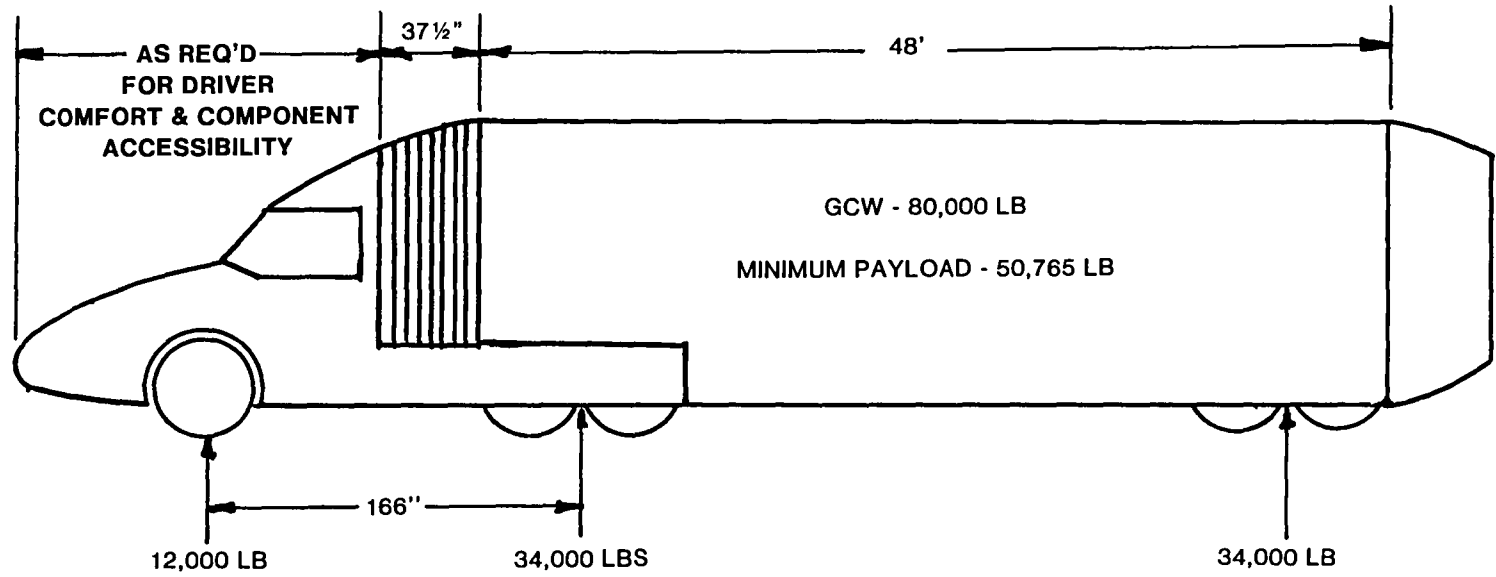
- a. Pulling doubles and longer combination vehicles in the western states. A longer combination vehicle is one comprised of a tractor and two 45 foot or 48 foot trailers, (Turnpike Doubles) or a tractor and one 45-48 foot trailer plus one 28 foot trailer (Rocky Mountain Double), or a tractor and three 28 foot trailers (Triples) (see glossary). These would be in addition to widespread use of the current

doubles combination comprised of a tractor and two 28 foot trailers. Distances would typically be 1,500 miles. The term "western" means western states including western portions of the plains states - that is a region marked by a low population density and a relatively undeveloped rail network.

- b. Pulling two 28 foot trailers or the longest allowable single trailer in the non-western states over distances that probably will not exceed 600 to 700 miles.
- c. Pulling single 28 foot trailers and the longest allowable semitrailers from trucking terminals and rail heads to destinations in the local area - implying distances of up to 100 miles. This would apply nationwide. It would be largely a new role for heavy duty tractors.

2.3.2 The kinds of tractors required to fill these roles were projected as follows:

- a. In the west the tractor would be a conventional cab type, either single or tandem drive axle (depending on the type of trailers being pulled), having an average horsepower of 350 with a few fleets asking for 400 (Figure 1).



b. In the rest of the country the single axle conventional tractor will predominate. Average HP will be less than 300. This tractor will pull the twin trailers from truck terminal to truck terminal during the night and then pull one of the twin trailers in the local delivery area during the daylight hours. This tractor will be what would be called by today's classification a heavy class 7 or a light class 8 (see Figure 1). There is no proper definition of this multi-role tractor, especially as it will be lighter, more comfortable, and much more efficient than its precursors, which are on the roads today (Figure 2). To complicate matters there are some who believe a much improved more productive class 6 type straight truck will supplant class 7 & 8 combinations on certain runs.

There will be then, essentially, two types of heavy duty tractors possibly doing what several kinds of tractors and straight trucks do today. A heavy duty tractor doing line haul duty, and a heavy duty tractor doing both line haul and local service duty. The question is, as the use of doubles increases, whether to down-rate a heavy duty class 8 tractor to economically perform the local service role, or to upgrade a class 7 tractor to handle the long haul role reliably. This report is essentially

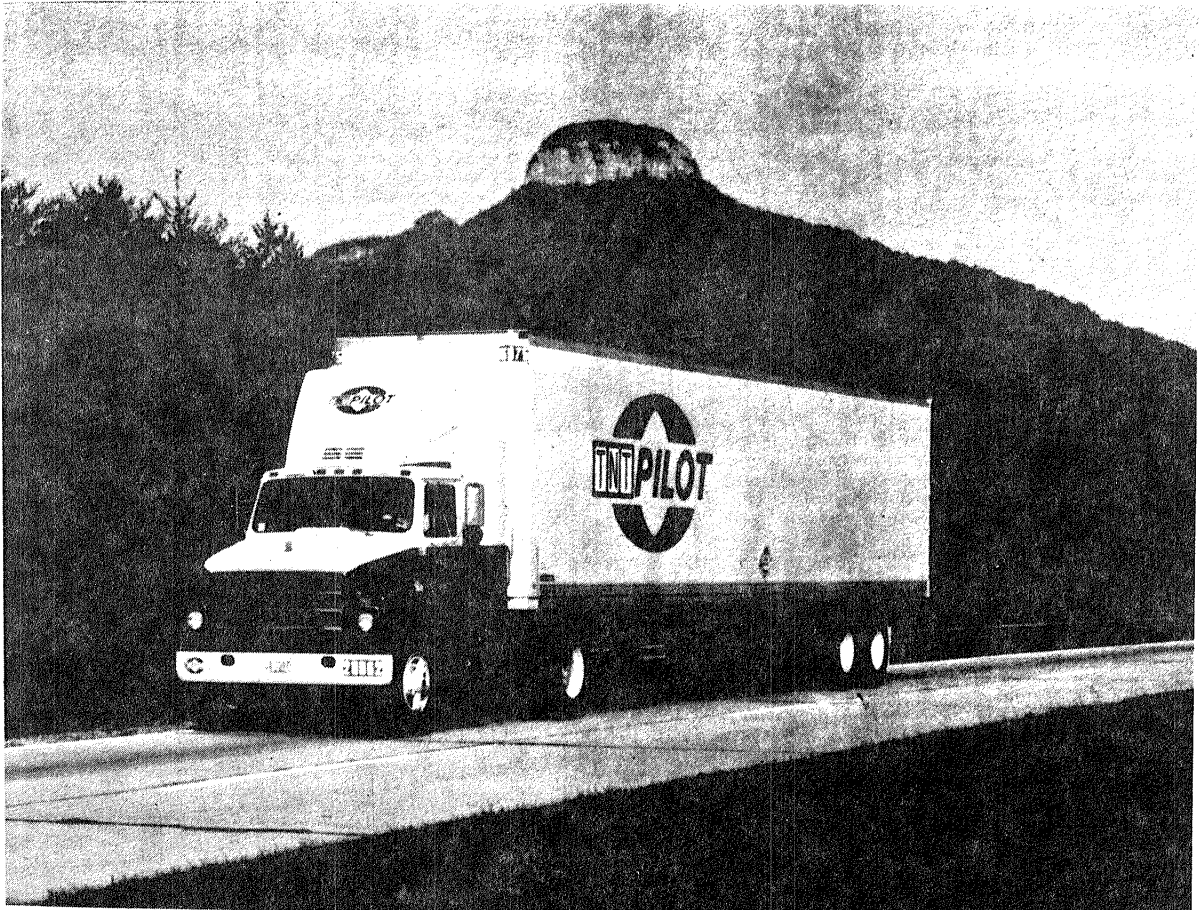


FIG. 2

introducing a question of "point design" versus a design range for future vehicles.

2.3.3. The numbers of such vehicles - total number in service in 1998 - will be less than some earlier estimates. It is estimated that about two million so called heavy duty trucks will be in service then. This compares to about 1,500,000 in 1982.<sup>4</sup> Only 20% of the fleets interviewed felt that the population would reach the 2,700,000 to 3,500,000 range projected by some<sup>5</sup> for the year 2000.

The majority felt that there would be no doubling of current numbers, and a few indicated they felt that the class eight market would be only a replacement market. One reason for this is that it will take fewer tractors to pull doubles and triples than the equivalent number of single trailers.

Another reason is that it appears that much of the freight going over 600 to 700 miles will be going by trailer-on-flatcar.<sup>6</sup> Truck fleets may substitute

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<sup>4</sup> See Appendix D for an explanation of how this conclusion was reached.

<sup>5</sup> See Figure D-2, Appendix D.

<sup>6</sup> See Appendix D for an explanation of how this conclusion was reached.



piggyback for the highway on the longer trip lengths. Fewer heavy duty tractors will be required to run trailers to railheads than would have been needed to truck them cross country.

2.3.4 There will be large growth in truck classes 4, 5, and 6 (14,001 - 26,000 lb). This is because it is anticipated that the larger manufacturers will adopt the just-in-time transportation and inventory concept, and motivate their suppliers to move closer to them. At the same time, retailers and other distributors are expected to increase the number of distribution centers. Thus, for any given region of the country, the number of short trips will increase dramatically, while the number of long trips will stay the same or decrease. This will result in a great demand for medium duty diesel engines. Currently class 6 sales are 24% diesel; class 5 sales are 3% diesel<sup>7</sup>(2).

This brings up two questions that merit consideration. Since these classes are converting to diesel, what will

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<sup>7</sup> Figure for class 6 is for 1983 sales, and for class 5 it is for 1982 sales. However, taking total sales for each class from 1972 through 1983, and dividing by total sales of diesel vehicles in those classes gives only 8% penetration for class 6 and nil for class 5. Data from pages 10 and 11 of reference 2.

be the impact of future Environmental Protection Agency (EPA) emissions rules, and ought alternatively fueled/multi-fueled engines be more intensively investigated?

There are many qualifications to the conclusions just given. Many respondents emphasized that their answers to the questions posed depended on the outcome of events over which they had little or no control. Obvious ones are the future cost of fuel, the competitive stance of the railroads, legislation pro and con, and effect of EPA emissions requirements. The competitive situation with the Railroads and EPA requirements are discussed in appendices D, and E.

### 3. TASK 2

#### Fleet Engine Requirements

##### 3.1 Engine Requirements

Through the interviews it was determined that the following factors are used by fleets to compare or evaluate engines:

##### Operational Factors

Miles between overhaul  
Miles per gallon  
Torque  
Training and tools required  
Horsepower  
Weight  
Reliability  
Ease of maintenance  
(Maintainability)  
Driver acceptance  
Oil consumption  
Downtime  
Life  
Availability of service and parts  
Relationship with supplier -  
product support  
Noise level  
Cold starting

##### Financial Factors

Engine maintenance cost per mile  
Cost of overhaul  
Resale value of vehicle  
Parts prices  
Cost of fuel per mile  
Initial cost  
Cost of fuel  
Total vehicle cost per mile  
Labor cost  
Labor and material as a % of  
revenue

All fleets do not use all these factors. Most fleets use only a few. Note that there are factors which are quantitative and several which are qualitative.

A logical approach to performing Task 2 appeared to be one of first determining values for these various parameters, based on current fleet experience, and then extending these values into the future. Unfortunately, fleets now guard their operational and maintenance data. (This is one of the less well known side effects of deregulation. By making trucking more price competitive, it has put a premium on maintenance and operational cost information.) Several recent surveys were drawn upon. However, what is presented represents only a small percentage of the fleets. The sample size of the various surveys is very small. Furthermore, there is no guarantee that those fleets which participated in the various surveys use a uniform accounting procedure on which to base various statistics. On the other hand, what follows, while by no means complete, is a start. It is, as far as is known, the first time motor carriers have given such a needs/desires statement to a major sponsor of research.

It is fairly difficult to define a motor carrier statement of future need because fleets believe the service to which vehicles are put has a tremendous influence on their needs. With some 2,227 Class I and II fleets there is bound to be a great variety in types

of service. This creates a situation wherein for any given parameter there will be a wide range of industry experience.<sup>8</sup> Hence, average values are used in many cases. However, of the 2,227 fleets 28% are general freight and 58% are specialized carriers. (Of the specialized carriers the largest subcategory is liquid petroleum carriers which account for 4% of the 2,227.) So the general freight carrier experience, on which this study draws, should be satisfactory for the purpose of Task 2. This is expected to become even more the case in the future as the need for a large variety of equipment is reduced by carriers seeking multi-role capability for their vehicles, seeking to reduce the volume of spare parts they carry, and manufacturers strive to develop "standard" vehicles.

Table 1 gives certain engine/vehicle factors for which current fleet experience is documented. As mentioned before, in some instances the engine cannot be separated from the vehicle. The miles per gallon is an average for all fleets. Fleets obtain from three to eight miles per gallon, but differ in what they count as fuel consumed.<sup>9</sup> Some maintenance related factors such as ease of maintenance, training and tools required, parts prices and labor costs are reflected in the cost per mile to maintain the vehicle.

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<sup>8</sup> This study is defining needs as opposed to experience. However, experience is taken as the first step in defining future needs. The assumption is that experience varies greatly, but needs, as time goes on, should become more common among the various fleets.

<sup>9</sup> Some count fuel purchased and stored in terminals as "consumed" while others count only fuel consumed by the vehicle.

TABLE 1

Engine/Vehicle Evaluation Factors Current Experience		
<u>Engine/Vehicle Evaluation Factor</u>	<u>Current Fleet Experience</u>	
Miles per gallon	5-6 mpg	(3)(4)
Maintenance:		
Cost per mile, tractor (Ease of maintenance reflected in costs)	0.112 \$/mi	(5)
Labor & materials as a % of revenue	3%	(6) <sup>1</sup>
Engine maintenance cost as a percentage of total vehicle maintenance cost	18% <sup>2</sup> (.02 \$/mi Avg 300,000 mi)	(7)
Reliability:		
Unanticipated repairs	7% of road calls due to engines	(8)
Frequency of repair	5.4% of repairs are engine repairs	(9)
Down Time	13.8 days/yr tractor is out-of-service	(8)
Durability:		
Miles between overhaul	300,000 <sup>3</sup>	(8)
Life	500,000 mi	(8)
Personnel:		
Miles run per hour of maintenance total tractor	8,695	(9)
Ratio of tractors per mechanic	3.5:1	(5)
Average years experience	10.6	(8)
Percent having factory or other technical training	55%	(8)

<sup>1</sup> Not directly reflected in reference 6. Obtained by adding entries 13 and 14 and dividing by freight revenue.

<sup>2</sup> This percentage is actually amount of service time spent on engines as a percent of total time spent on the power unit. But since labor is the largest portion of repair costs, time has been taken as equal to money, so that 18% of time spent on engines approximately equals 18% of the cost.

<sup>3</sup> Some fleets today routinely achieve 600,000 miles between overhaul.

But which fleets count what is difficult to tell. Engine maintenance cost is given in two forms. This cost varies with the life of the engine. The average, over a term of 300,000 miles, was taken. This is one of those factors which is also influenced by type of service the vehicle/engine encounters. The items falling under "personnel" are included because they shed light on the state of the work force which will have to cope with advanced equipment.

Other engine/vehicle factors are listed in Table 2. There is no adequate documentation of current experience for these factors but there are indications from the interviews as to desired or anticipated values. The footnotes to Table 2 serve to explain how several of them were treated.

### 3.2 Vehicle Requirements

Up to now engine characteristics have primarily been treated. Now vehicle requirements, implied by the roles for heavy trucks in the future, need to be explored. Payload, gradeability and cruising range will be investigated. In doing this the reason for interview questions 5 (Do you see significant changes from the Surface Transportation Assistance Act of 1982 over the next 15 years?); and 8 (Do you think a designated national highway system for longer double and triple combinations is possible?) will become apparent. Little more than half the fleets anticipate significant changes in the Surface Transportation Act. But 60% of the Eastern fleets, and 94% of the Western fleets feel a designated highway system is

TABLE 2

Other Engine/Vehicle Evaluation Factors

<u>Factor</u>	<u>Current Experience</u>	<u>Target for 1998</u>
Weight	See Task 3, Figure 6	See figure 6
Horsepower	280 Avg in East	300 East
Horsepower	309 Avg in West	325-350 West
Oil Consumption	No data <sup>1</sup>	-- <sup>3</sup>
Noise Level	Avg 83 db <sup>2</sup>	80db <sup>3</sup>
Cold Startability <sup>4</sup>		
Initial Cost	See Task 3	See task 3
Cost of Overhaul <sup>5</sup>	--	See task 3
Parts Prices <sup>6</sup>	--	--
Resale Value of Vehicle <sup>6</sup>	--	--

<sup>1</sup> This is too variable. New developments in synthetics will obsolete any targets assigned.

<sup>2</sup> Average for existing tractors 50 feet from cab.

<sup>3</sup> Based on EPA requirements of 80 db for model year 1986 possibly postponed to 1988.

<sup>4</sup> This is a factor for fleets using air starters. If the quality of diesel fuel continues to decline it will become more of a problem for all diesel engines.

<sup>5</sup> As with most costs this varies depending on type (in frame, out of frame) and who does it.

<sup>6</sup> Too variable to treat.



possible. However, the manner in which these questions were answered indicated that they were answered affirmatively, more out of a belief that the industry must get relief rather than out of a conviction that it in fact would. At any rate, this response implies the following:

- there is only a slim possibility for vehicle size and weight increases in the next 15 years by Federal legislation. However, various states or regions may permit the use of longer combinations, (e.g. in the West).
  
- productivity gains will have to come from more intensive utilization of current longer combinations, design of much more efficient vehicles, and more efficient operational practices.

This means that payload and gradeability requirements will remain the same as they are today.

### 3.3 Cost Factors

Cost factors pertaining to operation and maintenance have been addressed in Table 1. Initial cost, cost of overhaul, parts prices and resale value of the vehicle will be addressed in this section.

3.3.1 Initial Costs -- Fleets do not in the main, purchase new engines separate from the vehicle. The engine cost is submerged in the vehicle cost. Currently engines are 20% to 29% of the class 8 tractor price. In terms of specific costs, today's heavy duty engines run from \$45 to \$52 per hp. It would be beneficial if these values could be reduced to compensate for the cost of future government mandated devices, such as noise absorption panels and particulate traps that may be required because of EPA regulations. For instance, depending on the type of trap envisioned, additional costs could range from \$1,200 to \$2,140 per engine. A full discussion of costs is in Task 3.

3.3.2 Cost of Overhaul -- This varies depending on a number of factors. There is little data to go on in determining a target. This factor does not seem to be one for which a target can be provided because pricing decisions by parts suppliers can obsolete any preconceived target. Furthermore, when future engines begin to incorporate "exotic" parts, or even ceramic coated metals, overhaul may effectively be removed from the shops of the major fleets. If decisions to overhaul in-house have been previously based on an advantageous cost trade-off vis-a-vis other sources, fleets will find overhauls more costly. What, for instance, will a fleet face when it

comes to grinding valve seats or removing cylinder liners? Will the fleets' choice boil down to buying much more expensive tools, or farming the job out to someone else, who uses much more expensive tools. However, engines today can be overhauled for approximately 1/3 the cost of a new engine.

3.3.3 Parts Prices -- This is one criteria also used by fleets. The comments under "Cost of Overhaul" apply here also, with the added question of whether fleets will even be able to purchase these parts.

3.3.4 Resale value of the Vehicle -- This is a volatile factor and one for which a target cannot be offered. It is established that vehicles with certain makes and models of engines retain more value than other vehicles. Some fleets are going to have to be pioneers and see what the market decides.

#### 3.4 Other

There were several other needs or desires expressed in the interviews which can be included in any definition of requirements for future heavy duty diesel engines. These were not factors for which current experience is necessarily a consideration, and they are not factors which are used to compare or evaluate engines, but they are certainly pertinent, and have been included in Table 3.

TABLE 3

Requirements for 1998 Time Frame Vehicle/Engine

<u>Factor</u>	<u>Value/Remarks</u>
<b>Vehicle Performance:<sup>1</sup></b>	
Miles per gallon (Tractor-Trailer combination)	>15
Gradeability	As Today
Payload to Combination Vehicle Empty Weight Ratio	> Today <sup>2</sup>
Gross Combination Weight	As Today
Reliability	> Today
<b>Engine Performance:</b>	
Horsepower	300 East 325-350 West
Size	< Today
Weight	Minimum consistent with good durability. Not to exceed 7 lb/hp for 300 hp engines and 6 lb/hp for 350 hp engines
Durability	At least 650,000 miles to overhaul
Reliability	> Today Eliminate road calls by capability to predict parts failure and/or redundant systems.
<b>Costs:</b>	
Maintenance cost per mile - Total Vehicle	< 0.112 \$/mile
Maintenance cost per mile - Engine only	< .02 \$/mile
<b>Others:</b>	
Simple <sup>3</sup>	
Provisions to accept lower quality fuel <sup>4</sup>	
Engine rebuildable in Fleet Maintenance Facilities	
Down time halved by improved diagnostics, better lubricants	
Improvements pay back in 18-24 months	

<sup>1</sup> Combination vehicle - tractor plus semitrailer.

