# ANALYSIS OF HEAVY DUTY TRUCK FUEL EFFICIENCY TO 2001

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# 1. INTRODUCTION

Heavy-duty trucks are an increasingly important source of carbon dioxide emissions, since the rate of growth of fuel consumption has been substantially higher than for other on-highway transportation sectors. Currently, heavy-duty trucks, defined by EPA as all trucks with a gross vehicle weight (GVW) greater than 8500 lb, account for about 28 percent of total on-highway fuel consumption. As a result, there is considerable interest regarding this market segment's future fuel consumption. The EPA's interest lies in identifying areas where there is scope for the implementation of policies to reduce fuel consumption without changing the level of service provided by the trucking industry.

Unlike the light-duty segments of the fleet, there is no standardized measure of fuel economy for heavy-duty trucks. The only reliable source of information on truck fuel economy is the Truck Industry and Use Survey (TIUS). This survey is conducted by census once every five years and the 1987 TIUS, conducted in calendar year 1988, is the most recent publicly available version. The TIUS was analyzed to establish historical values of fuel economy and fuel economy improvement The TIUS also contains a wealth of other data on truck annual use, scrappage, distribution by weight class and body style, etc all of which are relevant to a fuel economy study. The analysis of TIUS data and the results are documented in Section 2

Truck fuel economy is more accurately measured in terms of ton-miles of payload carried per gallon, which is affected by operational and technological factors. Operational factors that affect fuel productivity include average payload weight, empty backhaul, and maximum allowable size and weight. All of these issues have become important, since the competitiveness of the trucking industry not only depends on truck technology but also on operational factors. Two factors - empty backhaul and maximum allowable size/weight are analyzed in Section 3. This analysis relies on TIUS data as well as on information obtained from the American Trucking Association and other organizations about the operational characteristics of heavy-duty trucks.

Truck technology is also a major force in improving truck fuel productivity. The advent of stringent new emission standards has created the argument that future technological benefits to increase fuel efficiency may counterbalance the negative effects of emission standards and, thus, that an increase in fuel productivity may not take place. A detailed analysis of all of the technological improvements likely to occur over the next decade is provided in Section 4. Data for this Section were developed from interviews with major U.S. and European manufacturers of trucks and truck engines (European manufacturers have recently acquired major U.S. truck manufacturers). Even in the absence of any regulatory incentives, EEA's analysis shows that truck fuel economy will continue to improve, at least at the historical rate

# 2. HEAVY-DUTY TRUCK FLEET CHARACTERISTICS

## 2.1 INTRODUCTION

The term "heavy-duty" truck encompasses a wide range of weights and operating characteristics of trucks used in on-highway operations. Trucks with a Gross Vehicle Weight (GVW) higher than 8,500 lbs are considered by EPA as heavy-duty. This rating gives the low end of the heavy-duty GVW spectrum, while the maximum rating allowed for on-highway tractor-trailers is 80,000 lbs. Industry, on the other hand, classifies the market differently. Until recently, all trucks with a GVW rating of 10,000 lbs or less were regarded as light-duty. However, this definition has changed to include trucks with a GVW rating to 14,000 lbs, as premium versions of models rated above 10,000 lbs have been introduced in the 10,000 to 14,000 GVW range. In industry terms, this range is referred to as Class 3, and is a new market where few trucks were sold previously Trucks in Class 4 (14,001 to 16,000 lbs) and Class 5 (16,001 to 19,500 lbs) were also limited in sales until recently

Trucks in Class 6 (19,500 to 26,000 lbs) and Class 7 (26,000 to 33,000 lbs) are typically referred to by industry as medium-heavy-duty trucks. Class 8 trucks include those trucks with GVW ratings between 33,000 and 80,000 lbs. However, the lower weight range of Class 8 trucks shares many of the characteristics of medium-heavy-duty trucks To assure that these common vehicle characteristics are accounted for, EEA found it necessary to disaggregate Class 8 into two sub-categories. Class 8A includes those trucks with GVW ratings from 33,001 to 60,000 lbs, and Class 8B refers to those trucks with GVW ratings from 60,001 to 80,000 lbs. Class 8A trucks are also considered to be medium-heavy-duty, or 'super-mediums' in industry terms, while trucks in Class 8B are referred to as heavy-heavy-duty

This section presents fleet characterization data for the medium-heavy-duty and heavy-heavy-duty truck markets (i.e, Classes 6 to 8B). Such data analysis is integral in understanding technological and policy effects on fuel efficiency. Technological innovations influence truck classes differently, while policy may only affect a certain subset of the heavy-duty truck fleet. It is, therefore, important to characterize the physical and operational characteristics of each GVW class independently. Section 2.2 describes data used in this analysis. Section 2.3 describes physical and operational characteristics of the heavy-duty truck fleet.

## 2.2 DATA USED IN THE ANALYSIS

This study uses data from the 1987 Truck Inventory and Use Survey (TIUS) The TIUS is conducted every five years by the Bureau of Census, and is the only publicly available survey providing data on the physical and operational characteristics of the nation's truck population. It is based on a probability sample of private and commercial trucks registered in each state during 1987. However, vehicles which are owned by federal, state and local governments are excluded from the sample universe, as well as ambulances, buses, motor homes, and farm tractors.