<sup>2</sup> This ratio varies from 1.9:1 to 2.4:1 today. It will have to get better.

<sup>3</sup> Some fleets feel that even turbocompounding is complicated.

<sup>4</sup> As fuel degrades fuel economy decreases and emissions increase.

The results of Task 2 can be summarized as defining a single or tandem axle conventional tractor, capable of pulling loads handled by current class 7 and 8 tractors, with the same speed and gradeability performance, and having the characteristics listed in Tables 2 and 3.

## 4. TASK 3

### Potential Future Engine Characteristics

#### 4.1 Background

In carrying out Task 3, the end result of two approaches to engine development was projected: the normal evolution of the basic diesel engine over time (product improvement) and the more "radical" approach represented by adiabatic engine development with various waste heat recovery systems. These two approaches were presented to the executives interviewed. Typical possible payoffs in increased horsepower and fuel economy, from proceedings of the Department of Energy Contractor Coordination Meetings, were provided the interviewees. (There is more detail on this in Appendix B.)

The work in this task involved defining the probable characteristics of engines 15 years hence based on improvements resulting from either normal product improvement efforts or from advanced research leading to adiabatic engines. The performance and cost characteristics of these future engines are then discussed in regard to fleet preferences, developed in Task 2.

Task 3 was accomplished in a manner similar to Task 1. A consensus on characteristics of future engines, following the product improvement approach, was obtained by interviewing several engine manufacturers. They were provided ATA's interpretation of

where engine performance would stand in 15 years, the fleets' maintenance and reliability experience, as developed in Task 2, and were asked, individually, to verify or correct the extrapolations and comment on the fleets' current experience. These visits were made two way communications by briefing the companies on what ATA had found in Task 1. As with the fleet interviews personnel contacted were promised that all the information obtained would be pooled and not be identified by company.

The companies visited were Adiabatics, Inc., Cummins Engine Company, and Detroit Diesel. Caterpillar and MACK Trucks were not visited, but most of the desired information was obtained through the good offices of The Maintenance Council. Argonne National Laboratory was also visited.

## 4.2 Results

The information obtained is summarized in the following paragraphs.

4.2.1 Fuel Consumption -- Figures 3, 4 and 5 give the decrease in brake specific fuel consumption over time, given existing trends and EPA proposed emission standards.

Figure 3 shows the various estimates in existence when the interviews were conducted with the engine manufacturers. Of particular interest are the curves from

FUEL CONSUMPTION TRENDS AS PREDICTED BY VARIOUS SOURCES

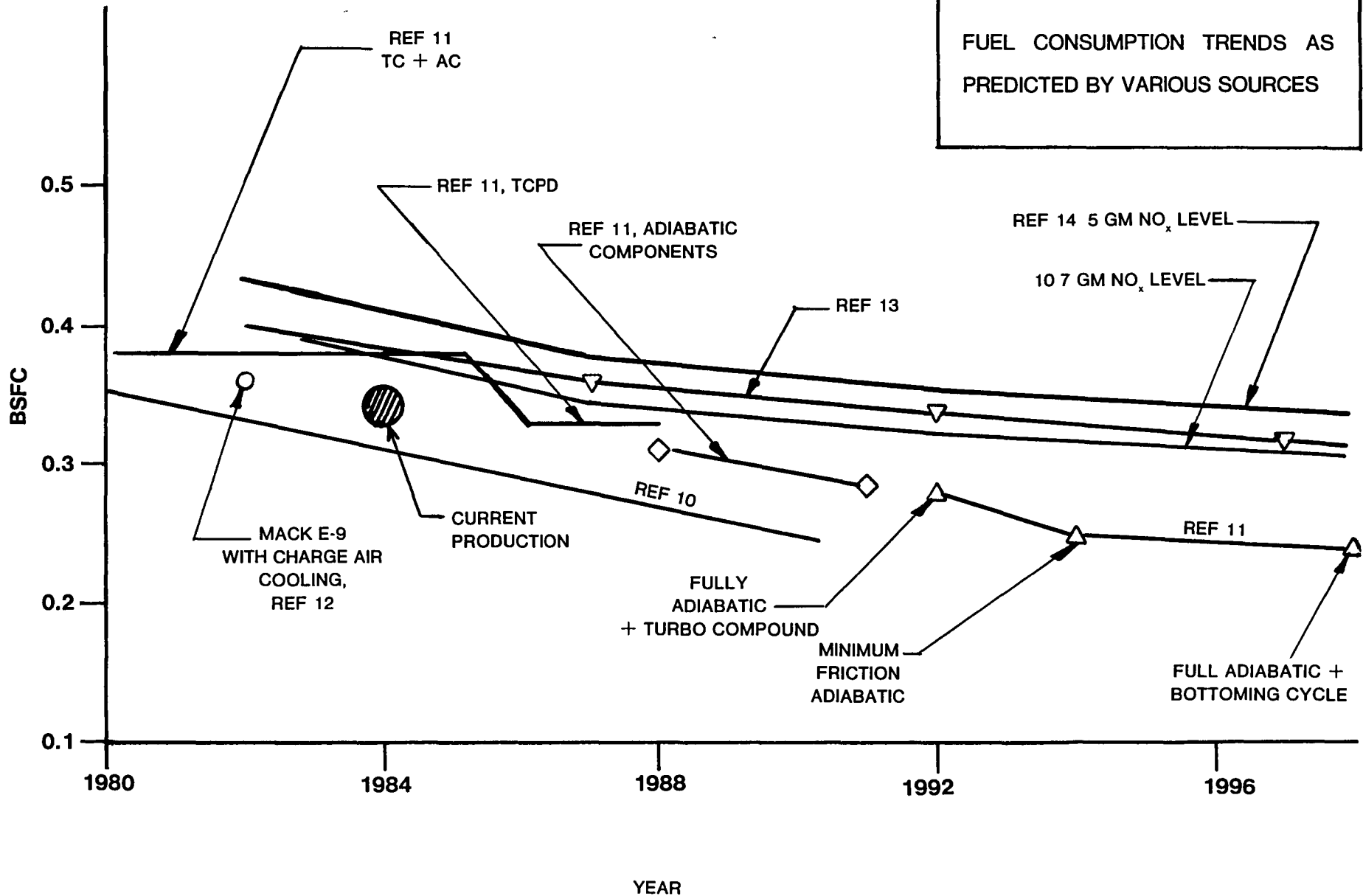


FIG. 3  
-36-



**BSFC, 2000**

TC + AC = TURBOCHARGED + AFTER COOLED	0 32
TCPD = TURBO COMPOUND + TC + AC	0 305
AD + TCPD = ADIABATIC + TCPD + AC + TC	0 285
AD + TCPD + RANKINE BOTTOMING	0 26

FUEL CONSUMPTION FROM INTERVIEWS COMPARED TO SELECTED REFERENCES

**BSFC @ RATED POWER LBS/HP-HR**

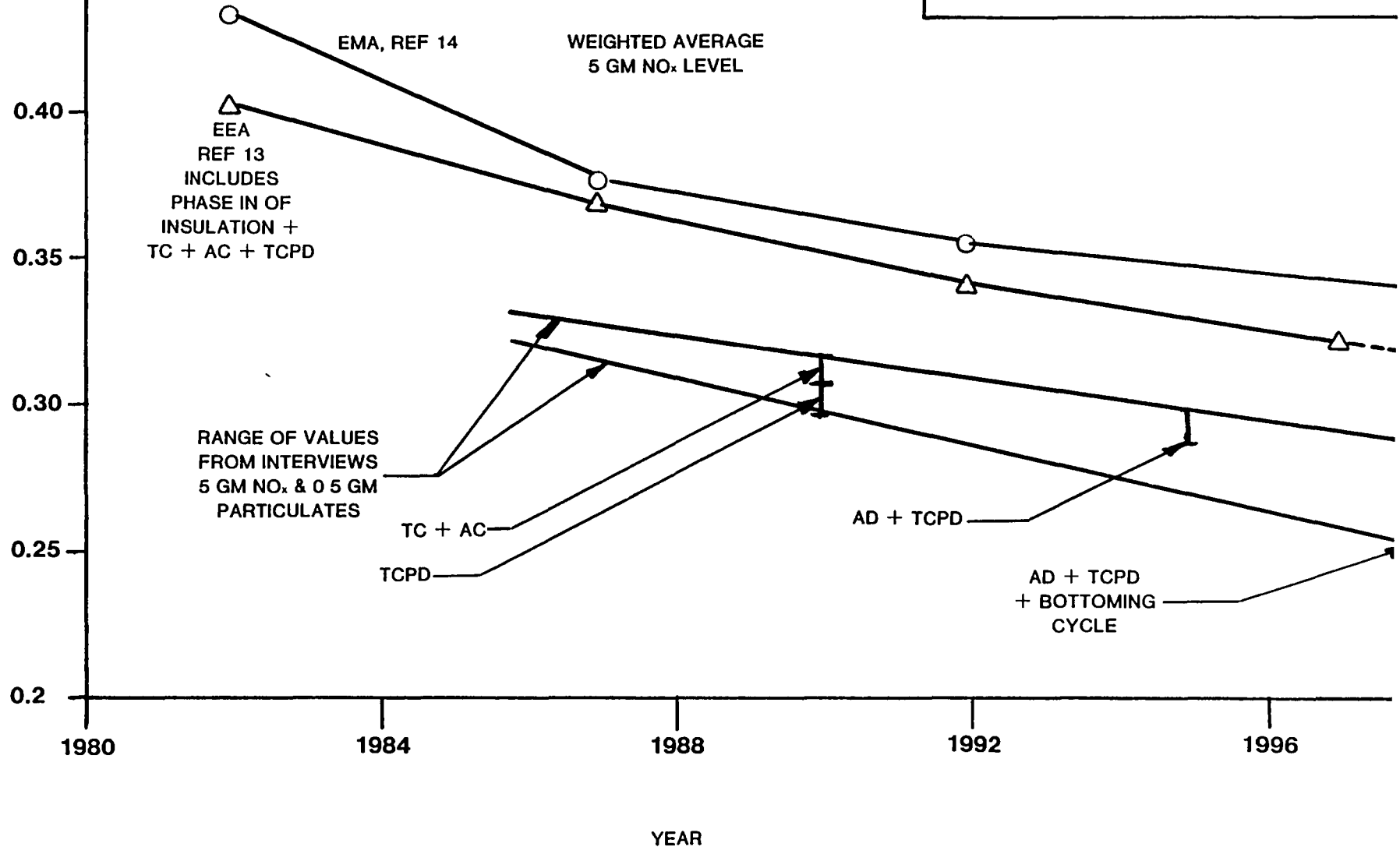


FIG. 4

BSFC  
@ RATED  
POWER  
LB/HP-HR

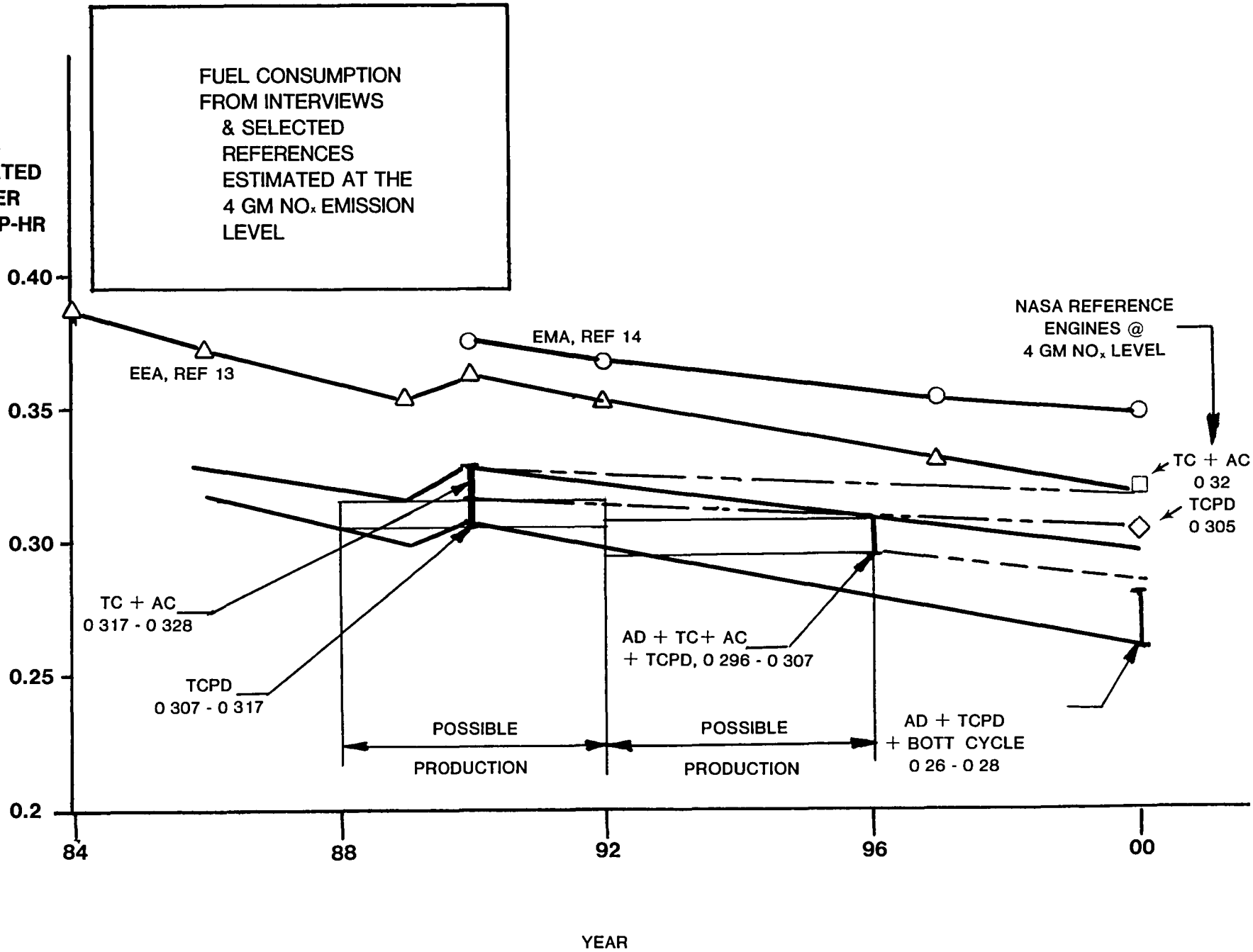


FIG. 5  
-38-

reference 10 and reference 14. The curve from reference 10 was published in 1979. Those from reference 14 were compiled in 1983. The relative position of these curves indicates the upward creep of the projections as a function of when they were made. The band from reference 14 is also of interest because it was made as part of a study of the effect of proposed EPA emission requirements on diesel engines, and indicates the difference the various levels of nitrogen oxide emission control makes. An island of BSFC levels from current production engines is also included.

Figure 4 was prepared to portray the consensus obtained from the interviews with the engine manufacturers. Note the short hand definitions on Figure 4 which will be used in the rest of the report:

TC+AC = turbocharged and aftercooled. The engine in common use today.

TCPD = turbocompound engine. It is turbocharged, after cooled, and water cooled as current engines.

AD+TCPD = adiabatic turbocompound engine, with turbocharging and aftercooling, but no water cooling.

AD + TCPD + Bottoming Cycle = the AD + TCPD engine with a heat exchanger system to obtain additional energy from the high exhaust gas temperatures of the adiabatic engine.

The curves from references 13 and 14 are also on the Figure for comparison. The Engine Manufacturers Association (EMA) estimate is given for the 5 grams NOx level. However, future EPA emission standards, if enacted, could further reduce these projections. A full discussion of the impact on heavy duty vehicle fuel consumption is in Appendix E. From Appendix E a proposed reduction of NOx emissions to the 4 gram level will increase BSFC by 15.5% from the BSFC obtained at the 10.7 gram level and approximately 8.2% from the BSFC obtained at the 6 gram level, and possibly 4% from the 5 gram to the 4 gram level. Hence, we increased the values of the 5 gm NOx curves in Figure 4 by 4% and plotted the results in Figure 5. Also shown on Figure 5 are the fuel consumption rates for the NASA reference engines used by various NASA contractors, of which more will be explained in the next section. These were increased by 4% to bring them to the 4gm NOx level. Possible time frames for production of the turbo-compound and adiabatic turbocompound engines are indicated. Extrapolations are made to the year 2000, and estimated fuel consumption rates for these various engines noted in the table on Figure 5.

- 4.2.2 Specific Weight -- Figure 6 presents specific weight (lbs/HP) as a function of rated horsepower. Estimates for 2,000 are from engine manufacturers. It appears that specific weight cannot be reduced very much because of its effect on durability.
- 4.2.3 Initial Cost -- Figure 7 provides the variation of cost per hp of current engines with engine power. Figure 8 indicates the variation of specific cost in the year 2000. Figures 7 and 8 were developed using information received from the interviews with engine manufacturers, and incremental costs due to addition of particulate traps to these engines. (See Appendix E for these costs). Manufacturers expect to reduce engine costs over time, and this is reflected in Figure 8.
- 4.2.4 Maintenance Cost per Mile -- Generally, reductions of 30% to 50% are projected. The trend is to develop more reliable and durable engines requiring less maintenance and operating longer before first overhaul. However, addition of emission control devices will add some cost. If bottoming cycle systems are adopted they will also add cost. These are treated in the tables that follow.

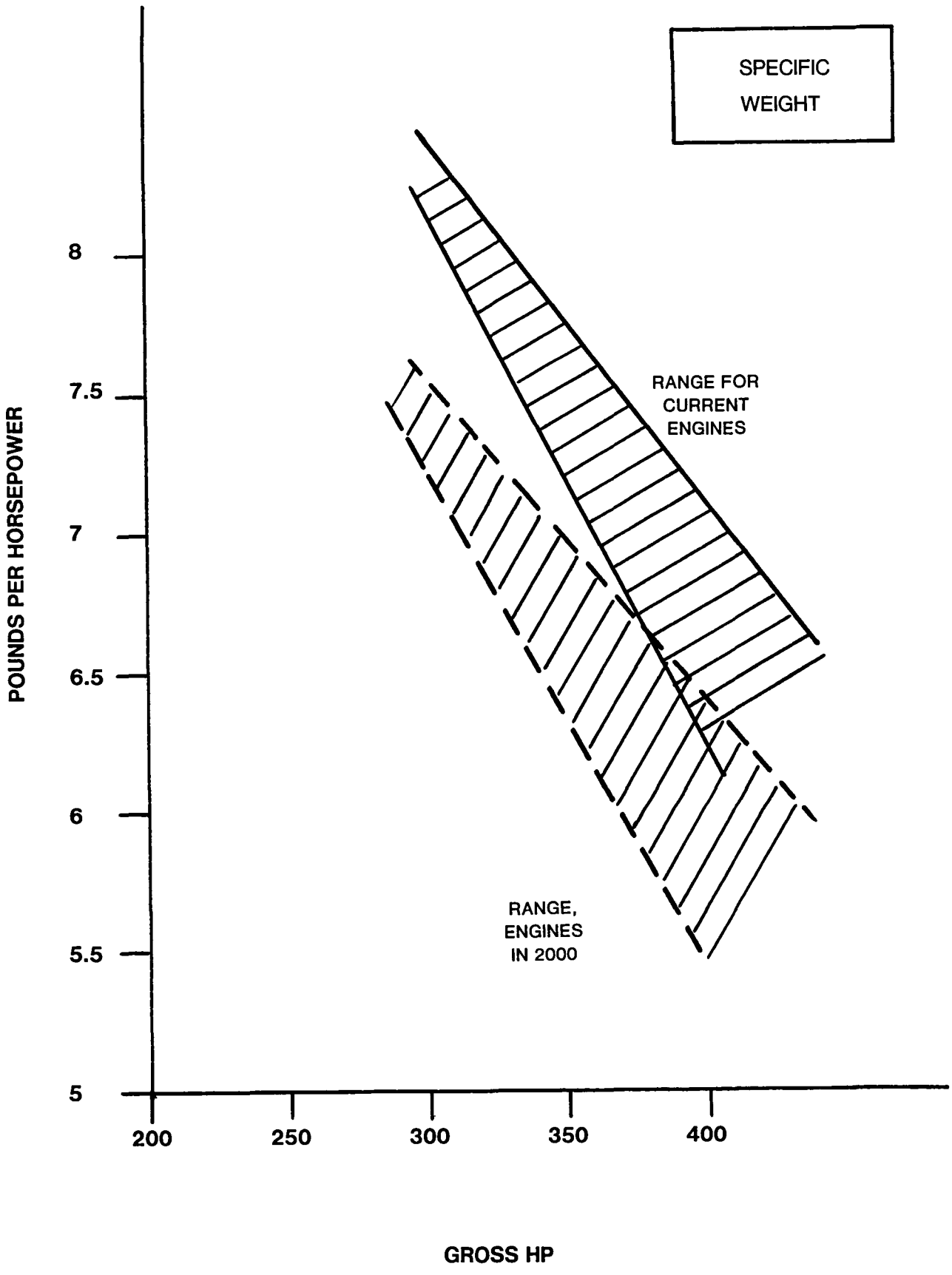


FIG. 6

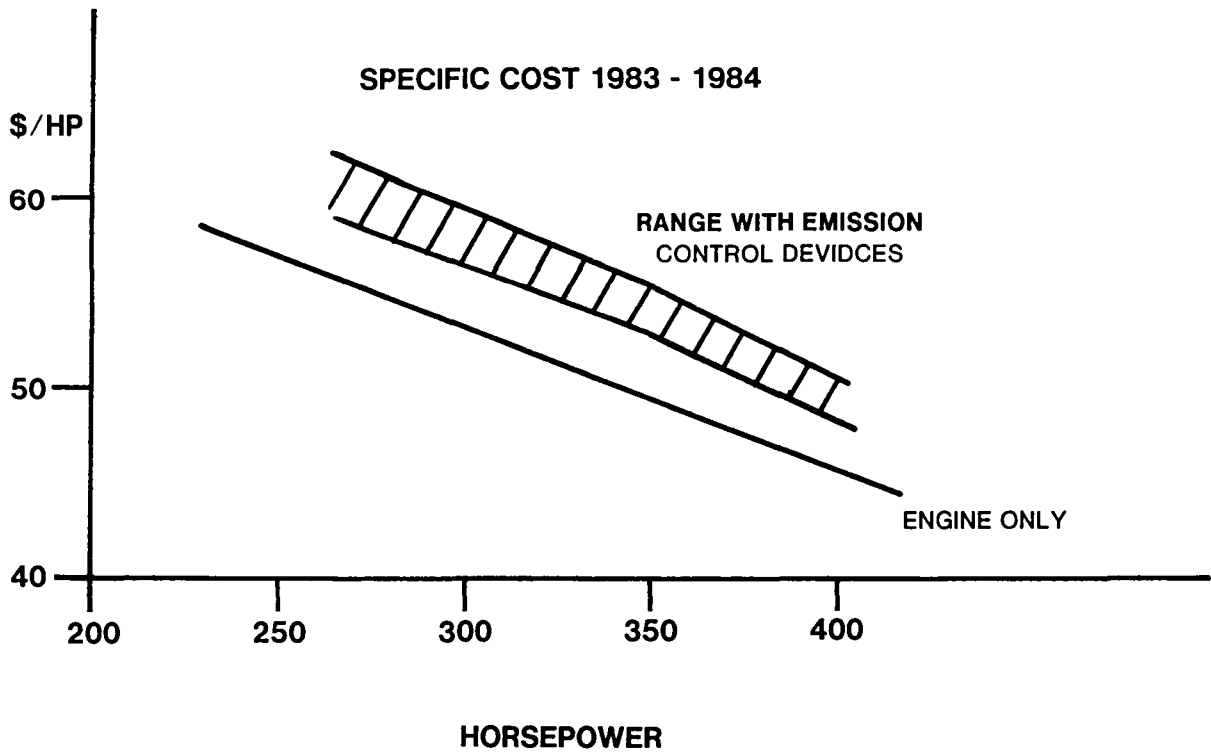


FIG. 7

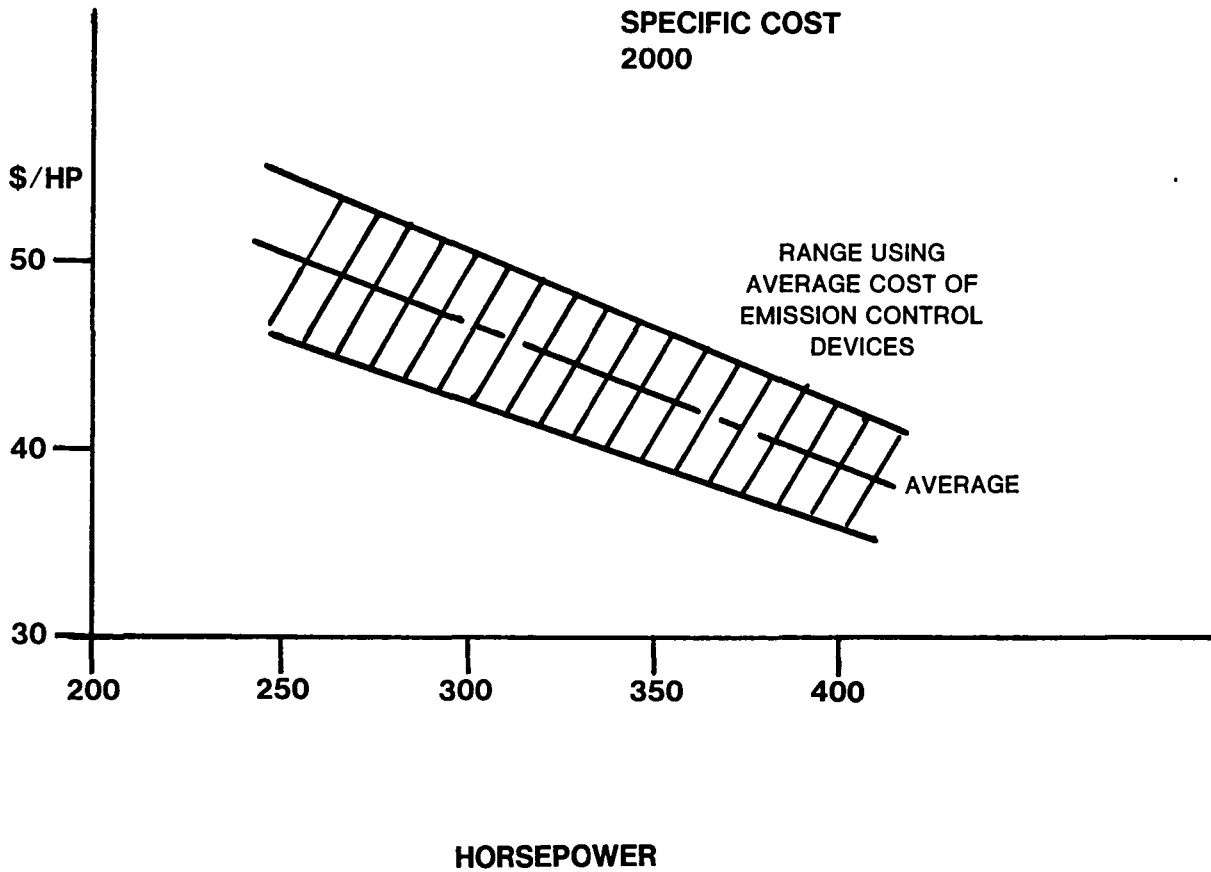


FIG. 8

4.2.5 Reliability -- The trend is to develop more reliable engines. Some foresee a 30% improvement in the repair frequency of an engine (reducing the number of repairs now required, over a specified time period by a third.

4.2.6 Durability -- In terms of engine life and miles between overhaul, the consensus appears to be that by the year 2000 the engine will have a life of 500,000 to 650,000 miles. None of the companies volunteered an interval for life to scrappage. However, indications, from more than one source, are that certain engines today, by dint of conscientious care, last a million miles. This is noted to put into perspective a projected miles to overhaul of 500,000 miles. If certain of today's engines, considered on the average to be good for 300,000 miles between overhaul, can last a million miles, how long would one last that has a time to overhaul of 650,000 miles?

#### 4.3 Probable Future Engine Characteristics

4.3.1 Product Improved Engine -- Using the information outlined above a projected engine, product improved over time, would be turbocharged, aftercooled, and of 300 hp in Eastern fleets and 350 hp in Western fleets.



These engines would have the following characteristics:

BSFC = .32 lb/HP-Hr (EEA curve, Figure 5)

Specific Wt. = 7.2 lb/hp from Figure 6. This indicates a 300 hp engine weighing 2,160 lbs compared to approximately 2,500 lbs today.

Cost per hp = 46.37 \$/hp for 300 hp and 43.16 \$/hp for 350 hp engines (Figure 8).

Maintenance Cost per mile = 0.0102 - 0.015 \$/mile including (indexed to 1983) estimated maintenance of emission control devices at .0015 \$/mile

Life 500,000 - 650,000 miles

A more refined development would be the adding of turbo-compounding to the product improved engine. An engine was developed by Cummins based on their NH engine. The engine was turbocharged, aftercooled, and conventionally cooled. The turbocompound system consists of a low pressure power turbine to recover exhaust gas energy, a high speed gear box; and a low speed gearbox. This

engine, as it exists today, has the characteristics given in Table 4. Characteristics of an advanced turbocompound water cooled are also in the table. These characteristics are from reference 15 with weight and cost factors from Figures 6, 7 and 8 to project the engine into the 2000 time period.

For the purposes of comparison the advanced engine characteristics in Table 4 will be used to represent the ultimate performance achievable from normal product evolution. The values indicated in footnote 1 to Table 4 will also be used to obtain calculated mpg in the comparisons which follow. While it is understood that these mileage figures are not accurate, because it is not known what the BSFC is at other than full power, they will be used for comparison among the various alternatives.

- 4.3.2 Advanced Engines with Bottoming Cycles -- Turning to the second engine improvement approach, the adiabatic engine plus various enhancements plus bottoming cycle, results of various investigations, reported in the literature were used. (It is assumed that there will be a gradual adoption of ceramic components in the product improvement approach, but not to the point where the cooling system would be totally eliminated and where bottoming systems would be worth considering.) NASA has defined a set of

TABLE 4

Characteristics of Turbocharged, Aftercooled Turbocompound Engines			
Characteristic	Existing Engine	Advanced Engine	
		Today	Projected to 2000
		5 NOx	4 NOx
BSFC @ rated power	.318	.310	0.305 <sup>4</sup>
Calculated mpg <sup>1</sup>	5.38	5.52	5.61
VMS program mpg <sup>2</sup>	5.40	5.75	--
Weight, lb	--	2,160	2,160
Estimated Cost <sub>3</sub> 300 hp version	17,900	17,900	15,911

<sup>1</sup> Calculated from  $\text{mpg} = \frac{\text{Fuel density} \times \text{Speed, mph}}{\text{HP} \times \text{BSFC}} = \frac{7 \times 55}{\text{HP} \times \text{BSFC}}$

For our calculations we obtained required power from reference 16 of 225 hp, for a 6x4 tractor/van semitrailer with 102 sq ft. frontal area, and loaded to 80,000 lb.

<sup>2</sup> Reference 15 test parameters were 73,000 lb GCW, and 55 mph.

<sup>3</sup> Existing engine cost from Figure 7 + \$2,000 extra for turbo-compounding (17); advanced engine cost using Figure 8 + \$2,000 extra.

<sup>4</sup> From Figure 5.

baseline reference adiabatic diesel engines having characteristics given in Table 5.

The engines were used as the source of exhaust gas heat for recovery and utilization by alternative bottoming cycle systems. The power cycles were the Rankine and Brayton. Under the Rankine cycle steam and organic bottoming systems were investigated. These combinations of the reference engines coupled with the various bottoming cycle systems, and the results of normal product improvements represent the range of engines which may confront the user in the future. Tables 6 & 7 provide summaries of the projected characteristics of these future engines.

The steam bottoming system adds a small steam powerplant to the engine. Components include a boiler; an oil lubricated V-twin expander; a radiator core condenser with shutters, fan subcooler and oil cooler; a two cylinder piston type boiler, feedwater pump with solenoids; microprocessor based control system; and sensor and plumbing. Power transfer is through a clutch and then high velocity chain to the diesel output shaft. It is possible that the boiler feed pump will have to be replaced once a year. It was estimated that the water side of the boiler tubes would require an annual acid wash. Freeze protection will be required. It is a 1000<sup>o</sup>F, 1000 psia system. (18)

TABLE 5

<u>NASA Reference Engines (17)</u> <u>(All Engines are Adiabatic)</u>				
Type	Degree of Insulation	Horsepower	BSFC lb/hp-hr	Selling Price (19)
Turbocharged (TC)	0.88	317	0.315	\$14,000
Turbocharged & Aftercooled (TC/A)	0.83	320	0.310	\$14,500
Turbocharged & Turbo-compounded (TCPD)	0.86	335	0.297	\$16,000
Turbocharged, Turbo-compounded and Aftercooled (TCPD/A)	0.84	340	0.293	\$16,500

TABLE 6

PERFORMANCE CHARACTERISTICS OF VARIOUS BOTTOMING CYCLE SYSTEMS (17, 18, 19)

SYSTEM	BASE ENGINE BSFC, lb/hp-hr	SYSTEM BSFC lb/hp-hr	% BSFC IMPROVEMENT OVER BASE ENGINES	ADDED HP	% BSFC IMPROVEMENT OVER TCPD/A ENGINE	TOTAL HP
Brayton Bottoming System + TC Engine	0.315	0.280	11.1	38	4.4	355
TC/A	0.310	0.284	8.3	29	3.1	349
TCPD	0.297	0.273	8.1	30	6.8	365
TCPD/A	0.293	0.272	7.2	26	7.2	366
Organic Rankine Bottoming System + TC Engine	0.315	0.268	14.9	56	8.5	373
TC/A	0.310	0.267	13.9	52	8.9	372
TCPD	0.297	0.258	13.1	50	11.9	385
TCPD/A	0.293	0.250	14.7	46	14.7	386
Steam Bottoming Cycle + TC Engine	0.315	0.264	16	61.2	9.9	378.2
TC/A	0.310	0.266	14.2	52.8	9.2	372.8
TCPD	0.297	0.255	14.1	53.5	13	388.5
TCPD/A	0.293	0.262	10.6	40.6	10.6	380.6

TABLE 7

MAINTENANCE & COST CHARACTERISTICS OF VARIOUS BOTTOMING CYCLE SYSTEMS						
SYSTEM	SYSTEM WEIGHT, LBS	SELLING <sup>1</sup> PRICE BOTT. SYSTEM	TOTAL PRICE ENGINE + BOTT. SYSTEM	PRICE \$/HP	MAINTENANCE COST PER MILE \$/MI	SIMPLE <sup>2</sup> PAYBACK PERIOD, YRS.
Brayton Bottoming System + TC	330 <sup>3</sup>	6,460	20,460	57.63	.003 <sup>4</sup>	
TC/A	330	4,930	19,430	55.67	.003	
TCPD	330	5,100	21,100	57.81	.003	
TCPD/A	330	4,420	20,920	57.16	.003	3.13
Organic Rankine System + TC	740	8,378	22,378	59.99	.011 <sup>4</sup>	2.12
TC/A	740	8,378	22,878	61.50	.011	2.35
TCPD	740	8,378	24,378	63.32	.011	2.61
TCPD/A	740	8,378	24,878	64.45	.011	2.95
Steam Bottoming System + TC	560	6,070	20,070	53.07	.0058 <sup>4</sup>	2.3
TC/A	560	6,070	20,570	55.18	.0058	
TCPD	560	6,070	22,070	56.81	.0058	
TCPD/A	560	6,070	22,570	59.3	.0058	

<sup>1</sup> Selling price to manufacturing cost ratio was taken as 2:1.

<sup>2</sup> Based on fuel @ \$1.20/gal, & 100,000 annual miles for tractor.

<sup>3</sup> Does not include gear box.

<sup>4</sup> This is an addition to the estimated maintenance cost of the TCPD/A engine.

The Brayton system uses air or combustion products as the working medium (as opposed to steam or organic fluids). Brayton systems are comprised of small high speed turbomachines like those used for turbocharging or turbocompounding, and gas to gas heat exchangers like those used as supercharger aftercoolers. Components are turbines, compressors, a heat exchanger, intercooler and gearbox and coupling. It is reported that the only maintenance required would be filter replacement and cleaning of the heat exchanger.(17)

The organic Rankine cycle uses an organic working fluid (as opposed to steam in the steam bottoming system). Apparently, no satisfactory organic fluid yet exists that will provide high performance with a minimum of fire and health hazard while remaining chemically stable at temperatures in excess of about 700<sup>o</sup>F. With such fluids, elaborate seals must be used to minimize leakage.(17) The system includes a turbine, gearbox, fuel pump, vapor-generator, oil cooler, regenerator, condenser, electric motor, boost pump, lubrication pump and clutch fan. The maintenance expense estimate in Table 7 is based on experience with the operation of similar componentry in other applications and an actual maintenance service contract. Also, from this experience the probable maintenance requirements are suggested as vapor-generator cleaning at the same interval as oil



changes, lube, organic filter cartridge changes and replacement of half of the quantity of the organic fluid annually. This is a 750°F, 1000 psia system.(19)

#### 4.4 Summary

The preceding material is summarized to project the possible engine choices facing users in 2000. These alternatives will be compared to a current turbocharged and aftercooled engine whose characteristics have been projected to the year 2000 using Figures 5, 6 and 8. These possible future engines are described in Table 8.

The values reflected in the comparison reflect future proposed EPA standards. The power required by the vehicle is assumed to be the same as today, i.e. no significant aerodynamic improvement is assumed. The power required for a tandem axle tractor, hauling a 13.5 foot high semitrailer at 55 mph, and loaded to 80,000 lb gross weight is 225 HP (16). This power requirement is used to calculate the theoretical miles per gallon these engines will attain.

#### 4.5 Discussion of Probable Future Engine Characteristics

First, with few exceptions, fleets respect the achievements of engine builders. Reliability and durability, while never good enough, are still praised by fleets. The potential reliability improvements that are mentioned are welcome, and it is assumed that the engines represented in Table 8 will indeed have this improved

TABLE 8

Characteristic	Possible Future Engine Characteristics				
	NORMAL EVOLUTION		ADVANCED		
	TC + AC	Turbocompound TCPD	Adiabatic + Turbocompound (AD+TCPD)	"Best" Bottoming Cycle-Organic Rankine + AD + TCPD	"Worst" Bottoming Cycle + AD+TCPD
BSFC @ Rated Power	0.32	0.305	.285	.26 <sup>5</sup>	0.28 <sup>5</sup>
Calculated mpg	5.34	5.61	6.00	6.58	6.11
% improvement in mpg	--	5	12.4	23.2	14.4
Cost, 1983 \$:					
Basic engine + particulate trap	13,911 <sup>1</sup>	13,911 <sup>1</sup>	16,500 <sup>3</sup>	16,500 <sup>3</sup>	16,500 <sup>3</sup>
+ turbocompounding	--	2,000	included in above	included in above	included in above
+ bottoming cycle	--	--	--	8,378	4,420
Total Cost, \$	13,911	15,911	18,170 <sup>4</sup>	26,548 <sup>4</sup>	22,590 <sup>4</sup>
Cost Increase, % over TC+AC	--	14.4	30.6	90.8	61.7
Weight, lbs	2,160	2,160	2,160	2,900	2,490
No. of major components added to basic engine	0	3	3	11	6
Maintenance Cost, \$/mi					
o basic engine	.01 - .014	.01 - .014	.01 - .014	.01 - .014	.01 - .014
o emissions devices <sup>2</sup>	.0002 - .001	.0002 - .001	.0002 - .001	.0002 - .001	.0002 - .001
o bottoming cycle	--	--	--	.0058	.003
Total Maintenance Cost, \$/mi	.0102 - .015	.0102 - .015	.0102 - .015	.0160 - .0208	.0105 - .018

<sup>1</sup> From figure 8, which uses average of high and low costs for particulate traps.

<sup>2</sup> From Appendix E.

<sup>3</sup> From Table 5.

<sup>4</sup> Includes \$1,670 average cost of particulate trap.

<sup>5</sup> Increased per Figure 5 to account for proposed emission requirements.

reliability. The same is true of durability. It is assumed that these future engines will go 650,000 miles or better before overhaul.

Maintenance costs for the engine itself are projected to be substantially reduced, but it is also projected that add-ons such as emission control devices will add cost. Hence, hope for gains may not be fully realized here. Except for the organic Rankine Bottoming Cycle system, estimates of maintenance costs for the other bottoming cycle systems (as well as the emission control devices) seem unrealistically low. Air conditioning systems maintenance, in well managed fleets, runs 0.0026 \$/mi, and cooling systems 0.0018 \$/mi.<sup>1</sup> Given the increased level of complexity of bottoming cycle systems over relatively simple air conditioning systems perhaps these estimates should be rethought.

A real disappointment is that BSFC can not be lowered, without having to go to the complex bottoming cycle systems. The complexity of these systems gives pause for thought. The reason for including the "number of major components added to basic engine" characteristic is that the number of parts directly influences reliability.

Another way to put this in perspective is to repeat that fleets today have a difficult time keeping air conditioning systems

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<sup>1</sup> Private Communication from a Southeastern U.S. fleet, 1983.