The TIUS data base consists of 104,606 records and approximately 200 variables that describe the characteristics of each truck in the sample universe. To assure that the analysis recognizes differences between physical and operational characteristics across the in-use truck fleet, EEA devised a data clean-up and accuracy check routine. This routine classified each truck to its corresponding industry weight class

The TIUS data clean-up process involved three steps. First, some trucks were re-assigned to different GVW classes A preliminary screening of the data revealed that a number of trucks reported maximum loads well outside the appropriate range of the TIUS assigned GVW category A set of re-classification rules were developed to re-assign these vehicles to the correct category. These rules were based on available information regarding a truck's make, fuel type, fuel economy, engine size, horsepower, number of cylinders, and maximum loaded weight. A total of 7,212 trucks were assigned to different GVW categories on the basis of these rules Second, engine and performance parameters were compared for each truck to the expected range of values for the appropriate GVW category. Reported values for make, fuel type, fuel economy, engine size, horsepower, number of cylinders, and maximum loaded weight were compared to expected values (or ranges) for the truck's appropriate GVW category. An 'exception' score was kept for each truck. Every out-of-the-expected-range value added 1.0 to this score. If a truck did not report a value for some parameter, the score was incremented by 0.5. Third, trucks with 'exception' scores of 2.0 or greater were eliminated from the data set. A total of 6,661 trucks were eliminated on this basis. Trucks with 'exception' scores of 1.5 or less were accepted in the cleaned data set There were 18,545 trucks (out of 97,945) in the cleaned data base that had 'exception' scores of 1.5 or less. The majority of these trucks simply exhibited missing values for engine size, horsepower, or weight.

This clean-up procedure resulted with the following truck distribution by GVW class

| CLASS | GVW | Sample Size |
|---|---|---|
| 1 | 6,000 or less | 31,367 |
| 2 | 6,001 to 10,000 | 10,895 |
| 3 | 10,000 to 14,000 | 3,334 |
| 4 | 14,001 to 16,000 | 1,768 |
| 5 | 16,001 to 19,500 | 1,934 |
| 6 | 19,501 to 26,000 | 8,927 |
| 7 | 26,001 to 33,000 | 5,251 |
| 8A | 33,001 to 60,000 | 12,415 |
| 8B | 60,001 to 80,000 | 20,521 |

The small samples for Classes 4 and 5 verify low sales volumes in this market. Although this market is technically recognized by industry to be part of the heavy-duty truck market, the fact that only 5% of all heavy-duty trucks are light-heavy-duty trucks allows for analytical emphasis on the heavier populations. Therefore, EEA disregards Classes 4 and 5 from the analysis, as well as light-duty vehicles (i.e , Classes 1, 2, and 3). Finally, 1,533 trucks were found to typically operate beyond 80,000 lbs. These trucks do not posses consistent physical and operational characteristics, so they were also disregarded from most of the analysis.

## 2.3 CHARACTERISTICS OF HEAVY-DUTY TRUCKS

Class specific physical and operational characteristics are important in determining the policy and technological options that best improve fuel efficiency. The physical characteristics of a given truck include, among other things, the truck's engine type (i.e., gasoline, diesel, LPG, or other), engine size, and horsepower rating. Table 2-1 demonstrates the distribution of trucks by engine type and GVW class. Over 50% of trucks in Class 6 and Class 7 are propelled by gasoline. In contrast, only 20.5% of trucks in Class 8A have gasoline engines, while all trucks in Class 8B have diesel engines. This suggests that diesel engine improvements, such as electronic fuel injection timing control and improved intake and exhaust porting, will have significant effects on the average fuel efficiency of Class 8A and Class 8B trucks, but more modest effects on Class 6 or 7 trucks. However, sales data in Table 2-2 shows that diesel penetration has increased markedly in these classes. In 1980, 24.4% and 62.2% of new sales in Classes 6 and 7, respectively, consisted of diesel powered trucks. By 1990, diesel sales percentages had increased to 71.05% for Class 6 and 81.55% for Class 7, and a shift away from Class 6 trucks to Class 7 and Class 8A trucks has taken place Similarly, Class 8A is slowly being fully dieselized, while Class 8B has been completely dieselized since the mid-1970's, as it exclusively consists of line-haul trucks.

Trends in engine size and horsepower ratings can help to explain changes in average fuel efficiencies across GVW classes. Figure 2-1 shows average engine size (CID) for gasoline trucks by GVW class and vintage. For virtually all classes, no significant changes have taken place in average CID. The small dip in Class 8A trucks during model years 1982 to 1984 reflect the fact that Navistar, the maker of the largest gasoline engines in the early 1980's, exited that market. Similar data analysis for diesel trucks also showed no significant engine size trends in any of the GVW classes.