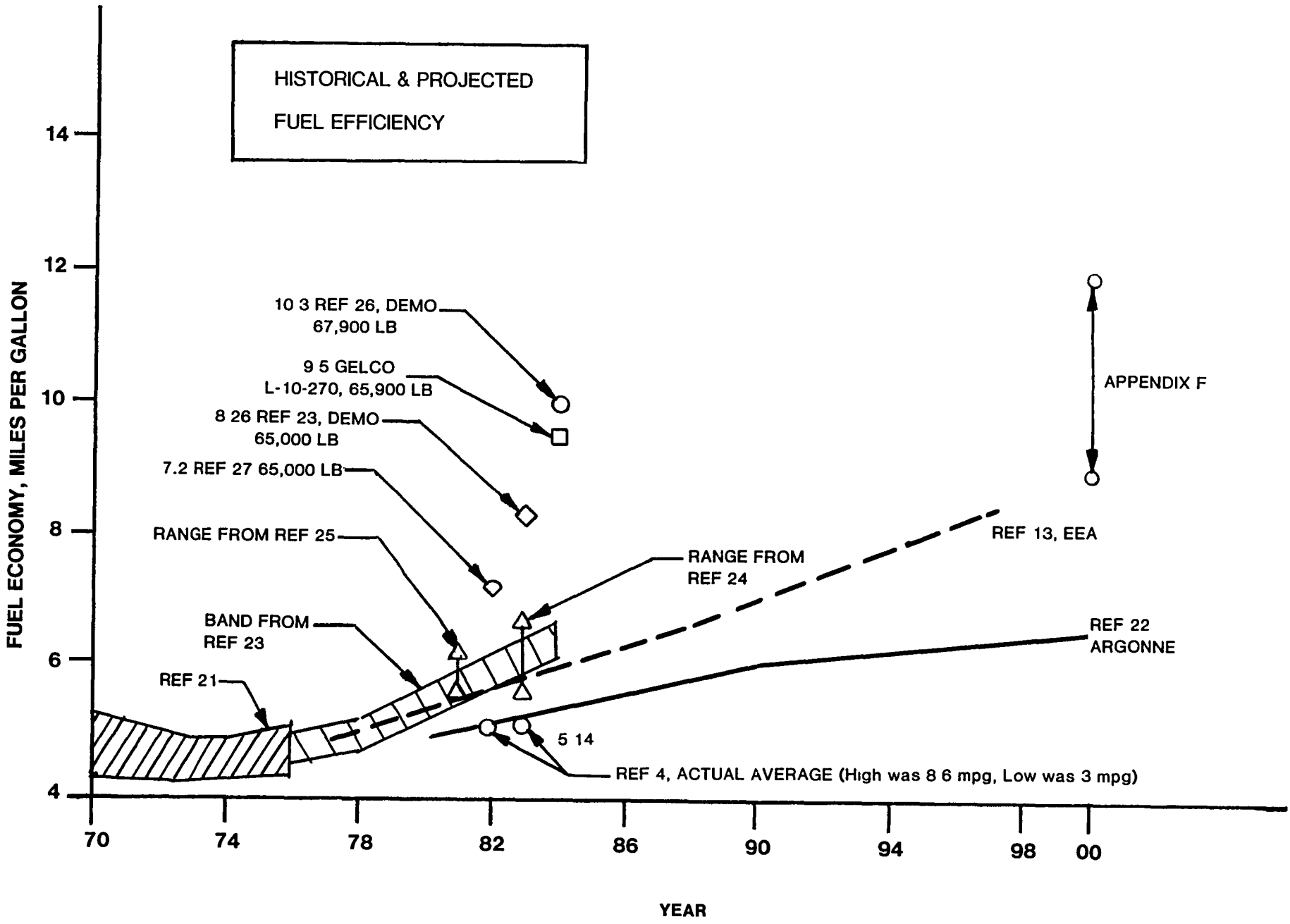
working. This degree of complexity is reflected in the estimated maintenance cost of a powerplant with the Organic Rankine Bottoming system. Its cost per mile (0.0208) could well exceed today's cost per mile (0.02) in spite of a projected substantial decrease in maintenance cost for the basic engine.

If it is asserted that bottoming cycle systems are too complex and costly for heavy duty trucks, reliance has to be placed on the adiabatic turbocompounded engine, and the balance of the fuel efficiency lost to more stringent emissions requirements has to be obtained from aerodynamic improvements. Appendix F indicates that this can be done, and that fuel economy targets can be reached, without bottoming cycles, by simpler methods. Figure 9 was developed to put the possibilities in terms of miles per gallon. It presents historical and projected fuel efficiency.

Figure 9 cannot be taken literally since vehicle factors play a role. Its purpose is to indicate the wide range among projections and the fact that current vehicles are achieving fuel economies well above those forecast for the 1998 to 2000 time frame. The points from references 23, 26 and GELCO, labeled "demo", are for one of a kind vehicles which were carefully driven. However, there are no hardware obstacles preventing these vehicles from being duplicated and put into service immediately. All the components are on the shelf or can be fabricated in maintenance shops.

HISTORICAL & PROJECTED  
FUEL EFFICIENCY

FIG. 9  
-57-



These vehicles are not aerodynamically optimum either. This leads to the question of theoretically just how high can mpg go, and what portion of this theoretical ultimate fuel efficiency will be achieved aerodynamically. This question is addressed in Appendix F, and indications are that fuel efficiency can approach 15 mpg with an engine BSFC of 0.30 and modest refinements to a technology demonstrator vehicle which is already on the roads.

In essence, fleets find no great divergence between what will evolve in time with engines, and what they can live with. There are reservations concerning the cost and complexity of bottoming cycle systems. Even if objections to initial cost could be overcome, and payback time reduced to 18-24 months there would still remain the matter of system weight and complexity. In this regard, it should be noted that an addition of 1000 lbs to a vehicle will reduce its fuel economy by approximately 1%.<sup>(13)</sup> Fleets desire increased payload to weight ratios - i.e., lower tare weight, and manufacturers are trying to comply. Fleets need this reduced tare weight to make up for the likelihood of not getting an increase in gross weight from Congress. The strong desire for more reliability (which was second to fuel economy as a fleet concern) runs counter to the researchers' pursuit of complex systems.

The results of the interviews on the question of satisfaction with the engine development approaches are given in Appendix C, question 16. To summarize, forty-eight percent of those interviewed were satisfied with the present research, typified by

the development of the adiabatic engine. Twenty-nine percent wanted even more improvement in fuel efficiency than the research trends indicate. Generally, the responses could be divided among six themes:

1. Stick to improving existing engines (product improvement approach).
2. Advanced developments do not provide enough payoff.
3. Must consider other influences on fuel efficiency besides engines (e.g. transmissions).
4. Should consider alternative fuels,
5. DOE should consider operational factors, e.g. Surface Transportation Assistance Act provisions.
6. Satisfied with the direction of research of advanced engines.

## 5. CONCLUSIONS

This is an interesting time in which to do a study of this kind. Because of recently enacted legislation, the motor carrier industry, and indeed, the entire transportation sector is in a state of flux. Conclusions drawn from this kind of investigation could be made irrelevant by a yet undetected new development. The transportation business could be ripe for a conquering force from outside the transportation industry to come in and shake it up thoroughly and put it into the 21st century. But at the same time nothing is on the horizon which will change the basics of motor carriage - vehicles, engines, fuels and laws which dictate how fleets run and the kind of vehicles which can be built. However, it is believed that several trends have been detected in this study:

1. A leveling off in the numbers of heavy duty tractors - low growth with total population of class 7 and 8 vehicles reaching only two million by the year 2000.
2. High growth in classes 4-6.
3. Emergence of a multi-role tractor doing both line-haul and local delivery work - a hybrid - a "heavy" class 7 or "light" class 8.



4. The anticipated gains, resulting from DOE sponsorship of technology for advanced engines, may be adversely affected by proposed Environmental Protection Agency emissions standards.
5. Normal evolutionary development of current engines promises lighter, more reliable, longer-lived engines, requiring less maintenance.
6. In order to achieve substantial gains in fuel economy, given EPA proposals, bottoming cycle systems may have to be used, or some other alternative found. However, even though initial costs might be acceptable in some cases, it is extremely doubtful that fleets could live with the complexity of these systems.
7. Except for the reservations about the complexity of bottoming systems, there is no great disparity between the characteristics of projected engines and those characteristics acceptable to, and desired by fleets.
8. Aerodynamics plays a significant role in increasing fuel economy and much of the fuel economy penalty due to emissions standards can be lessened by rational design of an integrated tractor/trailer. However, this would require a drastic change in the way truck fleets purchase equipment and manufacturers do business, because there is no single builder of a tractor/trailer vehicle.

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## 7. GLOSSARY

Adiabatic - A process in which no heat is gained or lost by the system.

Adiabatic Engine - An engine in which heat loss is minimized by keeping most heat in the system. The adiabatic engine insulates the diesel combustion chamber with high temperature materials to allow high temperature operation with minimized heat transfer. Additional power and improved efficiency derived from an adiabatic engine are hence possible because thermal energy, normally lost to the cooling water and exhaust gas, is converted to useful power.

Aftercooler - A heat exchanger which reduces the temperature of the air going to the engine cylinders, increasing its density and thus increasing power output of the engine.

Air Deflector - An aerodynamic device attached to a truck, body or trailer to reduce air resistance of the body or trailer.

Air Resistance - The retarding effect caused by air pressure on a vehicle in motion. This force is greatly affected by the speed of the truck and the speed and angle of the wind. Air resistance is negligible at speeds below 20 mph but becomes a major resistance force at speeds over 45 mph.

Allowable Payload - The maximum cargo weight which may be carried without exceeding either the truck manufacturer's designated maximum rating, or the limit established by state or federal law.

Backhaul - A term used to denote the return leg of the truck's trip after it completes its primary or front haul job from initial origin to initial destination.

B.H.P. - Brake Horsepower which is the power available from an engine as measured by a dynamometer.

Boundary Layer - A thin coating of air along the surface of a vehicle in motion.

Brayton - An air-standard cycle describing the production of power by the extraction of work directly from combustion products, as in the internal combustion engine (Otto cycle, Diesel cycle, Sterling and Ericsson are other air standard cycles). The Brayton cycle is the basic air-standard cycle for all modern gas turbines.

Brayton Bottoming Cycle - A system for extracting work from an engine's exhaust by replacing the standard muffler with a heat exchanger and turbomachinery. Hot exhaust gas from the engine expands in a turbine and is then cooled in an air-to-air heat exchanger from whence it flows to a compressor where it is pumped up to atmospheric pressure and exhausted from the system. The turbine/compressor unit is on a single shaft which is geared to the engine output shaft.

BSFC - Brake specific fuel consumption of engines in terms of lbs of fuel per brake horsepower per hour.

Cab - The part of the vehicle that encloses the driver and vehicle operating controls. There are several types of cabs:

Conventional: In which the engine, steering gear, hood and front fenders are all located ahead of the firewall (the separation panel between engine compartment and cab interior).

Short Conventional: When compared to the normal conventional, the short conventional has a shortened hood and front fenders and the engine extends into the cab area.

Cab-over: Also identified by the initials COE for Cab Over Engine. The cab is located high enough to be entirely over the engine which allows the shortest possible cab. The cab-over provides good engine accessibility as it can be tilted forward to expose the engine and engine related components.

Cab Extenders - Panels affixed to the sides of a cab and extending rearward to decrease the apparent gap between the cab and the trailer. Used to decrease airflow in the gap in cross-winds thus decreasing vehicle drag.

Chassis - General term which represents (1) Entire vehicle including cab and sheet metal, less body; (2) Entire vehicle less cab and sheet metal; or (3) Frame & axles without cab and drivetrain.

Class I Carrier - Those receiving annual gross operating revenues (including interstate and intrastate) of \$5 million or more from property motor carrier operations.

Class II Carriers - Those receiving annual gross operating revenues (including interstate and intrastate) of \$1 million to \$4,999,999 from property motor carrier operations.

Class 8 - A description which classifies a commercial cargo carrying vehicle by its maximum gross vehicle weight rating, in the case of straight trucks; or maximum gross combination weight, in the case of combination vehicles.

Class 8 covers vehicle gross weights of 33,001 lbs and above. Others are:

Class 1 - 0-6,000 lbs  
2 - 6,001-10,000 lbs  
3 - 10,001-14,000 lbs  
4 - 14,001-16,000 lbs  
5 - 16,001-19,500 lbs  
6 - 19,501-26,000 lbs  
7 - 26,001-33,000 lbs

This rating system was developed by vehicle manufacturers in the late 1940's to provide a more uniform way of classifying loaded vehicles so states would have an easier task of regulating trucks. As states allowed ever higher gross weights Class 8 covered an ever wider range. Several attempts have been made to break out a Class 9, but agreement could not be reached on where to cut off Class 8. It is possible that in the future Class 7 will be redefined to extend into the current Class 8 range, and a Class 9 will be defined.

Combination, Combination - Motor truck or truck tractor coupled  
Vehicle to one or more trailers (including  
semitrailer)

Common Carrier - For hire carrier whose services must be made available to the general public on a non-discriminatory basis within the limits imposed by their ICC granted authorities.

Compressor - A machine which compresses gases to increase available energy of the gas.

Curb Weight - The empty weight (no payload) of the fully equipped truck. This weight includes oil, water and fuel. Also known as chassis weight or tare weight.

Doubles - A heavy-duty tractor unit with two trailers: a semitrailer and full trailer. (See figure 11)

Drag - Resistance of air to the passage of a vehicle through it. Measured in pounds. See also Air Resistance.

Drag Coefficient - A non dimensional factor used to indicate the relative aerodynamic efficiency of a vehicle. The lower the number, the more efficient or "cleaner" the vehicle.

Drivetrain - All components used to propel the vehicle - engine, transmission, drive shafts and axles.



Durability - How long an engine lasts. This report deals with two aspects of life - miles between overhaul, and life to scrappage.

Fifth Wheel - A plate type device, carried by a tractor with jaws which lock on to a pin mounted on a trailer so the trailer can be towed by the tractor.

Geared Speed - Maximum attainable road speed based on engine governed rpm, transmission gear ratio, rear axle ratio and tire size.

General Freight Carrier - Carriers of freight other than household goods, heavy machinery, petroleum products, refrigerated products, agricultural commodities, motor vehicles, building materials, film and associated products, forest products, ores, hazardous materials.

Gradeability - Percent of grade a vehicle will negotiate. One foot of rise per 100 feet of level distance would be a 1% grade.

Gross Axle Weight - The rated capacity for a particular axle Rating (GAWR) system, including axle, springs, brakes, tires and wheels.

Gross Combination - The total weight of the combined truck and  
Weight (GCW) trailer or tractor and trailer or  
semitrailer, with payload.

Gross HP or Torque - The power rating obtained by a dynamometer  
test of an engine without allowance for the  
power absorbed by the engine accessories.

Gross Vehicle Weight - The total weight of a loaded truck. GVW is  
(GVW) found by adding the payload weight to the  
curb weight of the empty truck.

Gross Vehicle Weight - The manufacturer's rating for the vehicle.  
Rating (GVWR) The maximum amount that the loaded truck  
was designed to weigh with payload.

Heat Exchanger - A device for transferring thermal energy from one  
fluid to another, such as a radiator.

Heavy Duty - As applied to vehicles it means class 7 and 8 trucks  
and tractors (see definition of vehicle classes). As  
applied to truck engines it means engines of 250 hp  
and above.

Horsepower - The speed at which an engine can do work or work per unit of time. A measure of force moved a certain distance in a certain time. (33,00 ft/lbs of work done in one minute = 1 Horsepower.)

Insulation - The shielding of metal parts in the engine with ceramic coatings.

Intercity - Carriers operating interstate and intrastate with the majority of their revenues derived from non-local cartage. These carriers are subclassified as either regular route - operating primarily over designated highways, or irregular route - authority to serve an area over any appropriate route. Also used to characterize the hauling of freight over distances of 200 miles or more with no loading or unloading enroute.

Intermodal - A carrier, device, vehicle or facility capable of contributing to transfer among shipping modes - air, rail, sea, motor carrier.

Linehaul - See Intercity.

Local Delivery - Motor Carrier operation principally within a single or contiguous commercial zone, yet having some aspect of operation subject to ICC authority. Taken to characterize delivery within the vicinity of the termination of the linehaul up to distances of 200 miles one way.

Longer Combination Vehicle - This phrase denotes Triples, Rocky Mountain Doubles, and Turnpike Doubles. (See figure 11.)

Maximum Gross Combination Weight (GCW) - Manufacturer's gross weight limitation on how much a truck or tractor can pull (including weight of the truck and trailer).

Maximum Gross Vehicle Weight Rating (GVWR) - Manufacturer's gross weight limitation on how much a truck can pull (including weight of the truck and body). The maximum is determined by component sizes and ratings.

Medium Duty - As applied to trucks it means class 6. As applied to truck engines it means below 250 hp.

MPH - Velocity (speed) in miles per hour.

Net HP or Torque - The power rating obtained by dynamometer test of an engine with allowance for the power absorbed by the engine accessories - just as it would be installed in the truck.

Owner-Operator - A private individual who owns and drives his own tractor or tractor-trailer combination. Owner-operators are independent businessmen who either lease their equipment and services to ICC regulated carriers or haul non-ICC regulated commodities also known as exempt commodities.

Organic Rankine Bottoming Cycle - A Rankine bottoming cycle system which uses an organic fluid as the working fluid. See Rankine Bottoming Cycle and Rankine.

Payload - Total weight of the commodity being carried on a truck at a given time. (This includes packaging, pallets, banding, etc.)

Piggyback - Jargon for the practice of hauling truck trailers on railroad flat cars. See TOFC.

Private Carrier - A carrier who carries primarily products of his own company. Until 1980 private carriers were prohibited by the ICC from carrying commodities/products not originating from their business. This meant many return trips were run empty. After 1980 private carriers were allowed to seek freight in competition with other carriers.

Radiator - Transfers heat from liquid coolant to the outside air, keeping the engine operating in an optimum temperature zone.

Rail Head - A rail yard where trailers are loaded or unloaded from rail flat cars and transferred to/from highway trucks. This would be an intermodal facility.

Rankine - A vapor cycle describing the production of power from the combustion of fuel by the transfer of heat from the combustion products to a cyclic heat engine such as a steam powerplant. Vapor cycles depend on a working fluid which is converted to a vapor which does work on an engine piston or a turbine wheel.

Rankine Bottoming Cycle - A system for extracting work from an engine's exhaust by replacing the standard muffler with a heat recovery vapor generator. As hot exhaust gases pass through the vapor generator, heat is transferred to an enclosed working fluid which turns into a superheated vapor. The vapor drives a small power turbine which is geared to the engine output shaft.

Reliability - The ability of an engine to be relied upon - its ability to perform in the intended manner when requested. Measures of reliability are frequency of repair and frequency of unanticipated repairs (inability to be relied upon).

Rolling Resistance - A measure of the retarding effect of the road surface to movement of the vehicle.

Semitrailer - A trailer having an axle (or axles) only at the rear; the front of the semitrailer is supported by the tractor fifth wheel. A semitrailer may be operated as a full trailer by using a converter dolly to support the front end.

Steam Bottoming - A Rankine bottoming cycle system which uses  
Cycle steam as the working fluid. See Rankine  
Bottoming Cycle and Rankine.

Straight Truck - A truck with the cargo body and engine mounted on  
the same chassis.

Tandem Axle - An assembly of two axles on a truck or tractor.  
Either or both may be driven by the engine.

Tare Weight - See Curb Weight.

Tilt Cab - Vehicle designed with the engine beneath the cab and  
having provision for tilting the cab forward to provide  
easy access to the engine.

Torque - Force applied at a distance having a twisting or turning  
effect. For engines it is the amount of work that can be  
done.

Tractor - A truck with a fifth-wheel mounted on the rear frame  
which supports and pulls a trailer called a semi-  
trailer.

Trailer - A trailing load carrier supported entirely by its own  
axles (2 or more). Also know as a full trailer.



Trailer-on-Flat-Car (TOFC) - A trailer loaded on to a rail flat car. These trailers may be conventional road trailers or trailers designed for rail flat cars.

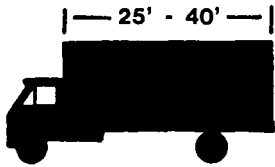
Triples - A tractor pulling three trailers: a semitrailer, a full trailer and another full trailer. See Figure 11.

Turbine Engine - An engine in which the working medium is a gaseous fluid throughout the cycle with the principal mechanical parts driven by turbines.

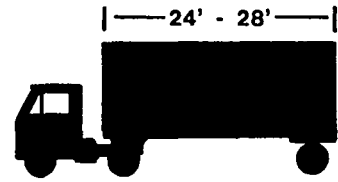
Turbocharger - An exhaust gas-driven rotary compressor that pressurizes engine intake air.

Turbocompound Engine - A diesel engine with a low pressure power turbine downstream of the turbocharger turbine and connected through a gear train to the engine's output shaft.