Figure 2-2 shows average horsepower by GVW class and vintage for diesel trucks There is a contention in industry that during the 1980s diesel engine horsepower ratings had steadily increased, especially in the heavier truck

**TABLE 2-1**

**DISTRIBUTION OF TRUCKS BY**

**ENGINE TYPE AND GVW CLASS**

| GVW Class | % Gasoline | % Diesel | % LPG | % Other[1] |
|---|---|---|---|---|
| Class 6 | 68.8 | 30.4 | 0.6 | 0.2 |
| Class 7 | 52.9 | 46.4 | 0.5 | 0.2 |
| Class 8A | 20.5 | 79.3 | 0 1 | 0.1 |
| Class 8B | 0.0 | 100.0 | 0.0 | 0.0 |

---

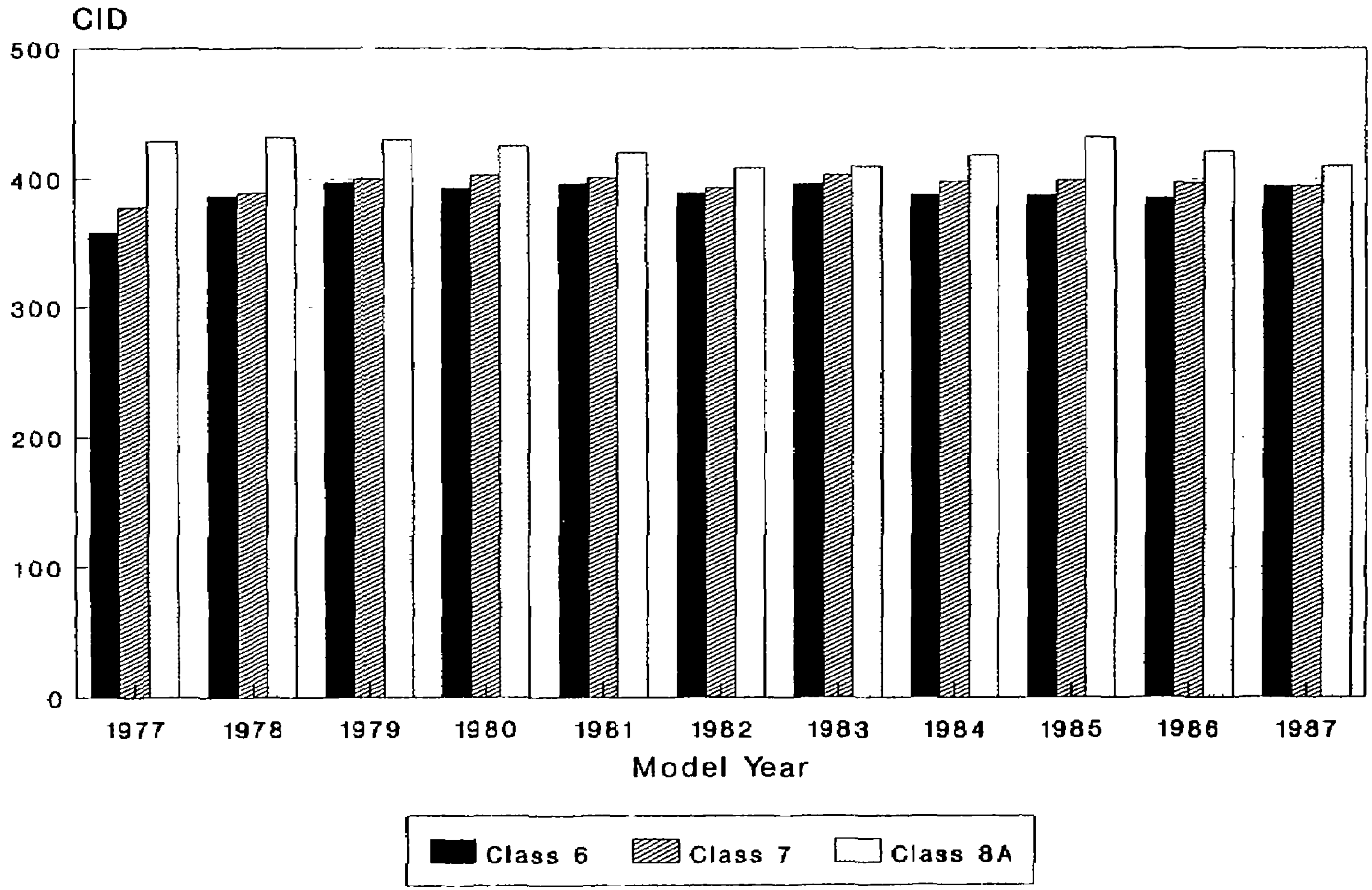
[1] Other includes those trucks for which engine type was unknown.

TABLE 2-2

SALES AND DIESEL PENETRATIONS
BY CLASS

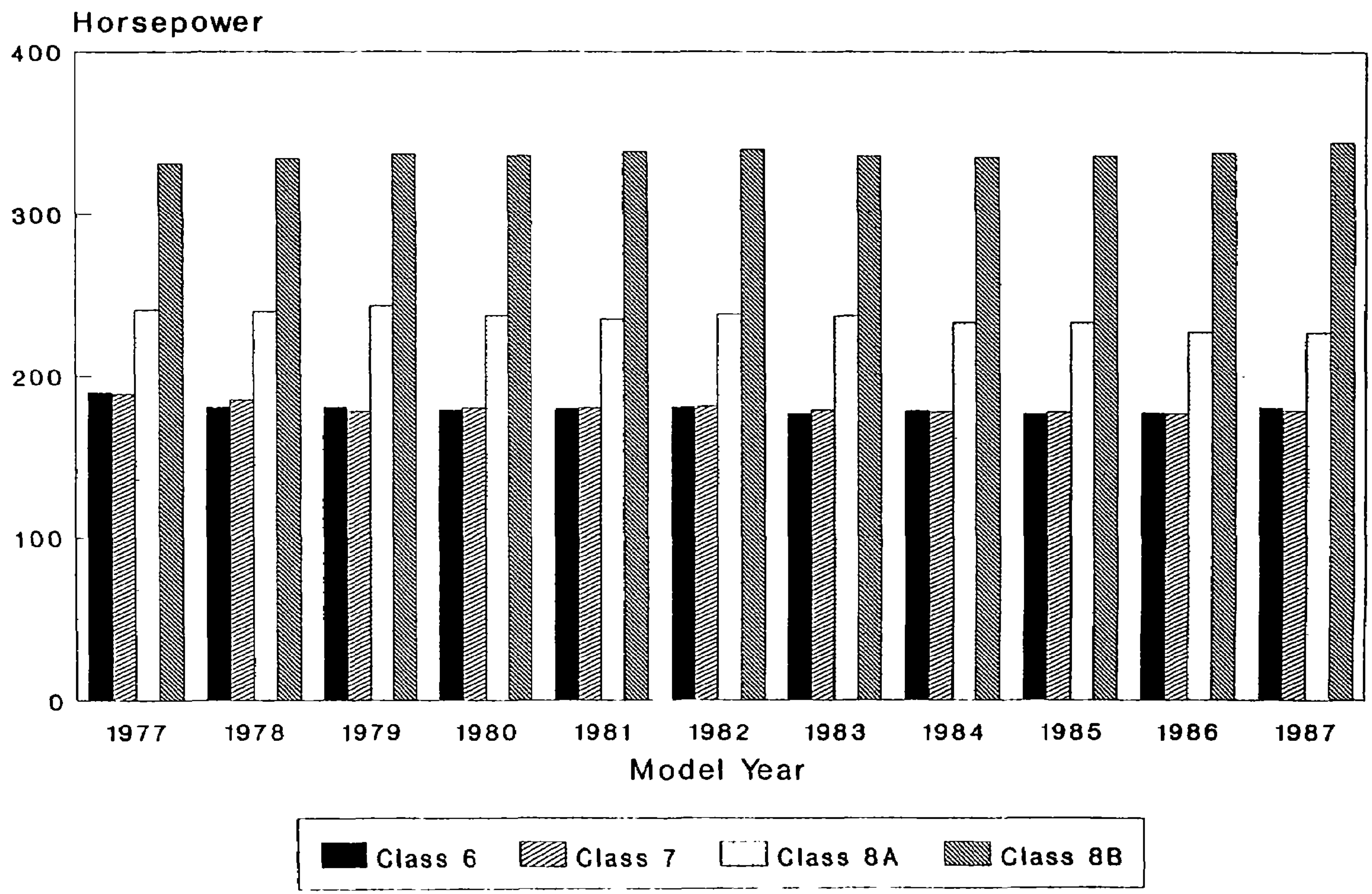
| | 1980 | | 1990 | |
|---|---|---|---|---|
| GVW Class | Sales | % Diesel | Sales | % Diesel |
| Class 5 | 1,860 | - | 1,726 | - |
| Class 6 | 51,170 | 24.4 | 17,687 | 71 05 |
| Class 7 | 54,360 | 62.2 | 61,010 | 81.55 |
| Class 8A | 10,400 | 74.5 | 11,981 | 99 70 |
| Class 8B | 93,490 | 100.0 | 122,181 | 100.0 |
| Buses | - | - | 32,731 | 78.2 |

FIGURE 2-1
Average CID By Vintage and GVW Class
Gasoline Trucks




Model Year 1977 includes 1977 and Pre-1977 models

# FIGURE 2-2
## Average Horsepower By Vintage and GVW Class (Diesel Trucks)




Model Year 1977 Includes 1977 and
Pre-1977 models

classes However, Figure 2-2 does not support this conjecture. No trends in average horsepower ratings are apparent in any of the GVW classes. The reader is cautioned that TIUS data on engine size and horsepower does not specify each truck's actual engine size or horsepower rating. Rather, the survey asks the responder to classify the truck into engine size and horsepower ranges that are provided by TIUS. The data shown in Figures 2-1 and 2-2 describe the average of the midpoints of the range for each vehicle in a given GVW category.