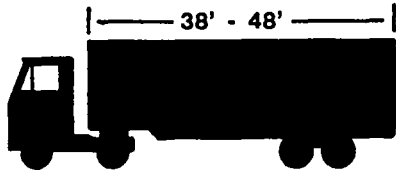
**STRAIGHT TRUCK**



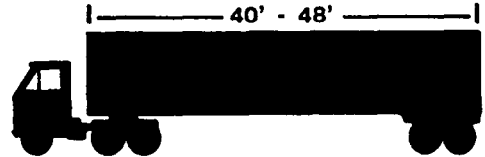
**3-AXLE TRACTOR SEMITRAILER**



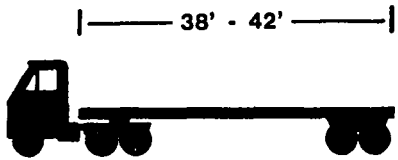
**4-AXLE TRACTOR SEMITRAILER**



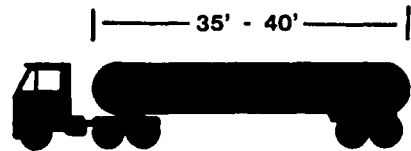
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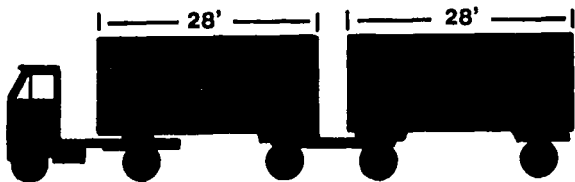
**5-AXLE TRACTOR FLATBED TRAILER**



**5-AXLE TRACTOR TANK TRAILER**

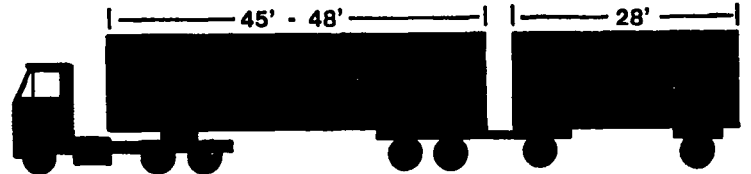


**TWIN TRAILER OR "DOUBLES"**



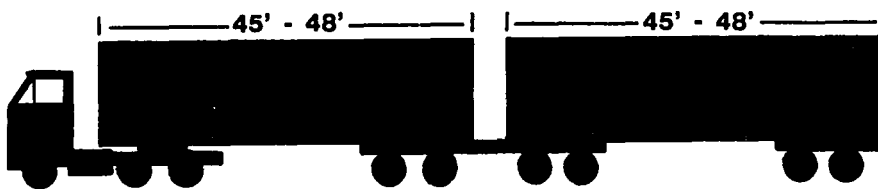
**ROCKY MOUNTAIN DOUBLES**

(operated only in certain states)



**TURNPIKE DOUBLES**

(operated only in certain states)



**LENGTHS SHOWN ARE TYPICAL; SHORTER OR LONGER LENGTHS ARE POSSIBLE DEPENDING ON CARRIERS' NEEDS AND STATE LAWS.**

**FIG. 10**

APPENDIX A

COMPANIES CONTACTED

<u>Fleet</u>	<u>No. of Tractors</u>	<u>Rank Among Trucking Companies</u>
United Parcel Service, Greenwich, CT	5349	1
Roadway Express, Akron, OH	7354	3
Consolidated Freightways, Portland, OR	6329	4
Yellow Freight System, Overland Park, KS	5412	5
Ryder/PIE, Jacksonville, FL	3239	6
ABF Freight System, Fort Smith, AR	1780	10
Overnite Transportation, Richmond, VA	2765	11
Smith's Transfer, Staunton, VA	2611	13
Carolina Freight Carriers Cherryville, NC	1944	14
Transcon Lines, Los Angeles, CA	1697	15
Preston Trucking, Preston, MD	1609	19
Hall's Motor Transport, Mechanicsburg, PA	1766	20
Signal Delivery Service, Atlanta, GA	1387	22
Matlack, Inc., Lansdowne, PA	1022	32
Pilot Freight Carriers, Winston Salem, NC	786	33
Mason & Dixon Lines, Kingsport, TN	1193	35
Delta Lines, Inc., Oakland, CA	1471	38

<u>Fleet</u>	<u>No. of Tractors</u>	<u>Rank Among Trucking Companies</u>
Bowman Transportation, Atlanta, GA	1309	45
Watkins Motor Lines, Inc., Lakeland, FL	288	43
Old Dominion Freight Lines, High Point, NC	642	49
Thurston Motor Lines, Charlotte, NC	705	52
Transus, Inc., Atlanta, GA	600	57
Murphy Motor Freight Lines, Inc. St. Paul, MN	498	62
Campbell "66" Express, Springfield, MO	648	63
CRST, Inc., Cedar Rapids, IA	500	65
BN Transport Service, Denver, CO	354	67
Northwest Transport Service, Commerce City, CO	454	75
Motor Convoy, Inc., Atlanta, GA	87	84
Ruan, Des Moines, IA	600	--
Paul's Trucking, Woodbridge, NJ	N/A	--
Bestway Transportation, Phoenix, AZ	136	--
Anderson Truck Line, Lenoir, NC	60	--
Saunders Leasing, Birmingham, AL	--	--
D.M. Bowman, Williamsport, MD	150	--
Ryder Truck Rental, Miami, FL	21,300	--
Trans Western Express, Denver, CO	250	--
ANR Freight System, Denver, CO	--	--
Includes Graves Truck Lines	525	78
Garrett Freight Lines	1,086	36
Associated Truck Lines	1,163	25

<u>Fleet</u>	<u>No. of Tractors</u>	<u>Rank Among Trucking Companies</u>
Midwest Specialized Transport, Rochester, MN	150	--
Contract Freighters, Joplin, MO	$\frac{N/A}{79,219}$	--

These fleets accumulated 4.3 billion miles and 44.1 billion ton-miles in 1983.

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## APPENDIX B

### QUESTIONS USED IN INTERVIEWS

1. Estimates indicate that total volume of intercity freight (in terms of ton-miles), will increase from 75% to 100% by the year 2000. Do you feel this is a reasonable prediction?
2. Researchers think piggyback shipments will represent 19% of the intercity freight by 2000. Do you think this is realistic?
3. Numbers of heavy duty diesel intercity (greater than 200 miles) trucks are projected to increase substantially (almost double 1979 numbers) by 1995. Do you see this happening?
4. How do you see the ratio of the number of line haul (over 200 miles) to local delivery trucks changing? No change?
5. The real constraints on our productivity growth are size and weight laws. Do you see significant changes from the STAA over the next 15 years?
6. If not, does this mean that horsepower levels will remain the same over the next 15 years?
7. If yes, will these changes create the need for higher horsepower? What is your fleet average line haul horsepower?

8. Do you think a designated national highway system (Interstate and limited access) for longer double and triple combinations is possible? If so, would you use these combinations, and what would be your power requirements?
9. Would you rather have more fuel efficient engines, more durable engines (longer life), more maintenance free engines, or more reliable engines?
10. How important is fuel efficiency?
11. Would you take a chance on a new kind of engine if it promised lower fuel consumption, and less maintenance, but cost more initially and has never been used in fleet service?
12. In what percentage of your fleet would you be willing to try advanced engines?
13. Other than maintenance cost per mile and miles between overhaul, what parameters do you use to rate engine performance or compare engines? Do you monitor downtime due to engine breakdown? Do you monitor maintenance man-hours relative to engine operating hours?



14. Do you think your company or other trucking companies would be willing to invest in new, innovative engines when choices have to be made between the various other demands for capital?
15. Describe the kind of vehicles you think you will be buying over the next 15 years. Much as today? Different?
16. Are you satisfied with the trends in diesel engine development or would you like to see other trends or other types of engines e.g. turbines?

Reasons for these particular questions:

- 1 -- The amount of freight available is fundamental to the trucking business. This question was meant to obtain consensus regarding predictions of the size of the future market, which will affect the number of vehicles needed in the future.
- 2 -- This question was included to elicit opinion as to how much of the market would be taken by piggyback, as this would also affect the number of vehicles needed.

3 -- This question directly confronts the issue of number of trucks needed or expected to be in use in the future. If the answer to question number 1 is "yes", and to number 2 is "yes", then the answer to this question should be no, and this is the way the majority of people interviewed responded.

4 -- If total intercity freight will increase as anticipated, but the increase in number of heavy trucks will not match this increase, then some vehicles must make up the difference. To some extent the "vehicle" will be the piggy-back car. But its increased use will create the need for more medium duty or local delivery type vehicles. This is what question 4 was attempting to explore. It was this question that brought to light the opinion that there will be large growth in classes 4-6 with, perhaps, even some line-haul being done by class 6; and that a dual role "light" class 8 or "heavy" class 7 will emerge as the use of double trailers increases.

The answers to questions 1-4 help indicate the possible size of the future heavy duty truck fleet, and those kinds of vehicles which will compose it.

5 -- Probably the second most basic factor affecting fleets, and one which is the factor affecting equipment is legislation. The intent of this question was to determine

whether fleets see changes coming about in the next fifteen years. If not, then we will be dealing essentially with the vehicle size and weight laws we have today with little change in engine horsepower.

6 & 7 -- were needed to determine the average horsepower in use today, and they relate to question 5 in that a "no" to question 5, means an automatic yes to 6.

8 -- One event, which would affect horsepower would be the emergence of a dedicated highway system for longer combination vehicles. The question was aimed at determining if fleets felt such a road system was likely to come about, and if so, what the horsepower requirements for longer combinations would be.

9 -- This question was included because everyone took for granted that fuel efficiency would rank number one. We wanted to see if it was so, and what would rank after it.

10 -- This question, while similar to 9, was meant to elicit fleet perspectives on fuel efficiency and its impact on their operations. It also turned out to generate comments on reliability.

- 11 & 12 -- These questions explore how willing fleets are to try new engines in revenue service.
- 13, 13a & 13b -- One of the things we had to find out was what parameters fleets use to evaluate and compare engines. This was needed to provide some correlation between parameters used by fleets and those used by researchers and manufacturers.
- 14 -- This question was used to find out what priority fleets would accord innovative equipment vis-a-vis other demands within the company for capital.
- 15 -- This question was used to determine the individuals expectations, and the answers could be used to indicate, in a general way the nature of future fleet specifications.
- 16 -- Individuals being interviewed were given two basic approaches to engine improvement: (a) a product improvement, gradual evolving of the existing block (the tweaking approach); and (b) advanced engine development as illustrated in figure B-1. This figure was used to "talk around", and generally discuss opinions regarding these developments in particular, and engine research in general.

# ADVANCED DIESEL BASE POWER PLANTS

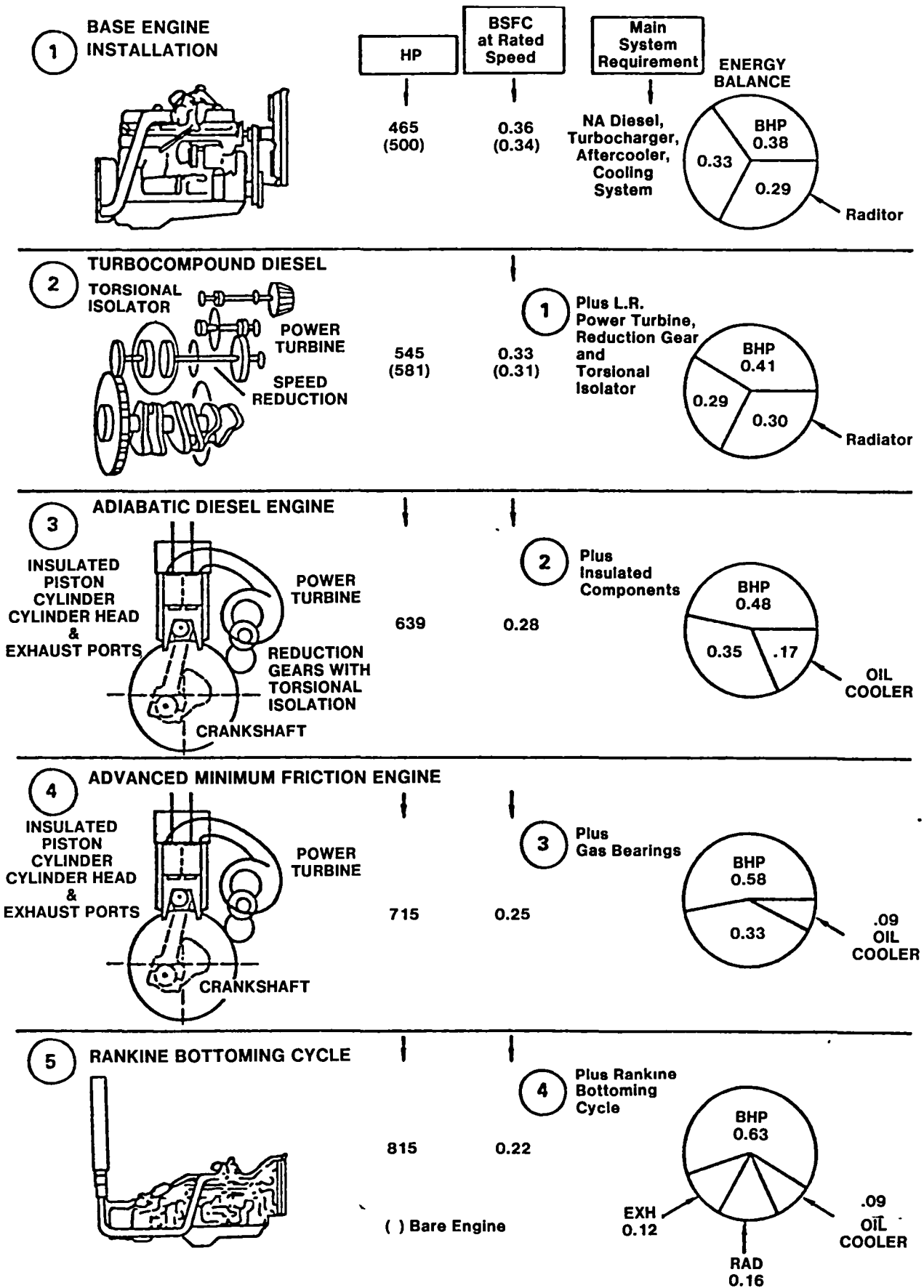


FIG. B-1

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APPENDIX C

RESULTS OF INTERVIEWS

1. Estimates indicate that total volume of intercity freight (in terms of ton-miles), will increase from 75% to 100% by the year 2000. Do you feel this is a reasonable prediction?

YES - 65%

NO - 20%

Qualified response from remaining 15%

COMMENTS:

- o Answer depends on degree of centralization of production facilities, or decentralization. Market is sensitive to cost of energy.
- o Their projection is 4 1/2% per year (72 1/2% over the time period). Manufacturers are attempting to centralize their operations.
- o Long distance hauls will decrease. There will be more regional and distribution points. Theoretically, costs to run piggyback will not increase as fast as costs to run trucks.

- o Their business did not increase 75% over the past 15 years even with the very good years of the late seventies.
  - o Loads are getting lighter. No question that number of loads would increase 100% but on ton-mile basis would not see such a large increase.
  - o Maybe 50% increase. Demographics don't support greater increase.
  - o There will be more imports of finished goods. Manufacturing that is left will be regionalized. Fortune 500 companies are willing to spend more on distribution than on inventory. They are building fewer warehouses and putting the money into truck transportation. However, don't see 75-100% growth.
2. Researchers think piggyback shipments will represent 19% of the intercity freight by 2000. Do you think this is realistic?

Yes, 19% or better - 74%      Yes, but not 19% - 18%

No - 8%



COMMENTS:

- o Use of teams for driving is a waste of manpower, plus have increased workmen's comp. exposure. Railroads can now easily get into trucking.
- o Trend in state legislation in eastern states is to discourage trucking use. Railroads have tax advantages.
- o Conservative, based on number of railroads looking for trucking companies and because the cost of fuel is certain to rise. (Has to increase in next 5 years)
- o As long as Interstates stay in good repair we can give service. Piggyback can't give service time-wise that general public desires.
- o Yes, for movement over 500 miles. Piggyback not feasible at less than 500-600 miles.
- o Where freight is not time critical railroads can do okay.
- o Depends on what kind of peace railroads can come to with their unions. If they reach accomodation railroads can achieve 19% market penetration easily.

- o Carriers will get their act together economically and out compete the railroads. Improvements in fuel economy will help.
  - o Railroads are not improving railbeds. There is not enough capacity to take increase of this magnitude and no more right of way left.
  - o Situation fluid and depends on rail rates, fuel cost, ability of industry to use triples.
  - o Everybody has got one (intermodal operation) going. If the railroads sharpen service piggyback will explode. Even without railroad cooperation there will be growth.
  - o On trips over 1000 miles they will have more than 19%. On trips less than 1000 miles they will have less than 19%.
  - o Railroads don't have the facilities at the railheads to move the amount of freight implied by 19%.
3. Numbers of heavy duty diesel intercity (greater than 200 miles) trucks are projected to increase substantially (almost double 1979 numbers) by 1995. Do you see this happening?

4. How do you see the ratio of the number of line haul (over 200-miles) to local delivery trucks changing? No change?

Only 20% see the number of heavy duty diesel trucks increasing by the amount stated in question three.

#### COMMENTS

##### On Questions 3 & 4

- o Impact of doubles will be to run fewer trips and have higher utilization.
- o They see more satelliting of operations, more of a shuttle operation - more efficient equipment utilization.
- o Going to doubles will hold number down and so will the use of 48 foot trailers. Using single axle tractors, which can double as city delivery tractors, will also reduce number of tractors. The single axle tractors will do line haul at night and city delivery during the day.
- o Will have more regional warehousing hence increase in local delivery vehicles.

- o Shrinking size and weight of freight and improved productivity will reduce need for large numbers of trucks. Decreasing empty backhauls alone will be a tremendous change.
- o Classes 3-6 are really going to burgeon.
- o See a great effort to get better utilization of line haul power units.
- o L-10 engine would be a line-haul engine at 270 hp and a city engine at 210 hp. More use of single axle line haul tractors in city delivery after used for line haul. More utilization of line haul tractors in city delivery would mean fewer numbers of trucks.
- o If railroads achieve 19% penetration then the number of line haul trucks will decrease.
- o Dedicated line haul will be reduced but will be more efficient. Local delivery will be more specialized - higher numbers of class 6 and 7. See a trend toward more efficient local delivery.
- o Will utilize same truck for local delivery and line haul. A twin plus single axle tractor will supplant the 20' straight truck, plus you won't have to transfer freight across the dock.

- o More and more will be shipping TL. Use of pups for local delivery will increase.
  
  - o Class 8 is basically replacing itself. There won't be any doubling. Class 5 & 6 will be moving what is now being moved by class 7 & 8 tractor. A lot of research benefitting big engines has bypassed mid-range engines. Use of mid-range diesel vehicles will increase way above use of gasoline powered versions because of greater durability and maintainability of diesel engines.
5. The real constraints on our productivity growth are size and weight laws. Do you see significant changes in the STAA over the next 15 years?

Yes - 47%

No - 53%

#### COMMENTS

- o No change until turn of the century - Teamsters, railroads and AAA are bent on limiting our productivity.
  
- o Definitely has to be a change. STAA is not working. Bridge formula needs to be rethought. Industry has to change the law to get better productivity.

- o STAA was step to help offset some taxes. Productivity of the nation will be addressed and more positive things done for increased productivity, especially over the next 5-10 years.
- o Study on longer combinations will result in double 45' trailers on Interstate once states have learned to live with shorter doubles. Use of Turnpike doubles would be the only way truckers could complete, on a coast to coast run, against piggyback.
- o If Western carriers can split off and can organize properly they could get triples throughout the West. East has gotten all it is going to get. An impossible public relations problem to get more in the East.
- o In the West gains will be made through permit extensions of triples and longer doubles.
- o No, unless can increase size of highways and go to triples. 48' is about as long as you can get; physical limitation of roads, curves and facilities restrict size of trailer.
- o Weights will have to increase. Maybe use of triples would be more widespread. If increased use tax comes in as projected we will have to get some kind of compensating productivity increase.

- o Not sure we got what industry really needs in present act, e.g. infrastructure limits use of 102" wide trailers. Has to be more coordination between vehicle and road design.
  - o Have to go to turnpike doubles.
  - o Changes over the next 15 years will be driven by what the country wants to pay for transportation and what these demands do to change the political climate.
  - o Yes, if the trucking industry takes the initiative to experiment and demonstrate productivity gains.
8. Do you think a designated national highway system (Interstate and limited access) for longer double and triple combinations is possible? If so, would you use these combinations, and what would be your power requirements?

<u>Eastern Fleets</u>	<u>Western Fleets</u>
Yes 60%	Yes 94%
No 40%	No 6%

Average HP Required = 326      Average HP Required = 346

## COMMENTS

- o Uncertain. Have problems in the East. May be restricted by temporal rather than spatial considerations. Great concern on part of analysts is increased numbers of trucks crowding out small cars, and there is little or no real estate left in the East for road building.
- o Since more roads will not be built, there will be restraints on highway usage. Trucks may be restricted to particular time and/or space slots.
- o Horsepower wouldn't change. Even with today's increases in vehicle size we have stayed with the lower horsepower.
- o Not practical, under present highway and Interstate System, except on a regional basis (i.e. out West).
- o Would benefit larger carriers but don't see return matching investment. Wouldn't benefit industry as a whole, just a segment of it.
- o One state has a law which requires triples to use 300 hp. California has a "pump code" with required settings to use when pulling triples. States may dictate minimum HP requirements for triples.
- o Theoretically sounds great, but too high a cost if had to build more lanes. Can't maintain the roads we have now.



- o Don't think it would be good for the industry since it would be equivalent to rubber tired trains.
9. Would you rather have more fuel efficient engines, more durable engines (longer life), more maintenance free engines, or more reliable engines?
10. How important is fuel efficiency?

Regarding question 9 - by more than 5-1 fleets preferred more fuel efficient engines. Reliability was second.

Regarding question 10 - 85% rate fuel efficiency the number one concern.

#### COMMENTS

- o Number one for years to come.
- o Fuel is second largest cost item after labor.
- o We are selling service - hence reliability.
- o Fuel efficiency - reliability is good now.

- o Have to look at positive tradeoff due to increased carrying capacity that may save two trips, but cost a couple of gallons more per trip. Better figure of merit is Ton-Mile or gallons per 1000 cu. ft/mi. gal
- o Western user is more interested in reliability and durability because of long distances involved and down time associated with breakdowns.
- o Fuel efficiency is the quickest way to save a buck.
- o Concerned about cost effective fuel economy. They are increasingly looking at the cost of keeping fuel economy up (rebuilding injection pumps, etc.)
- o It swings. Once problem is lived with long enough one accepts it. Really depends on the price of fuel.
- o If could gain enough fuel efficiency, could live with existing maintenance requirements and time between overhaul.
- o Fuel economy because can afford to rebuild engine (they are getting 400,000 miles before overhaul) if can get another 1 or 2 mpg. Would like a combination of both.
- o Fuel efficiency because fuel is 1/2 of cost of engine over its life.

- o Depends on fuel cost in the future. Have durable engines today. Fighting for more fuel economy. If pay less than \$3.00/gal would rather have durability.
- o Know what reliability and durability is for existing engines - need more fuel efficiency.
- o Economic factors predominate. Fuel costs can be dialed into rates more easily than reliability factors.
- o Very important. The whole combination vehicle must be optimized to reduce fuel cost and total cost of ownership.
- o Very important, but not at the expense of life and reliability.
- o Fuel efficiency pays off everyday. Have seen life increase as fuel efficiency goes up. Also see less maintenance on rest of vehicle. One cent a mile lower fuel cost will pay for an engine overhaul.
- o Maintenance cost greater vs. fuel costs at current fuel prices.
- o One of the most direct ways to save fuel is better equipment utilization though reduction of empty backhauls.

11. Would you take a chance on a new kind of engine if it promised lower fuel consumption, less maintenance, but cost more initially and has never been used in fleet service?
12. In what percentage of your fleet would you be willing to try advanced engines?

Regarding question 11 - Yes - 95% No - 5%

Regarding question 12 - Answers varied from "one or two" up to 1/3 of their annual purchase (75 vehicles in this instance).

#### COMMENTS

- o Degree of caution is influenced by degree of OEM support.
- o Yes if introduced, supported and covered by "right" manufacturer.
- o Resale value of advanced equipment impacts decision whether or not to take a chance at all.
- o Would be a pioneer under condition that manufacturer provided support. A year is not long enough to test.

- o "Presentation" is important. Would not discriminate against a newcomer or small company if presentation was good enough.

13. Other than maintenance cost per mile and miles between overhaul, what parameters do you use to rate engine performance or compare engines?

COMMENTS

- o Miles per gallon                      Horsepower  
Torque                                      Weight  
Cost of overhaul                      Reliability  
Resale value of vehicle              Parts prices  
Training and tools required          Ease of maintenance  
Cost of maintenance                  Driver acceptance  
Initial cost                              Life  
Cost of fuel                              Total vehicle cpm  
Oil consumption                      Labor cost  
Downtime  
Availability of service and parts  
Relationship with supplier - product support  
Labor and material as a % of revenue
  
- o Cost of fuel per mile. How forgiving it is to operational or maintenance abuse, its ability to perform the job, cold startability, noise and cost of quieting, ease of overhaul or internal repairs and potential for success.

- o PM interval and what they have to do to keep fuel economy up.

14. Do you think your company or other trucking companies would be willing to invest in new, innovative engines when choices have to be made between the various other demands for capital?

Yes - 94%

No - 6%

#### COMMENTS

- o Yes, as long as the investment saves fuel or has significant payoff.
- o Depends. Prioritize investments by ROI.
- o Must be proven by present value analysis.
- o Labor is #1 cost and company would invest in labor saving innovation first. Fuel is 2nd highest cost.
- o Depends if overall payback is there and on manufacturer support. Trade in value of equipment is important.
- o If it's cost-effective with a short time R.O.I., there should be a willingness. The longer the R.O.I., the harder to decide. If the capital demands are to simply stay in business, no one could afford development costs.

15. Describe the kind of vehicles you think you will be buying over the next 15 years. Much as today? Different?

#### COMMENTS

- o More Electronics
  
- o Better aerodynamics, more room for driver, smaller engines.
  
- o 300 HP SA conventional; enhanced aerodynamics; lighter, smaller engines.
  
- o 300 HP conventional, 7-10 spd, better aerodynamics.
  
- o More productive and more reliable. There will be a shrinking of componentry - i.e. tires smaller than today's low profile tires - hydraulic brakes etc., leading to decreased tare weight.
  
- o Assuming laws are as they are today improved aerodynamics will allow HP to go down. Do not see big break throughs on major component life. Engines will be more fuel efficient but not more durable. Over next 3-5 years gains will be through heat exchange devices. This is next big break through.

- o See adiabatic in the immediate future. When fuel gets to be \$2/gallon we'll really see something.
- o See much more electronics, 3 axle conventionals, smaller displacement higher rpm engines.
- o Going from COE to conventional; improved aerodynamics—have a long way to go on aerodynamics; electronics. Not a lot of changes in 15 years. New technology takes 5-10 years to implement, and we are just scratching the surface of new developments.
- o Would hope they would have better access and roomier cabs and better aerodynamics. Have a long way to go on aerodynamics.
- o Would expect same basic engine - highly sophisticated electronics - diagnostics; driver control/monitoring type reports; more sophisticated fuel and governor controls; audio cues to drivers about highway constraints, e.g., speed limit, traffic lights, and navigation aids.
- o Don't see radical changes except for aerodynamics. There are a lot of operating efficiencies to be gotten. There are 2 components to fuel efficiency: mechanical and human. Industry just now beginning to address driver influence on fuel economy. Past devices merely allowed driver to go faster.



Management has to capture these savings. In next 3-5 years will have electronic fuel control. Potential for onboard microprocessors is huge. Potential for diagnostics is tremendous. This all leads to tighter driver management.

- o See significant evolutions - driver comfort improved. Have to get hold of the driver. 30% of the fuel savings could come from the driver.
- o No radical changes - there haven't been any in past 15 years. Great improvement in diagnostics. Don't see a lot of changes unless government relaxes restriction on width and length.
- o They will be different in that they must be optimized to reduce parasitic losses, provide good weight distribution across the axles, be lighter in weight, controlled electronically to take the driver out of the loop, aid in self-diagnosis, be durable and reliable. In short, provide the lowest cost for transport service.
- o Won't look like they look today. Will have better aerodynamics, be lighter, and have smaller, lighter engines.
- o Low profile tires, cruise control (in their experience cruise control increased fuel economy 8%); more efficient transmissions, more electronics (but they have reservations

because of cost), improvements in driver comfort, automatic slack adjusters, non-asbestos brake linings, shrinking size of tractor - less frontal area, better fairing into trailer.

- o More standardization, tailored to regulations, lighter, better aerodynamics.
- o Better aerodynamics, electronics, lighter. Look for 400,000 mile engine without much need for maintenance.
- o Would hope to see 10 mpg, standard "utility" equipment available nationwide, easier maintenance (maintainability) better aerodynamics.
- o Elimination of cooling system very attractive, improved aerodynamics, longer doubles, triples, 102" width.
- o Depends on triples legislation. In line haul see single axle, short nose conventional, In local delivery see lightweight tractor. Smaller engines - 270-300 in line haul; 210-220 in local delivery. Enhanced aerodynamics.
- o More aerodynamic improvements, automatic transmissions, modular repair of engines, more reliable engines, smaller, lighter vehicles.

- o Quieter, more fuel efficient conventional; more sophisticated in overall design, lighter.

16. Are you satisfied with the trends in diesel engine development or would you like to see other trends or other types of engines e.g. turbines?

Satisfied - 48%

Want even more improvement - 29%

#### COMMENTS

- o Maintenance of cooling systems is a big problem. Elimination of the cooling system would be one of the best things. Advanced engines must be simple designs. Minimum maintenance or else will need a whole new maintenance training program.
- o Would like to see improvement utilizing still dormant potential of existing diesel engine technology before launching new products. Turbo compounding appears complicated.
- o Wonders why turbine was dropped so quickly. It should be explored further. Short sighted not to look at it.
- o Trends are reasonable, natural, evolutionary ones but don't go far enough. The industry should be addressing the recovery of potential energy, the energy expended in brak-

ing. Energy recovery systems may have as much potential to save fuel as developing new engines per se. We ought to transfer energy as heat pumps do, instead of producing it.

- o The greatest thing DOE could do would be to put pressure on DOT to get us the productivity gains promised in the STAA. DOE should know that if we can run, for instance, turnpike doubles, (per the dedicated highway system) this makes the investment in more costly engines more palatable. There has to be close coordination between DOE & EPA on emission requirements.
- o Cooling system failures cause most engine failures. The second greatest cause is lubing. Once people get into an engine problems really start. If didn't have to do lubrication would save a lot of trouble.
- o Reciprocating engine is hard to beat. Don't think application is there for the turbine. Ultimately have to address the problem of what happens when we run out of petroleum based fuel.
- o Continue optimizing what you have but a certain amount of research has to be done. Would buy an adiabatic diesel with a bottoming cycle tomorrow.

- o If fuel efficiencies indicated are correct, estimated prices are no problem. Ought to consider engine/drivetrain relationships. Very concerned about American leadership. Would be more inclined to invest in and experiment with American made products. Feels strongly that advanced engines are an area where America can and should lead.
  
- o Behind adiabatic. Use of rejected heat between engine and exhaust will be addressed even more before we get to an adiabatic engine.
  
- o Would like to see research on more advanced engines. Industry has done about all that can be done with existing engines and the cost of maintenance of the added, more complex components, to gain a small increase in fuel savings, might outweigh the fuel savings. There should be more emphasis on the advanced engines. It appears that the savings are there. But we don't need any increases in HP. Would rather reduce HP gains to obtain increased fuel economy.
  
- o Agrees strongly that all kinds of improvements are still to be made in the existing engine. The 18 month to 2 year pay-back period is on target.

- o Ought to go with evolution. Adiabatic still an unknown quantity. What about turbines? Is it possible to have an engine burning heavier fuels not now suitable for automotive use? Cost containment possible if use broader spectrum fuels.
  
- o Satisfied with trends-good for first ten years. For second decade sees photovoltaics coupled with electric motors to drive vehicles. Don't believe turbine can compete in freight hauling - its operating regime would be taken over by the railroads. Equipment has got to get simpler.
  
- o Goals shown are not high enough regarding fuel economy. Don't need increased HP shown. Would rather see more fuel economy. Quality control is important. Standardization is important.
  
- o Current trends are to reduce energy consumption. Whatever works well will sell irrespective of concept. Energy is simply going to cost more.
  
- o The use of charge air cooling, or flow cooling is a good move, lowering temperature of air into the engine with advantages of better fuel economy and emissions. Research into ceramics should be supported. Turbines and Sterling engines have no place in trucks in the present stage of development. Spark ignited diesels should be explored to

operate on the low quality fuel that will be available in the future.

- o Advanced technologies must be used. Maximize HP/wt ratio. Initial cost does not matter if the life cycle payback is there. The last 3-5 years trend if continued would be great.
- o Fuel economy has to be approached on a power train basis (engines, transmission, rear end). Have to get drivers trained and fuel quality up. Fuel quality varies all over the map. Government ought to set standards for fuel quality - it affects emissions also.
- o Initial price of improvements does not matter as long as payback is there.
- o Not satisfied. Want a simple 10 mpg engine. Engine/vehicle complexity increasing - will be expensive.
- o Satisfied with current trends except that improvement may be occurring too fast which increase costs of maintenance, parts, inventory, etc. The bottoming cycle developments do not seem very cost effective.

- o Satisfied with advances made to basic diesel engine, but would look at other avenues that promised larger % reduction in fuel use. Weight of developments not that critical because load factors aren't high and freight is becoming lighter. In any event, use of new developments depends on the price of fuel and fuel taxes.
- o Not really satisfied. Feels a lot is to be gained in fuel economy that has not been realized. Likes ceramics work.
- o Satisfied for now. But eventually advanced technologies must take over. Hence, would like to see effort into even more advanced research than illustrated.
- o Not satisfied. We are 5-6 years behind in development. Doesn't care which technology meets needs as long as basic productivity parameters - more fuel efficiency, more reliability, more durability - are met. Real problem will be the ability to get repairs on the road with new technology.
- o Not satisfied. Diesel will not live forever - pollution problems. Much more can be gained in fuel economy.
- o Not satisfied. Not enough fuel economy, lacks increased life and reliability. Would like to see drastic changes.



- o There should be a focused study of alternative fuels and oils in concert with engine developments. Engine developments have to be an evolutionary approach.

#### COMMENTS REGARDING HP

##### NOT RELATED TO ANY SPECIFIC QUESTION

- o Staying with traffic flow is the real driver of horsepower levels.
- o Average horsepower has been going down since mid seventies. It now appears that it is creeping up.
- o Intercity should average 250-350 hp industry wide throughout U.S.
- o 80,000 lbs. can moved at less than 300 hp; 115,000 lbs. can be moved at less than 350 hp.
- o Single axle tractor used in large numbers with doubles and triples has a limit to the HP that can be put through the single axle safely and efficiently - about 350 hp. Need development of a good 4 x 4 tractor which could handle higher HP.

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## APPENDIX D

### Bases for Numbers Used in Questionnaire

1. Referring to question 1 - the total volume of intercity freight (in terms of ton miles). A 75% to 100% increase by the year 2000, based on table D-1, was used.

The volume of intercity freight generated by the economy is predicted periodically by several groups. The fundamental fact seems to be that freight growth or decline matches growth or decline in the Gross National Product.

2. Referring to question 2, a figure of 19% was used as a possible percentage of intercity freight traveling by piggyback (also known as trailer-on-flat-car or TOFC) in the future. The individuals being interviewed were told that right now about 2% to 3% of this freight moves by piggyback. The question turned out to be poorly worded because it implied, that the 19% figure pertained to the total volume of intercity freight mentioned in the preceding question. Yet, the 2% to 3% figure used as a reference could apply almost equally to the percentage of tons moved in intercity movements, or the percentage of motor carrier miles that were accumulated on rail services. Further confusion was created by introducing the distance element. Intercity means a distance of 200 miles or more. Whereas piggyback, depending on a number of variables,

TABLE D-1

Various Forecasts of Intercity Freight for Year 2000

Source	:Tons x 10 <sup>6</sup>	:Ton-Miles x 10 <sup>9</sup>	:Approximate % <sup>1</sup>	
			:Increase Over 1982:	:Ton-Miles : Tons :
Seguin (28)	: --	: 4,400	: 69	: --
Faucett: (29)	:	:	:	:
For GNP of:	:	:	:	:
Low Growth	: 9,027.4	: 4,123.3	: 59	: 85
Medium Growth	:12,494.4	: 5,705.2	: 119	: 155
High Growth	:14,438.6	: 6,671.2	: 156	: 195
DRI (30)	: 6,700 (1995):	: --	: --	: 37
Argonne (22)	: --	: 4,705.5	: 81	: --

These estimates were made over the past five years.

<sup>1</sup> Based on 2,600 x 10<sup>9</sup> ton-miles and 4,893 x 10<sup>6</sup> tons in 1982, per references 28 and 30.

has a breakeven point of between 500 to 700 miles today. Compounding the matter is the lack of credible predictions for the percent of traffic piggyback may garner over the next 15 years. In fact, very few businesses, either manufacturing or transportation oriented, look much farther than 5 years ahead. The 19% piggyback figure means 19% of the freight moved over 700 miles. This is not a prediction. It means that, as of now, the majority of the fleets interviewed believe piggyback will achieve that percentage penetration of the market.

This study was not attempting to define what percentage of intercity freight will be hauled by rail intermodal fifteen years from now. It was trying to obtain a consensus regarding the order of magnitude of intermodal traffic. Instead of 19% we could have used 15%, or 25%. Regardless of the number used, (and intuitively the lower the percentage posed the greater the percentage of interviewees who would agree to piggyback reaching that level), the interviewees found such a magnitude plausible. Indeed many of them are using rail more and more in their operations.

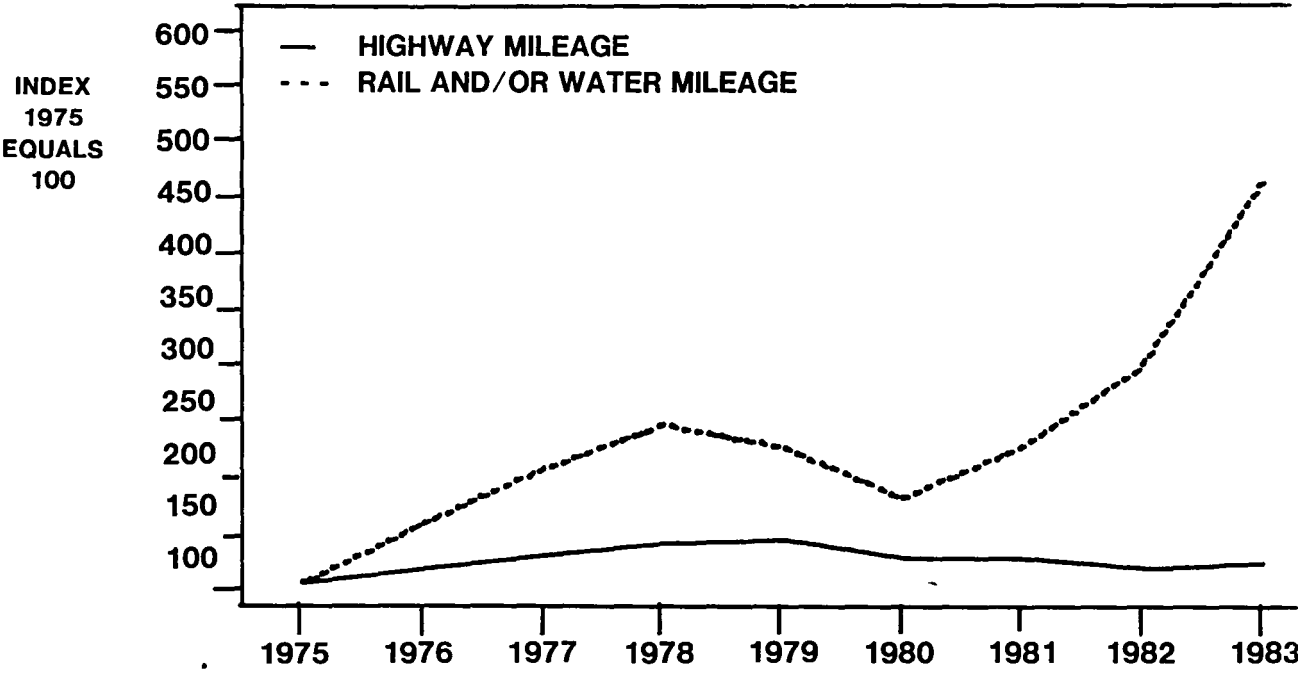
The following is what is known about piggyback:

1. It has grown faster than overall intercity freight, but still has captured on a relatively small share of its market potential (31). One source suggests that 4% of the eligible market in the 100-500 mile range; 14% of the eligible market

in the 500-900 mile range; and 23% of the eligible market in the over 900 mile range were actually covered by piggyback (32).

2. Piggyback carloadings, as a percentage of total carloadings increased from less than 6% in 1972 to 10.4% in 1982. In the same period total rail carloadings, excluding piggyback, fell from almost 25 million in 1972 to 18.5 million in 1982 (33).
3. General freight carrier use of rail has increased dramatically. Figure D-1 illustrates this in terms of an index with 1975 as the base year (34).
4. In 1982, class I railroads hauled 25.8% of the tons hauled in intercity traffic; and piggyback had 33% of that share, or 8.5% of the intercity tons (30). In 1995, class I railroads are predicted to have 28.1% of intercity tonnage and piggyback 3.8% of this share, or 10.6% of the intercity tonnage (30).
5. Labor is about 50% of carload cost and about 20% of truck-load costs (31).
6. For every 10% change in fuel prices truck costs change by 2 1/2% rail costs by 1% and TOFC by 1 1/2% (31).

GROWTH OF INTERMODAL VS HIGHWAY TRAVEL  
GENERAL FREIGHT CARRIERS: CHAIN LINK INDEX



SOURCE: REFERENCE 34

FIG. D-1

While few were willing to hazard predictions regarding the future piggyback share of intercity traffic a few indicators are appearing. In a survey of executives for 126 trucking companies the expectation is for piggyback traffic to increase 16% a year between 1983 and 1988 (35). If the 3.3% share in 1982 for piggyback, reported by reference 30, was increased by 16% for every year between 1983 and 1998 it would reach 33.6%. If increased by 10% per year it would reach 15% by 1998. Hence, 19% was taken as rough split of the difference between the 33.6% and 15% values.

3. Referring to question 3, the number of heavy duty (class 7 and 8) diesel intercity tractors, the reference used was a doubling of the number in service in 1979. Interviewees were told that some estimates placed the number of class 7 and 8 tractors at 2,500,000 to 3,500,000 by 1995-2000.

It is difficult to predict the number of tractors in a certain class because the base data are unknown. Most estimates of the truck population are based on results of the 1977 Truck Inventory and Use Survey (TIUS) carried out by the U.S. Bureau of the Census for the Department of Transportation. Trucks were randomly selected from each state's motor vehicle registration file as of July 1, 1977. Vehicles owned by Federal, State or Local governments were excluded.



Estimates of the number of combination vehicles, published by the Federal Highway Administration (FHWA) in its annual series, Highway Statistics, differ substantially from those derived from TIUS. A portion of this difference may be accounted for by straight trucks (not tractors) pulling trailers which FHWA included in their estimates. The TIUS data are also affected by non-response, misinterpretation of survey questions, or incomplete coverage of the list from which survey vehicles were selected. For example, an incomplete registration file provided by one state resulted in an underestimation of the number of tractor-trailer combinations in that state by 15,700.

The fact that two major sources of truck population data, TIUS and Highway Statistics, differ so significantly led to two other versions of the TIUS data being produced, one by the U.S. Department of Transportation's (DOT) Transportation Systems Center (TSC) and another by a DOT contractor, Systems Design Concepts, Inc. (SYDEC).