Besides engine size and horsepower, other physical attributes impact a truck's fuel efficiency. For example, fuel economy options like aerodynamic drag reduction devices, engines with low RPM, high torque rise, turbocharger, variable fan drives, radial tires, or axle/drive ratios that maximize fuel economy have important effects on average fuel consumption rates across truck classes. Table 2-3 presents the penetration rates of these fuel economy options by GVW class/engine type combination. The penetration of aerodynamic devices is more prevalent than any other fuel economy option. Newer trucks are designed with aerodynamic features, and, with the exception of radial tires, this technology is the most cost efficient to retrofit

However, in order to understand the future market penetration of technologies that truck buyers can select as options, it is necessary to know the operational characteristics of trucks by GVW class. While lubricant improvements, weight reduction, accessory drive improvements, and transmission improvements are applicable to all trucks, and are usually incorporated into the standard truck, aerodynamic drag reduction devices, radial tires and speed control devices are driver (or owner) selected options. For example, radial tires are not purchased by consumers who operate their trucks in 'rough' conditions because radial tires are more susceptible to sidewall damage than bias ply tires Similarly, aerodynamic drag reduction devices are only useful in trucks that have enclosed vans (dry vans) or trailers, and with tank trucks On open trucks (such as flatbeds, cattle racks, and dump trucks) drag reduction devices offer no useful fuel economy improvements TIUS data was used to estimate the percent of trucks operated in rough and agricultural

TABLE 2-3

PENETRATION RATES OF FUEL ECONOMY OPTIONS

BY GVW CLASS AND ENGINE TYPE

| GVW Class/Engine Type | % With Aero Devices | % With Fuel Efficient Engines | % With Variable Fan Drives | % With Radial Tires | % With Fuel Max Axle Ratios |
|---|---|---|---|---|---|
| Class 6 Gasoline | 1.0 | 0.1 | 0.0 | 0.1 | 0.4 |
| Class 6 Diesel | 6.3 | 2.8 | 0.5 | 1.3 | 3.7 |
| Class 7 Gasoline | 1 4 | 0.8 | 0.1 | 0.3 | 1 1 |
| Class 7 Diesel | 6.4 | 3.0 | 1.1 | 1.5 | 3 6 |
| Class 8A Gasoline | 0.9 | 0.2 | 0.0 | 0.0 | 0.5 |
| Class 8A Diesel | 9.8 | 5 6 | 1.4 | 2 7 | 6.2 |
| Class 8B Diesel | 22.5 | 15.9 | 4.3 | 7 3 | 17 3 |

applications and the percent of trucks that allow the use of drag reduction devices. The estimate is available by GVW class and fuel type - gasoline in Table 2-4 and diesel in Table 2-5. EEA has defined 'rough' operation as those trucks used in construction, forestry, and mining. 'Regular' use trucks, such as trucks used in wholesale or retail trade, mostly include enclosed vans and tank trucks.

Area of operation also has a direct impact on a truck's fuel efficiency. Long-haul trucks that mostly operate on interstate highways at constant speeds are expected to be more fuel efficient than short-haul trucks that operate at city cycles, all other things being equal. Table 2-6 characterizes each GVW class/fuel type combination by the percent of trucks that can be characterized as local, short-haul, and long-haul. As expected, the percent of Class 8B trucks operating locally is substantially less than in any other GVW class. Class 8B includes mostly line-haul vehicles that operate on interstate and intra-state highways at near constant speeds.

The single most important operational factor influencing a truck's fuel efficiency is it's average operating weight on a given trip. At any given moment in time, the operating weight of a truck is defined as the empty weight of the truck plus the weight of cargo being hauled. However, on any given trip a typical truck will encounter some empty mileage (i e, when no cargo is being hauled) and some loaded mileage (i.e., when cargo is being transported). To estimate the average operating weight of a truck it is necessary to account for both empty and loaded mileage TIUS variable PNOLOD describes the approximate percentage of a truck's annual mileage during which no payload was carried. Figure 2-3 shows average PNOLOD by GVW class/fuel type combination. Average PNOLOD is surprisingly high in all GVW classes, with gasoline trucks showing higher rates than diesel trucks. One would expect empty mileage to be substantially lower in Class 8B, since it largely consists of line-haul trucks. Line-haul trucks, and other commercial trucks, attempt to minimize empty mileage because fuel productivity (i.e., ton-miles per gallon of fuel consumed) is equal to zero when empty operation takes place The fact that

**TABLE 2-4**

**GASOLINE TRUCKS BY USE AND BODY STYLE**
**PERCENT BY GVW CLASS**

| | Agricultural | Rough Use | Regular Use | Total** |
|---|---|---|---|---|
| Class 6 | | | | |
| Non-Aero | 93.9 | 93.7 | 61.3 | 80.7 |
| Aero | 6.1 | 6.3 | 38.7 | 19.3 |
| Total* | 42.5 | 17.1 | 40.4 | 100.0 |
| Class 7 | | | | |
| Non-Aero | 94.5 | 94.2 | 65.1 | 82.6 |
| Aero | 5.5 | 5.8 | 34.9 | 17.4 |
| Total* | 41.1 | 18.7 | 40.2 | 100.0 |
| Class 8A | | | | |
| Non-Aero | 96.1 | 96.9 | 71.6 | 89.6 |
| Aero | 3.9 | 3.1 | 28.4 | 10.4 |
| Total* | 49.3 | 23.7 | 27.0 | 100.0 |

---

* Horizontal Total reflects % of trucks in a class by type of operation.
** Vertical Total reflects % of trucks in a class by body style.