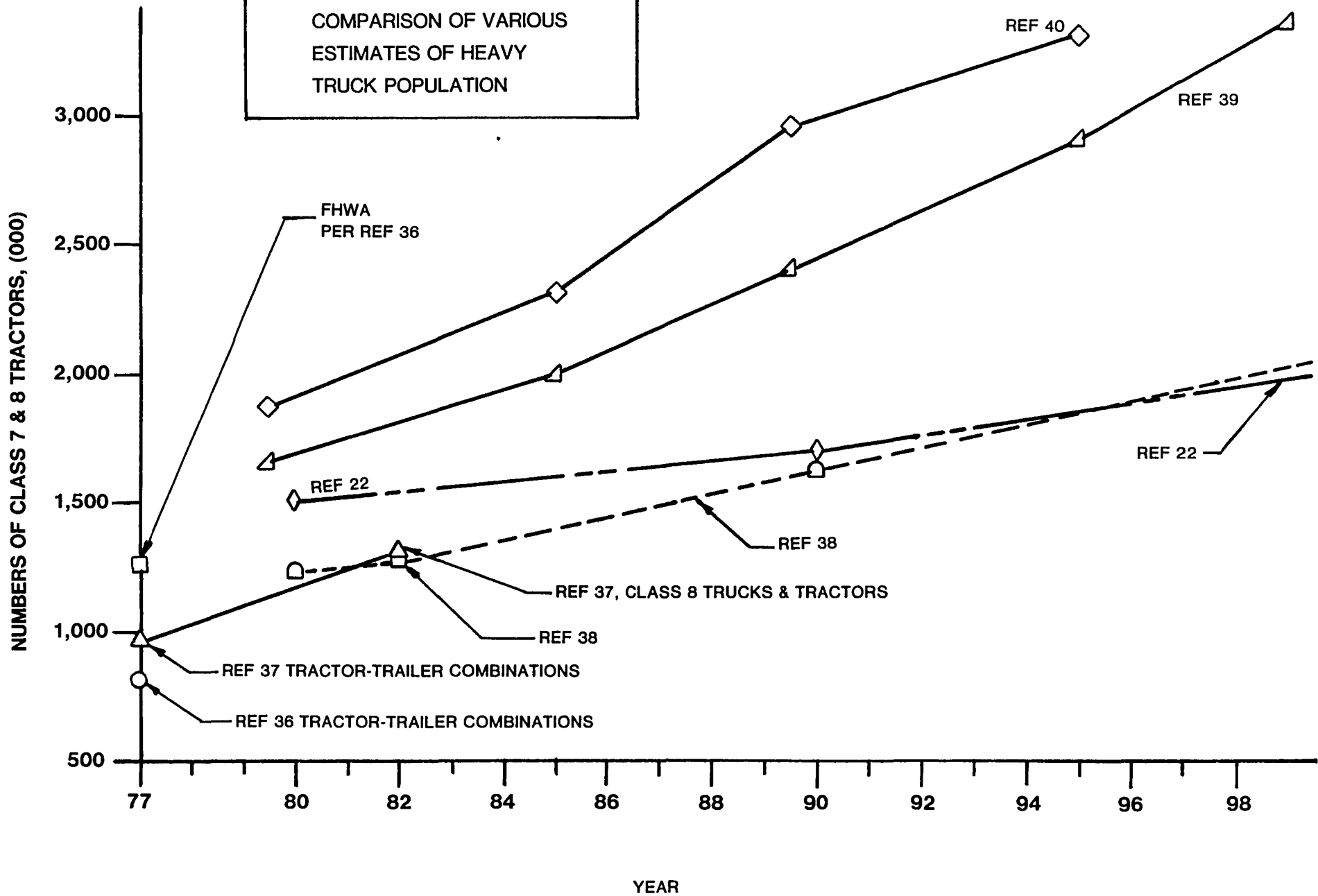
Hence, there are at least four versions of truck population derived from two major sources.

Several projections were placed on the same graph for comparative purposes. The starting point was the various interpretations based on the 1977 TIUS. This is Figure D-2. Also included is Table D-2, which in addition to providing a

population estimate for 1983, illustrates the confusion regarding the various interpretations of the 1977 TIUS. Referring to Figure D-2, it can be seen that 1979 numbers of tractors could range from 1,100,000 to a little over 1,300,000.

The ATA Engineering Department has used a 1982 figure of 1,500,000 class 7 and 8 tractors for other purposes. Based on the interviews (i.e. 1979 numbers would not double) the feeling is that the curve labeled reference 22 in Figure D-2 (Argonne National Laboratory) is realistic.

COMPARISON OF VARIOUS  
ESTIMATES OF HEAVY  
TRUCK POPULATION



**TABLE D-2**

**NATIONAL POPULATION ESTIMATES**

Straight Trucks<sup>1</sup> and Tractors

Truck Type	1977 TIU				1983 NTTIS <sup>3</sup>
	Census	TSC	SyDec	Eicher <sup>2</sup>	
Straight	2,505,870	2,523,400	2,883,703	4,447,700	1,691,022
Tractor	824,409	1,314,800	946,146	922,800	1,437,894
Total	3,330,279	3,838,200	3,829,849	5,370,500	3,128,916

<sup>1</sup> GVWR greater than 10,000 pounds

<sup>2</sup> J P Eicher, et al, **A Report to Congress on Large-Truck Accident Causation**, July 1982, DOT/HS 806 300

<sup>3</sup> Sampling frame totals for the NTTIS from R L Polk, November 27, 1984

## APPENDIX E

### Effect of EPA Emission Requirements

EPA regulations affect engines in two ways: (1), increasing their cost and, (2), increasing their BSFC. Before getting down to specifics the background of these regulations will be covered.

#### Clean Air Act Requirements

The Clean Air Act Amendments of 1977 created a heavy-duty vehicle (HDV) class of mobile sources of pollutants and established mandatory emissions reductions for that class. All vehicles over 6,000 lbs gross vehicle weight (GVW) were defined as "heavy duty" and required to achieve a 75-percent reduction in NOx emissions from uncontrolled levels of gasoline-fueled trucks effective with the 1985 model year.

With the 1979 model year, EPA expanded its standards for the light duty truck (LDT) class to 8,500 lbs GVW, thus defining the heavy-duty vehicle class as we now know it, as all vehicles over 8,500 lbs GVW.

#### New Emission Standards

The latest EPA proposal contains new NOx standards for heavy duty engines (HDEs) and new particulate standards for light-duty

diesel trucks (LDDTs) operated under high-altitude conditions and for heavy duty diesel engines (HDDEs) operated under both high and low altitude conditions. A two-staged NOx standard is proposed for HDDEs to allow for further development of control technology. The NOx standard for 1987-89 model year HDDEs is proposed at 6.0 g/BHP-hr, with a more stringent standard of 4.0 g/BHP-hr to be effective for 1990 and later model year engines.

A phased particulate standard is also proposed for HDDEs. Model year 1987-89 HDDEs operated under low-altitude conditions would meet a standard of 0.60 g/BHP-hr. For 1990 and later model years, low-altitude urban bus engines would comply with a proposed standard of 0.10 g/BHP-hr, while the remainder of the low-altitude HDDEs would meet a standard of 0.25 g/BHP-hr. Both of these proposed 1990 standards will require the use of trap oxidizers (discussed below) on diesel-fueled heavy-duty engines. According to the Agency, these standards represent the approximate lower limit of feasibility given the above-mentioned corresponding NOx standard. HDDEs operated under high-altitude conditions, including urban bus engines, would comply with standards of 0.72 g/BHP-hr in the 1987 model year and 0.30 g/BHP-hr (0.12 g/BHP-hr for urban buses) effective for 1990 and later model years. These proposed standards are summarized in Table E-1.

TABLE E-1

Proposed NOx and Particulate <sup>1</sup> Standards			
Effective Model Year	Vehicle Class	Applicable Standards	
		NOx	Particulate*
Low Altitude:			
1987	HDE	6.0 g/BHP-hr	0.6 g/BHP-hr
1990	HDE Urban Bus	4.0 g/BHP-hr	0.10 g/BHP-hr
	All Other	4.0 g/BHP-hr	0.25 g/BHP-hr
High Altitude:			
1987	HDE	6.0 g/BHP-hr	0.72 g/BHP-hr
1990	HDE	4.0 g/BHP-hr	0.30 g/BHP-hr
* Diesel-powered vehicles/engines only			
<sup>1</sup> <u>Federal Register</u> . "Control of Air Pollution From New Motor Vehicles and New Motor Vehicle Engines: Gaseous Emission Regulations for 1987 and Later Model Year Light-Duty Vehicles, Light-Duty Trucks, and Heavy-Duty Engines; Particulate Emission Regulations for 1987 and Later Model Year Heavy-Duty Diesel Engines" (49 FR 40258). October 15, 1984.			

## Dealing with Particulates

### Particulate Traps

The primary component of any system for the reduction of diesel particulate emissions is the trap oxidizer. In addition, other components are required to operate the system, with the specific requirements depending on the basic design used. A simple analogy to the trap oxidizer, because it is also an exhaust after treatment device, would be the catalytic converter commonly used on gasoline-fueled automobiles. The trap basically has two functions: (1) to filter and thus accumulate diesel particles from the exhaust stream; and, (2) burn off the collected particulate matter to remove it and reduce backpressure. The physical location of the trap may be either in the exhaust manifold or elsewhere in the exhaust stream, again much like the catalytic converter. Traps are also catalyzed or non-catalyzed according to the presence or absence of catalytic materials to aid in the oxidation (burning) of accumulated particulates.

A non catalyzed trap requires a regeneration system which injects diesel fuel into the exhaust stream near a sufficient heat source (the burner) just before it enters the trap. Burning the added fuel increases the exhaust temperature enough to ignite the accumulated particulate.



Catalyzed-trap requirements are, at this time, less clear since the system is extremely dependent on the type and location of the catalyst. While there is much uncertainty surrounding catalyzed systems, many different components are being studied as potential catalysts for particle oxidation, including some very toxic chemicals. These catalysts generally are either used as a coating on the trap (this method also usually requires some increase in exhaust temperature), injected into the exhaust stream, or introduced as part of the diesel fuel. Catalyzed traps avoid the extremely high and potentially unsafe exhaust temperatures required for the non-catalyzed systems - temperatures at or above 750° C (1300°F).

However, adiabatic engines could have exhaust temperatures approaching 1600°F. Even with partial adiabacity, exhaust temperatures rise roughly linearly with increasing percentage of adiabacity. An engine with 60% adiabacity would create exhaust temperatures of over 1300°F.(41) Also, an adiabatic engine should drastically reduce particulates because of the high combustion gas temperatures(11).

Some experience with emissions with advanced engines is given in Table E-2.

TABLE E-2

Advanced Engine Emission Experience Compared to EPA Standards						
EMISSION	TACOM/CUMMINS ADIABATIC ENGINE (11)	ENGINE INSULATED NH 450 TURBOCOMPOUND (41)	EPA g/BHP-hr			
			1987		1990	
			LOW ALTITUDE	HIGH ALTITUDE	LOW ALTITUDE	HIGH ALTITUDE
Particulates	< .01 mg/l (83% - 86% lower than conventional engine)		0.6	0.72	.25	.30
13 Mode BSNOx cycle (gms/hp-hr)	minimum 6  maximum 11	6  9	6	6	4	4
Hydrocarbons Gms/hp-hr		.25 - .4				

A review of statements made by individuals on the leading edge of trap oxidizer development and subsequent application to heavy-duty vehicles follows:(42)

1. No manufacturer of engines that would be used in Class VIII vehicles has indicated that traps will be available for these engines in 1990, and all but one remain skeptical as to their applicability in later model years.
2. One vehicle manufacturer (and future medium-duty diesel engine producer) believes traps may be ready by 1991 to meet a 0.25g particulate and a 4.0 g NOx standard, but at a cost of \$2,500 and a cumulative 13 percent fuel economy penalty. This company currently does not manufacture heavy-duty diesel engines for domestic use.
3. One manufacturer of medium and heavy-duty diesel engines has stated that it believes a trap standard of 0.40g/BHP-hr can be accomplished sometime after 1990 for medium-duty engines if the agency retains a 6.0 g NOx level for 1990 and later model year engines.
4. One manufacturer of class VIII vehicles/engines indicates that it may be able to meet a 0.25 trap standard after 1990 but only at a 6.0 g NOx standard.

The cost of the various types of traps and their effect on fuel economy are presented in table E-3.

### Dealing with Oxides of Nitrogen (NOx)

A wide variety of techniques, with varying degrees of success and effect on other engine parameters, are available to control NOx emissions in heavy-duty diesel engines including, but not limited to exhaust gas recirculation (EGR), electronic control of fuel injection timing, increased fuel injection pressure, and increased after-cooling. Ironically, most of these control techniques, with the notable exception of EGR, are used to increase engine fuel economy, but when they are used to control NOx, fuel efficiency is reduced dramatically. Figure E-1 illustrates the general relationship between NOx control and fuel use.

Table E-4 presents a compilation of expected fuel economy losses from the 1987 and 1990 proposed NOx and particulate emission standards.

Another way of determining fuel economy losses is in terms of no decrease in engine BSFC. Figure E-2 compares where total fleet fuel consumption will be under EPA's proposed 4.0g NOx standard to that of total fuel used by the fleet remaining at the current NOx standard. This analysis concludes that the total penalty is 15.5%. Figure E-3 presents the increase in fuel consumption in yet another manner. Here, increases are a function of NOx level as shown(43).

TABLE E-3(43)

Trap Cost and Effect on Fuel Economy				
Item	TYPE OF SYSTEM			
	Bypass-Burner Monolith	Additive/ Monolith	Catalytic Wire-Mesh	Silica "Candle"
Cost to Buyer, <sup>1</sup> \$	1,320	1,200	2,140	1,320
Maintenance Cost, \$ per mile	.001	.0005	.0002	.0005
Reduction in mpg due to trap, %	1.5	1	1	.75

<sup>1</sup> 100% allowance for Manufacturers and Dealers overhead and profit. Includes modification to vehicle.

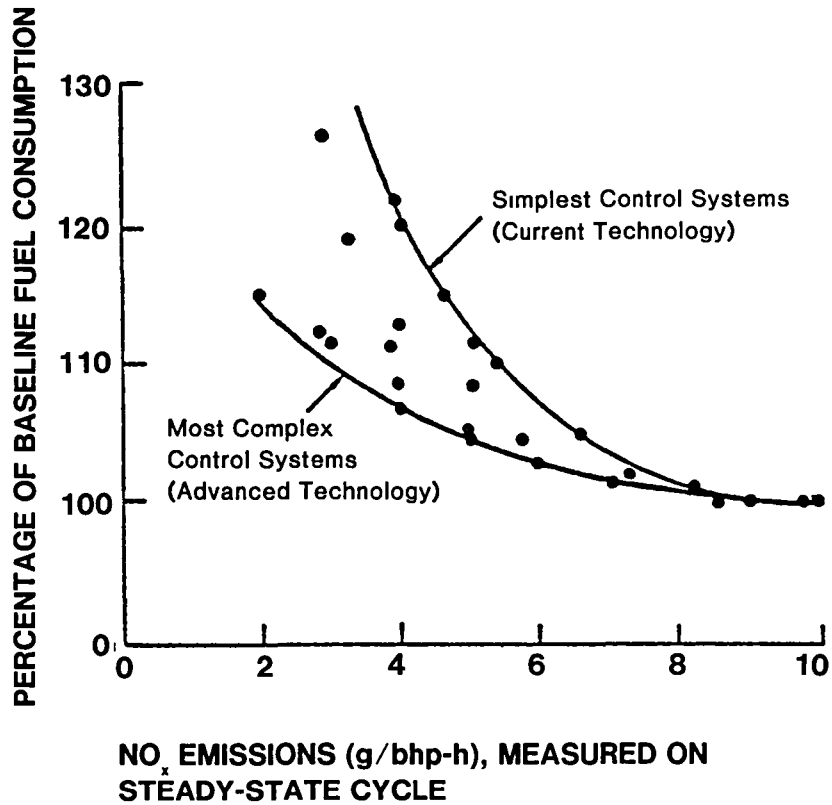


FIG. E-1

Fuel Consumption vs. NOx Emissions Level

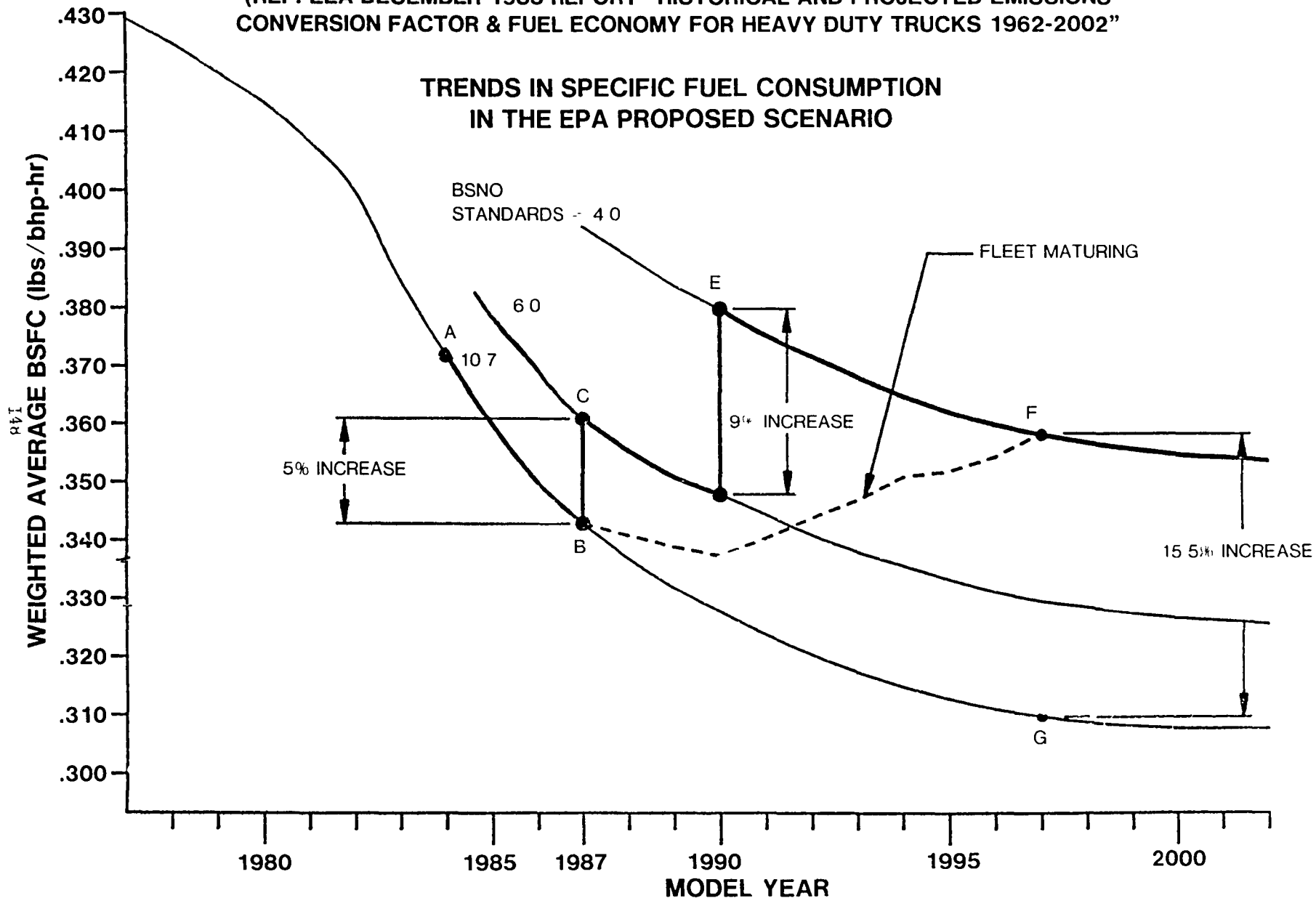
Source: "NOx Emission Controls for Heavy-Duty Vehicles: Toward meeting a 1986 Standard", Motor Vehicle Nitrogen Oxides Standard Committee, Assembly of Engineering, National Research Council, Washington, D.C. (1981).

TABLE E-4

Projected Heavy-Duty Diesel Engine Fuel Consumption Increases				
Source	Standards			
	1987 6.0 NOx, 0.6 Part (% increase)	1990 4.0 NOx, 0.25 Part (% increase)		
		NOx	Part	Total
Caterpillar		10	+ 0 - 2	10 - 12
Cummins		10	+ 0 - 2	10 - 12
Daimler-Benz	0	5		5
EPA	0 - 2	0 - 2	+ 0 - 2	0 - 4
FORD	6	7 - 13		7 - 13
GM	3 - 7	7 - 10	+ 0 - 2	7 - 12
IH	6.4 - 7.5	7 - 12	+ 0 - 2	7 - 14
MACK	4	9	+ 0 - 2	9 - 11
NAS		9 - 14	+ 0 - 2	9 - 16
ERC	<u>3.5 - 5.5</u>	<u>4 - 8</u>	+ <u>1 - 2.5</u>	<u>5 - 10.5</u>
	3.3 - 4.6	6.8 - 9.3	+ .1 - 2.4	6.9 - 11.0
	3 - 5	6 - 10	0 - 3	6 - 11

# EFFECT OF BSNO<sub>2</sub> STANDARD ON ENGINE FUEL CONSUMPTION

(REF. EEA DECEMBER 1983 REPORT "HISTORICAL AND PROJECTED EMISSIONS CONVERSION FACTOR & FUEL ECONOMY FOR HEAVY DUTY TRUCKS 1962-2002")



Source Preliminary Statement Statement of Mack Trucks, Inc Nov 13, 1984

FIG E-2



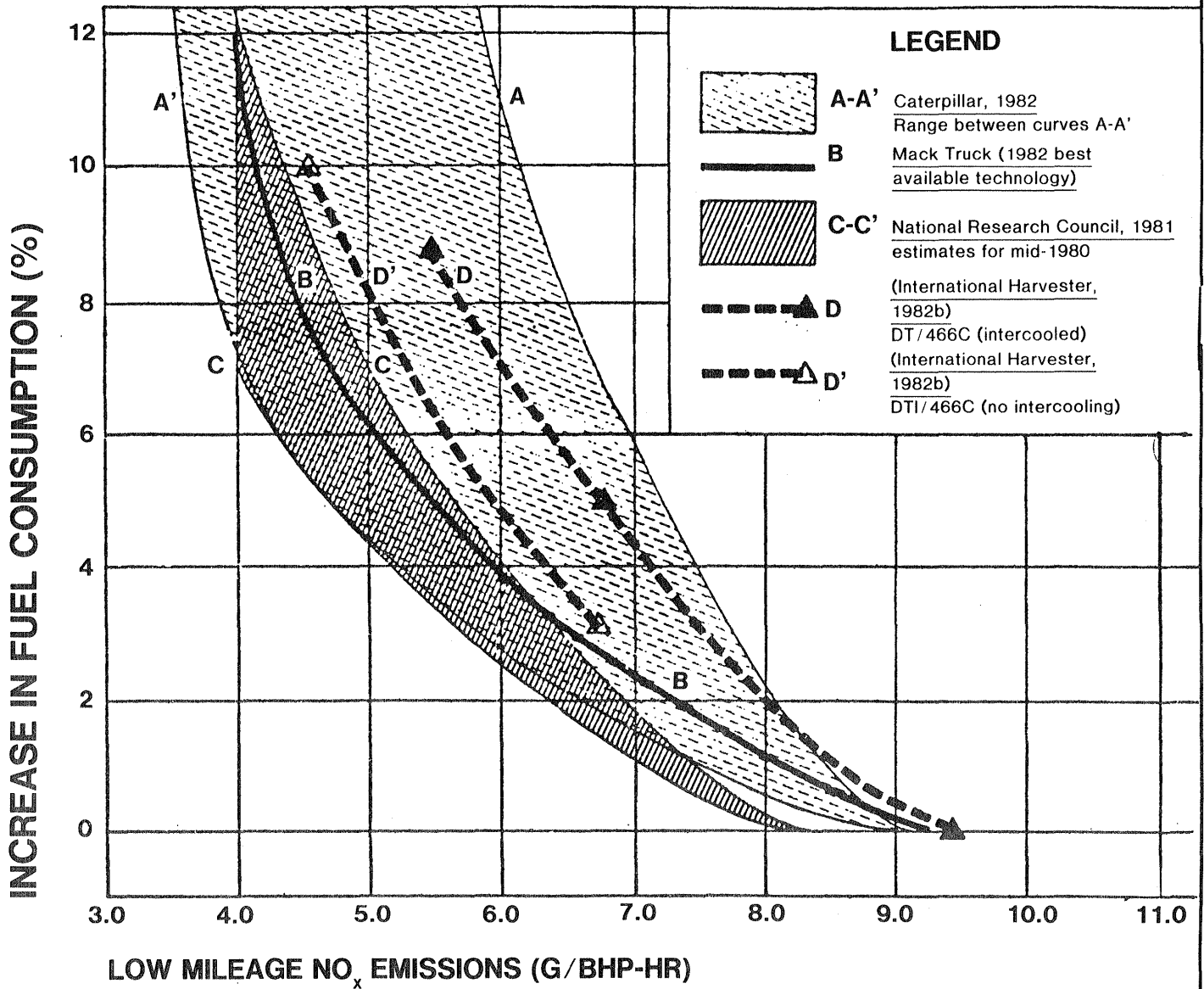


FIG. E-3: Relationship between NO<sub>x</sub> and fuel consumption (Near-term technology).

Per vehicle costs to meet a 4 gram NOx standard in the intermediate term are \$180 for the hardware, and a maintenance cost of \$0.0005 per mile (43).

## APPENDIX F

### Potential of Aerodynamic Improvements

Tractor trailer combinations are today achieving up to 8 and 10 mpg with the rudimentary aerodynamic treatments they are receiving. Engine developments promising to decrease specific fuel consumption may be made ineffective by future EPA emission standards. The one sure way, since it accounts for approximately half the power required at cruising speeds, to obtain substantial future improvements in fuel economy, is to reduce the power required to overcome air drag. Currently, this is done by adding devices to the cab and trailer nose to prevent flow separation (pressure drag results from flow separation). However, this approach works fully only when the airflow is directly into the front face of the vehicle. In crosswinds the performance of add on devices is greatly reduced, because the flow separates from the downwind side of the vehicle.

The purpose of the analysis in this appendix is to compare what could be achieved if an integrated combination vehicle design for low drag is used, as opposed to the limited gains (albeit substantial compared to no add-on devices) to be gotten using add-on aerodynamic devices.

This is not meant to be an exhaustive study. It is meant to point out the possibilities and provide the basis for determining possible future vehicle fuel economy gains, even in the face of upcoming emission requirements which will virtually wipe out any fuel economy gains from future engines.

The quickest and simplest way to go about this investigation is to construct a table, F-1 which gives the wind averaged drag coefficient ( $\bar{C}_D$ ) reduction due to various changes to the vehicle shape. Add-ons, such as cab mounted air deflectors, are not included, although modifications 3, 4, and 5 could be considered such, because we are investigating improvements designed into the vehicle, such as the Fruehauf FEV 2000. Boundary layer control, modification 10, has been demonstrated to prevent flow separation in crosswinds. This flow separation causes high drag. In preliminary tests (50) boundary layer control was found to be an effective means for reducing this drag. In fact, drag due to cross flow appeared to be eliminated. If this drag can be eliminated then the vehicle's drag will never exceed the  $0^\circ$  yaw case. Theoretically, this is achievable, but there are some costs associated with the blowing or suction of air to control the boundary layer.

TABLE F-1

Drag Reduction Due To Various Vehicle Modifications  
(Wind Averaged Except as Noted)

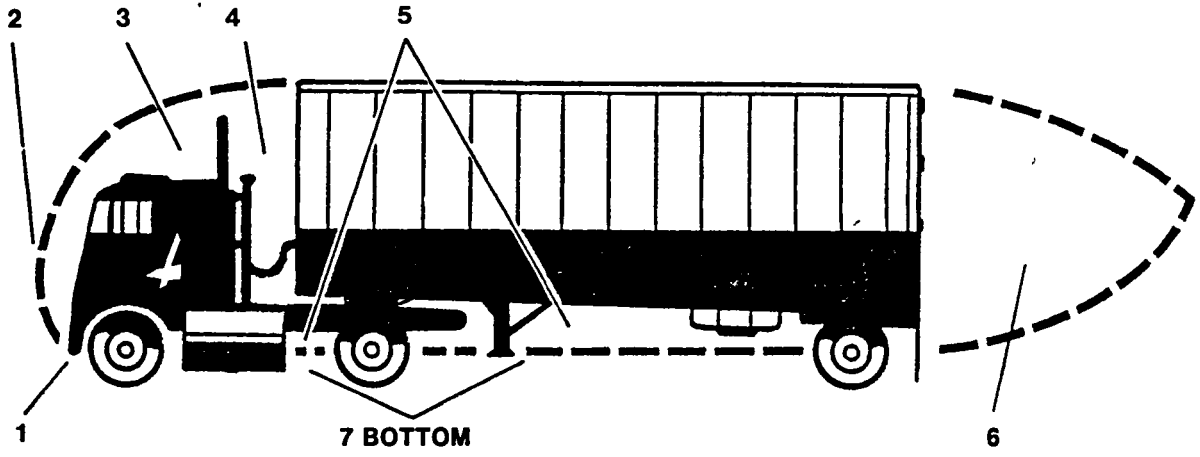
<u>Modification</u>	<u>% Decrease</u>	<u>Source</u>
1. Rounding Cab Nose	6 - 7	Fig. F-1(44) Fig. F-2(45)
2. Rounding Cab Top	8 - 9	"
3. Enclosing Tractor Trailer Gap	16 - 17	"
4. Extend Sides of Trailer Closer to Ground	18 - 19	"
5. Boattail Rear of Trailer	9 - 10	"
6. Enclose Bottom of Cab & Trailer	5	Fig. F-1 <sup>1</sup>
7. Ducted Trailer <sup>2</sup>	46.5	Ref. 46
8. Variation of 1 through 4 plus 6 above	64 <sup>3</sup>	Ref. 47
9. Cooling Air Flow <sup>4</sup>	6.5	Ref. 48
10. Boundary Layer Control	—	Ref. 50

<sup>1</sup> This is a controversial modification as some tests show little or no improvement in  $C_D$ . According to Ref. 49, there should be improvement as there is substantial improvement with automobiles.

<sup>2</sup> This was not wind averaged, but ducted configuration performance is independent of yaw angle since it will still add mass to the wake.

<sup>3</sup> Not wind averaged.

<sup>4</sup> This has to do with controlling internal airflow, the flow through the radiator and out of the engine compartment. The % reduction is for passenger cars. Internal flow generates a  $C_D$  of 0.4 based on the frontal area of the radiator core (49).



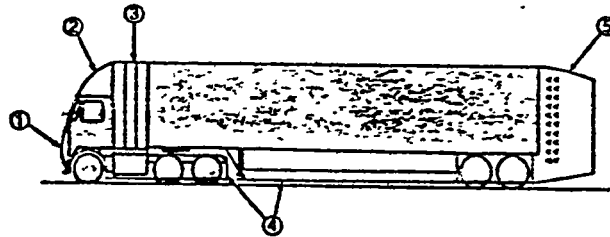
**Percent Change in Drag Coefficient by Configuration Changes (Wind Tunnel Data)**

Configuration		Drag			
		Zero		Wind averaged	
Part Modified	Number	Incremental Decrease	Cumulative Decrease	Incremental Decrease	Cumulative Decrease
Baseline	1	---	---	---	---
Cab nose	2	4.8%	4.8%	7%	7%
Cab top	3	15.7%	20.5%	9%	16%
Gap enclosed (Top and sides)	4	19.7%	40.2%*	17%	33%*
Lower side	5	8.7%	48.9%	19%	52%
Boattail	6	4.8%	53.7%	10%	62%
Bottom (Cab and trailer)	7	5.9%	59.6%	5%	67%

\* Cumulative reduction in the drag coefficient for a full-scale low drag truck (Configuration 4) was approximately 37% at near zero wind conditions and 55 mph.

**FIG. F-1**

## ANTICIPATED AERODYNAMIC RESULTS



AERODYNAMIC TREATMENT	% DRAG REDUCTION OVER BASE VEHICLE
None (Base Vehicle)	—
1 Front of Cab	6%
2 Fairing	8%
3 Gap Seal	16%
4 Skirting	18%
5 Boatall	9%
<b>TOTAL</b>	<b>57%</b>

FIG. F-2

There are certain aspects of the integrated design (modifications 1 through 6 of Table F-1) that may be difficult to implement. These are the boattail at the rear of the trailer and the closing in of the bottom of the vehicle. Trailer boattail may only be feasible to the degree shown in Figure F-2 (the Fruehaut design) rather than the fuller design tested by NASA (Figure F-1).

"Belly pans" covering the underside of tractors and trailers are thought to hamper maintenance. However, partial covering of the underside may be possible. Quick and easy removal of these panels for maintenance access should be a straight forward design challenge.

Data from Table F-1 was used to "construct" several vehicle configurations indicated in Table F-5, which could be available by 2000. These configurations were ranked in order of increasing degree of sophistication and drag reduction. There are obviously other combinations of drag reduction devices and techniques that can be devised. Since one of the configurations will be representative of current aerodynamically advanced combination vehicles its drag coefficient has to be determined. Using data from reference 51, and adding drag reductions, Table F-4 is developed.



TABLE F-4

Approximate Reduction in Drag For Current  
Advanced Tractor-Trailer Combination (51)

<u>Add-on</u>	<u><math>\Delta \bar{C}_D</math></u>
Air Deflector	0.15
Rounding Front Edge of Tractor <sup>1</sup>	0.06
Rear Extenders on Cab	0.08
Front Face Fairing on Trailer	0.16
Side Skirts on Trailer <sup>2</sup>	<u>0.07</u>
Total Reduction	0.52

<sup>1</sup> Not an add-on but included because most new tractors are being produced this way.

<sup>2</sup> While not an option available from manufacturers they are easy to implement. Certain van trailers, i.e., household goods vans, in effect have them by virtue of their design for high volume capacity.

The wind averaged drag coefficient of a tractor-semitrailer without any aerodynamic devices is taken as 1.116 (51).

Hence, the drag coefficient of the current advanced combination vehicle is estimated to be  $1.116 - 0.52 = 0.596$

TABLE F-5

<u>Possible Future Vehicle Configurations and Drag Coefficients</u>		
<u>Configuration</u>	<u><math>\overline{C}_D</math></u>	<u><math>\Delta\overline{C}_D</math></u>
1. Baseline Configuration No Aerodynamic devices	1.116	--
2. Current Advanced Aerodynamic Treatment (Table F-4)	0.596	0.520
3. Integral Design <sup>1</sup> Practical Today (Fig. F-2)	0.407	0.709
4. Advanced Integral Design <sup>2</sup> (3 above + greater boattail + belly Pans)	0.296	0.820
5. Blue Sky <sup>3</sup> 5 above + B.L. Control	0.26	0.720

<sup>1</sup> Baseline minus 57% per Figure F-2; minus 6.5% item 9, Table F-1.

<sup>2</sup> Baseline minus 67% per Figure F-1; minus 6.5%, item 9, Table F-1.

<sup>3</sup> Calculated by taking 0° yaw  $C_D = .98$  for baseline configuration and deducting 67% + 6.5%.

It should be noted that the drag coefficient of future combination vehicles has been estimated to possibly reach 0.3 by designing the tractor-trailer as an integrated vehicle(51).

To illustrate what these lowered drag coefficients can mean in terms of fuel economy the horsepower required for the various configurations of Table F-5 will be calculated along with the mpg each combination would achieve as a function of BSFC and drag coefficient. Combined rolling friction and air drag power required is:

$$P_r = \frac{\left[ \frac{W \times \text{mph} \times (C_R + R_S)}{375,000} + \frac{C_D \times A \times (\text{mph})^3}{157,029} \right]}{E} \quad (52)$$

Where:  $P_r$  = Road Load HP (to overcome rolling resistance and air drag)

W = Vehicle gross weight, use 80,000 lb

mph = Vehicle speed, mph

$C_R$  = Tire Rolling Resistance factor, use 5.76 for radial ply tires

$R_S$  = Road Surface Factor, use 0 for typical highways

$C_D$  = Vehicle Drag Coefficient

A = Vehicle Frontal Area, sq. ft. use 102 sq. ft.

E = Driveline Mechanical Efficiency, use 0.86 for vehicles over 35,000lb

Grade horsepower was not considered but 4 hp was added for accessories (52).

Calculating with the values given for the various parameters:

$$P + \text{Accessory Power} = 78.6 + 125.6 C_D + 4 = 208 C_D$$

Fuel economy, in miles per gallon, is calculated from:

$$\text{mpg} = \frac{\text{Fuel density} \times \text{mph}}{\text{HP} \times \text{BSFC}}$$

- Fuel density taken as 7 lb/gal
- mph = 55
- BSFC is taken from the engines' fuel map.

A fuel map for the advanced turbocompound engine (Table 4) is in reference 15. This engine's BSFC is projected to decrease from 0.31 to 0.305 in 2000, a decrease of 1.6%. Hence, it is safe to use the fuel map in reference 15 to approximate the 2000 engine. No fuel map for the future engine with the best BSFC, the adiabatic turbocompound

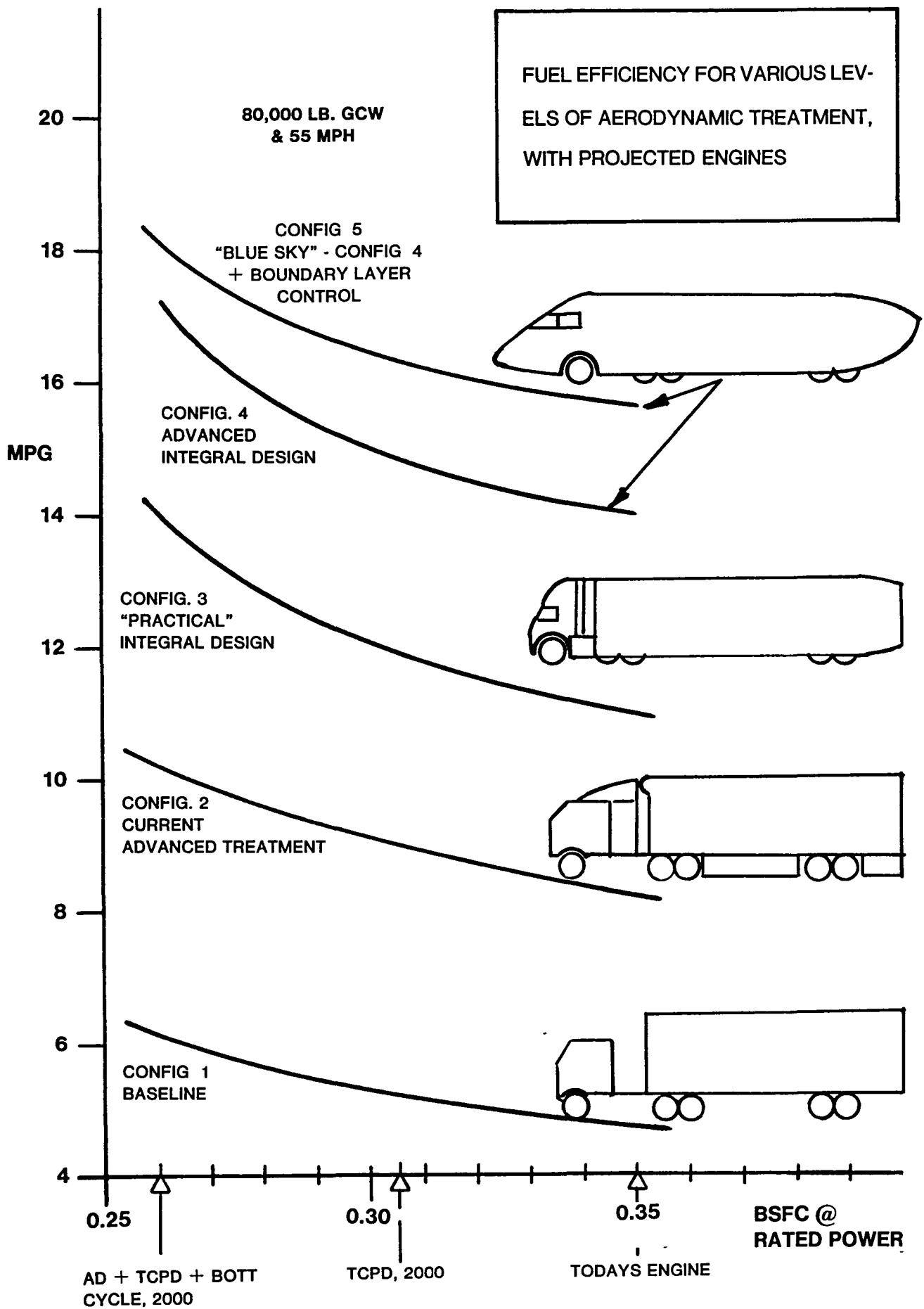
with bottoming cycle could be found. Therefore, since its level of fuel consumption is:

$$\frac{.305 - .26}{.305} = .148$$

of the turbocompound engine the fuel map values in reference 15 decreased by 15% can be used. For an engine representative of today's, as the baseline case, the fuel map for the 3306 DITA engine (53) was used.

The results of these calculations are plotted in Figure F-3 as a function of engine BSFC at rated power (which is a number easier to find) and vehicle configuration. These results do not reflect the benefits which could accrue from electronic engine controls or innovations in tires.

The indications are, that with no improvement in the BSFC of today's engines, fuel economy could be increased 25% by going from today's advanced aerodynamic treatments to a practical integrated design, which has already taken to the road.



**FIG. F-3**

1 Report No <b>NASA CR-174996</b>		2 Government Accession No		3 Recipient's Catalog No	
4 Title and Subtitle <b>Future Heavy Duty Trucking Engine Requirements</b>				5 Report Date <b>March 1985</b>	
				6 Performing Organization Code	
7 Author(s) <b>Larry W. Strawhorn and Victor A. Suski</b>				8 Performing Organization Report No	
				10 Work Unit No	
9 Performing Organization Name and Address <b>American Trucking Associations, Inc, 2200 Mill Road Alexandria, Virginia 22314</b>				11 Contract or Grant No <b>NAG 3-457</b>	
				13 Type of Report and Period Covered <b>Contractor Report</b>	
12 Sponsoring Agency Name and Address <b>U.S. Department of Energy Office of Vehicle and Engine R&amp;D Washington, D.C. 20585</b>				14 Sponsoring Agency Code Report No. <b>DOE/NASA/0457-1</b>	
				15 Supplementary Notes <b>Final report. Prepared under Interagency Agreement DE-AI01-80CS50194. Project Manager, James C. Wood, Propulsion System Division, NASA Lewis Research Center, Cleveland, Ohio 44135.</b>	
16 Abstract <p>Developers of advanced heavy duty diesel engines are engaged in probing the opportunities presented by new materials and techniques. This process is technology driven, but there is neither assurance that the eventual users of the engines so developed will be comfortable with them nor, indeed, that those consumers will continue to exist in either the same form, or numbers as they do today. To ensure maximum payoff of research dollars, the equipment development process must consider user needs. This study defines motor carrier concerns, cost tolerances, and the engine parameters which match the future projected industry needs. The approach taken to do that will be explained and the results presented. The material to be given came basically from a survey of motor carrier fleets. It provides indications of the role of heavy duty vehicles in the 1998 period and their desired maintenance and engine performance parameters.</p>					
17 Key Words (Suggested by Author(s)) <b>Trucking; Engines; Heavy duty diesel engines; Fuel economy</b>			18 Distribution Statement <b>Unclassified - unlimited STAR Category 85 DOE Category UC-96</b>		
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**End of Document**