TABLE 2-5

DIESEL TRUCKS BY USE AND BODY STYLE
PERCENT BY GVW CLASS

| | Agricultural | Rough Use | Regular Use | Total** |
|---|---|---|---|---|
| Class 6 | | | | |
| Non-Aero | 76.6 | 88.8 | 43.4 | 53 6 |
| Aero | 23 4 | 11.2 | 56.6 | 46.4 |
| Total* | 10 4 | 14.7 | 74.9 | 100 0 |
| Class 7 | | | | |
| Non-Aero | 71 5 | 93.8 | 46.0 | 56.6 |
| Aero | 28.5 | 6 2 | 54.0 | 43.4 |
| Total* | 10 2 | 16 6 | 73.2 | 100.0 |
| Class 8A | | | | |
| Non-Aero | 79 8 | 94.8 | 44.8 | 62.7 |
| Aero | 20.2 | 5.2 | 55.2 | 37.3 |
| Total* | 10.4 | 28.4 | 61.2 | 100.0 |
| Class 8B | | | | |
| Non-Aero | 72 2 | 92.7 | 37.7 | 51 2 |
| Aero | 27.8 | 7.3 | 62 3 | 48 8 |
| Total* | 9 3 | 18.6 | 72 1 | 100.0 |

* Horizontal Total reflects % of trucks in a class by type of operation.

** Vertical Total reflects % of trucks in a class by body style

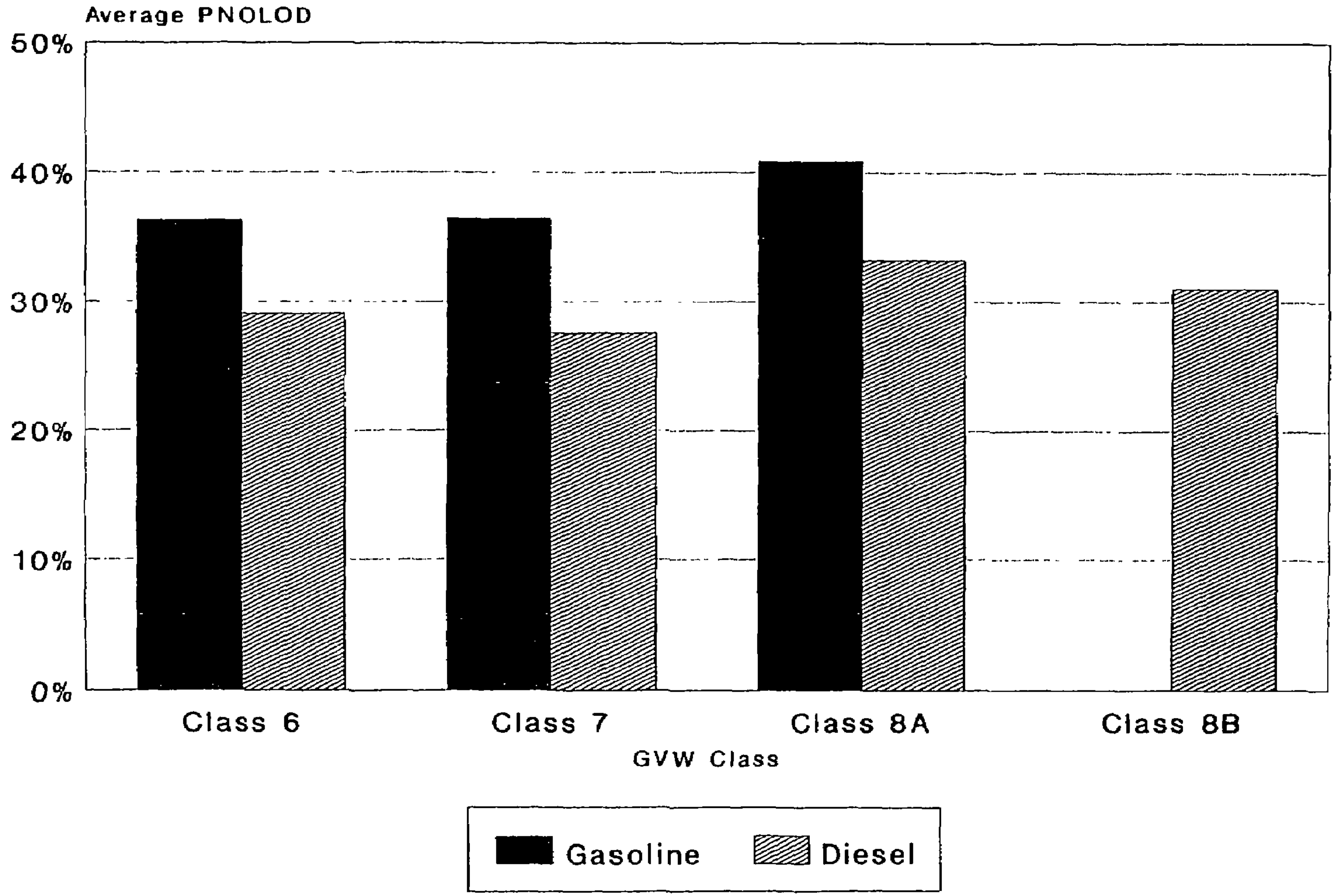
TABLE 2-6

PERCENT OF TRUCKS BY AREA OF OPERATION
BY GVW CLASS AND FUEL TYPE

| | Area of Operation[1] | | |
|---|---|---|---|
| GVW Class/Engine Type | % Local | % Short-Haul | % Long-Haul |
| Class 6 Gasoline | 84.4 | 13.8 | 1.8 |
| Class 6 Diesel | 66.1 | 27.8 | 6.1 |
| Class 7 Gasoline | 86.2 | 12.5 | 1.3 |
| Class 7 Diesel | 66.4 | 29.0 | 4.7 |
| Class 8A Gasoline | 86.3 | 11 9 | 1.8 |
| Class 8A Diesel | 63.4 | 24 4 | 12 1 |
| Class 8B Diesel | 25.4 | 32 9 | 41.7 |

[1] Local if greatest percentage of annual miles were accrued within a 50 mile radius of home-base. Short-haul if greatest percentage of miles were accrued between 50 to 200 mile radius of home-base. Long-haul if greatest percent of miles were accrued beyond a 200 mile radius of home-base.

FIGURE 2-3
Average Percentage of Annual Mileage
When No Load Was Carried, By GVW Class



PNOLOD rates are so high implies that carriers can benefit greatly by reducing empty mileage.

Having characterized the average annual mileage that trucks operate without a load, average operating weight can be estimated using TIUS variables EMWGHT and AVWGHT. The EMWGHT variable describes a given truck's empty weight, while AVWGTH describes the empty weight plus weight of cargo of a truck when carrying a typical payload. Therefore, the average operating weight of a truck can be defined by the following weighted sum:

[AVWGHT*(1-PNOLOD) + EMWGHT*(PNLOD)].

EEA defines this estimate of average operating weight as equivalent weight (EQUIVWT). The equivalent weight of a vehicle will have a considerable impact on the vehicle's average fuel consumption rate (MPG). Figure 2-4 shows average EQUIVWT by GVW class/engine type combination.

Model year trends in gasoline fuel economies (MPGs) are plotted by class in Figures 2-5 through 2-7 for Classes 6, 7 and 8A The error bars give the high and low ends of the standard deviations of the means An increasing trend in fuel economy is apparent since 1984 for both Class 6 and Class 7 gasoline trucks, while Class 8A gasoline trucks show no trend in MPG. Diesel fuel economy trends are plotted in Figures 2-8 through 2-11. In each GVW class, diesel MPGs have consistently increased since model year 1977.

**FIGURE 2-4**
**Average Operating Equivalent Weight**
**By GVW Class**

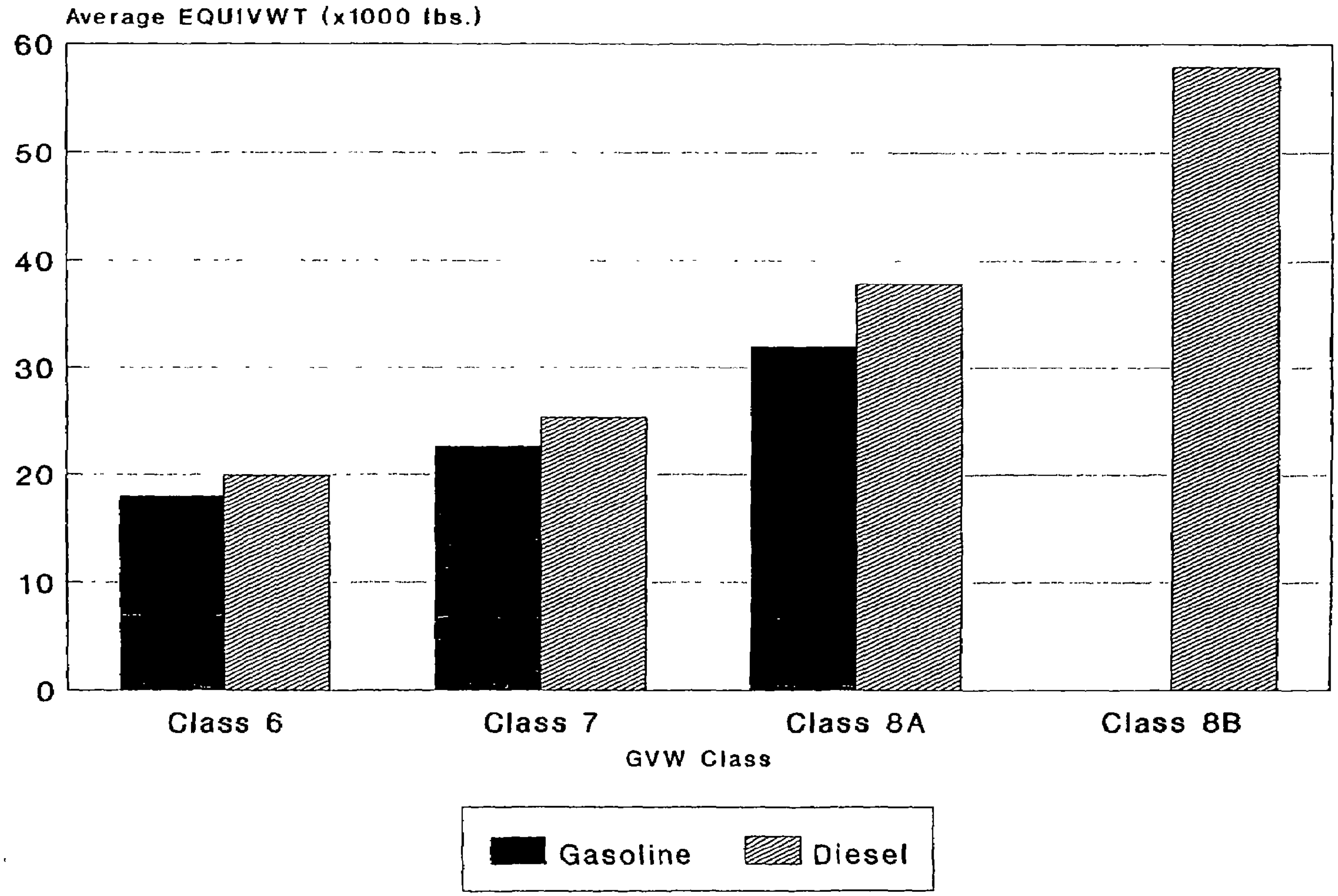
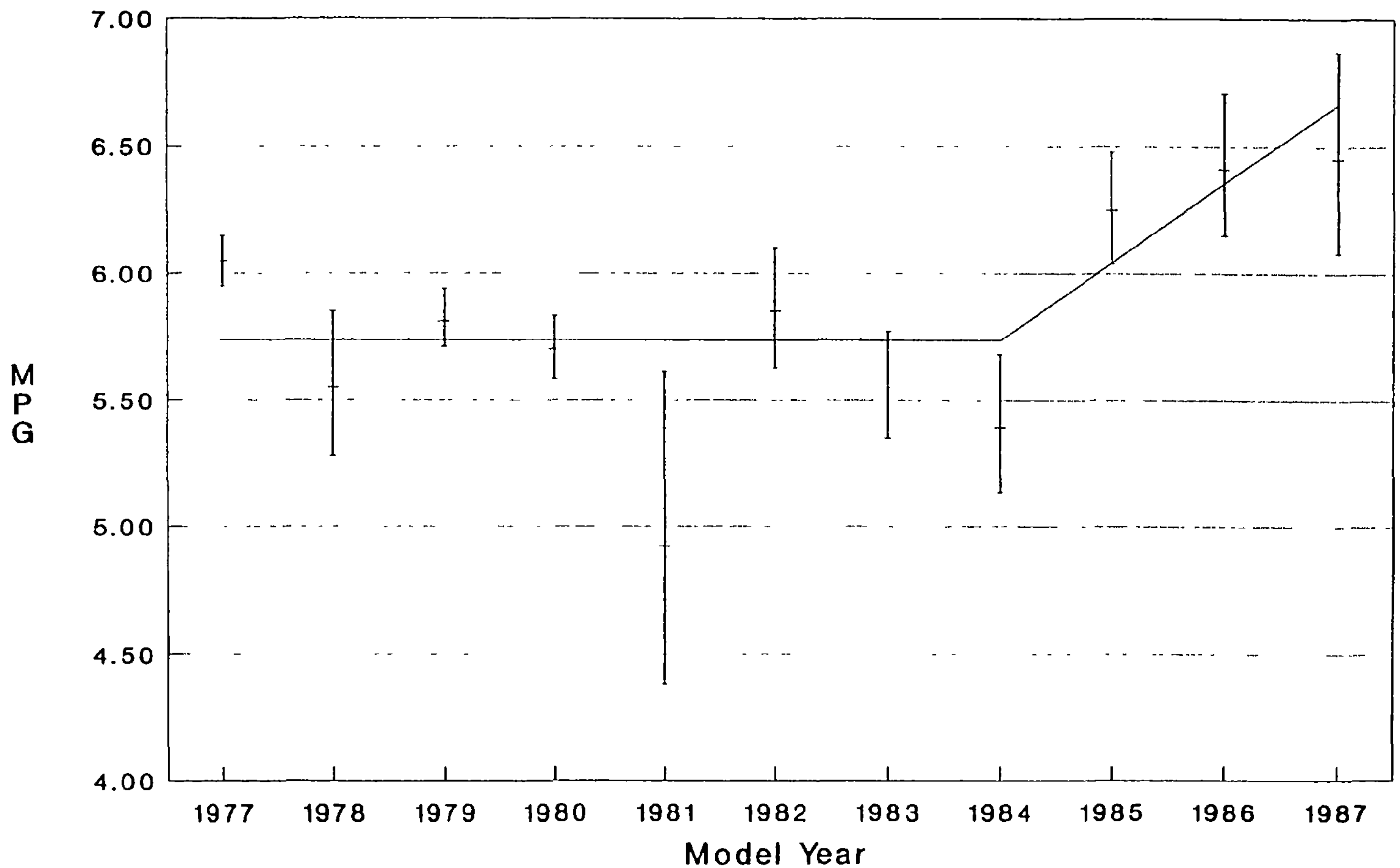
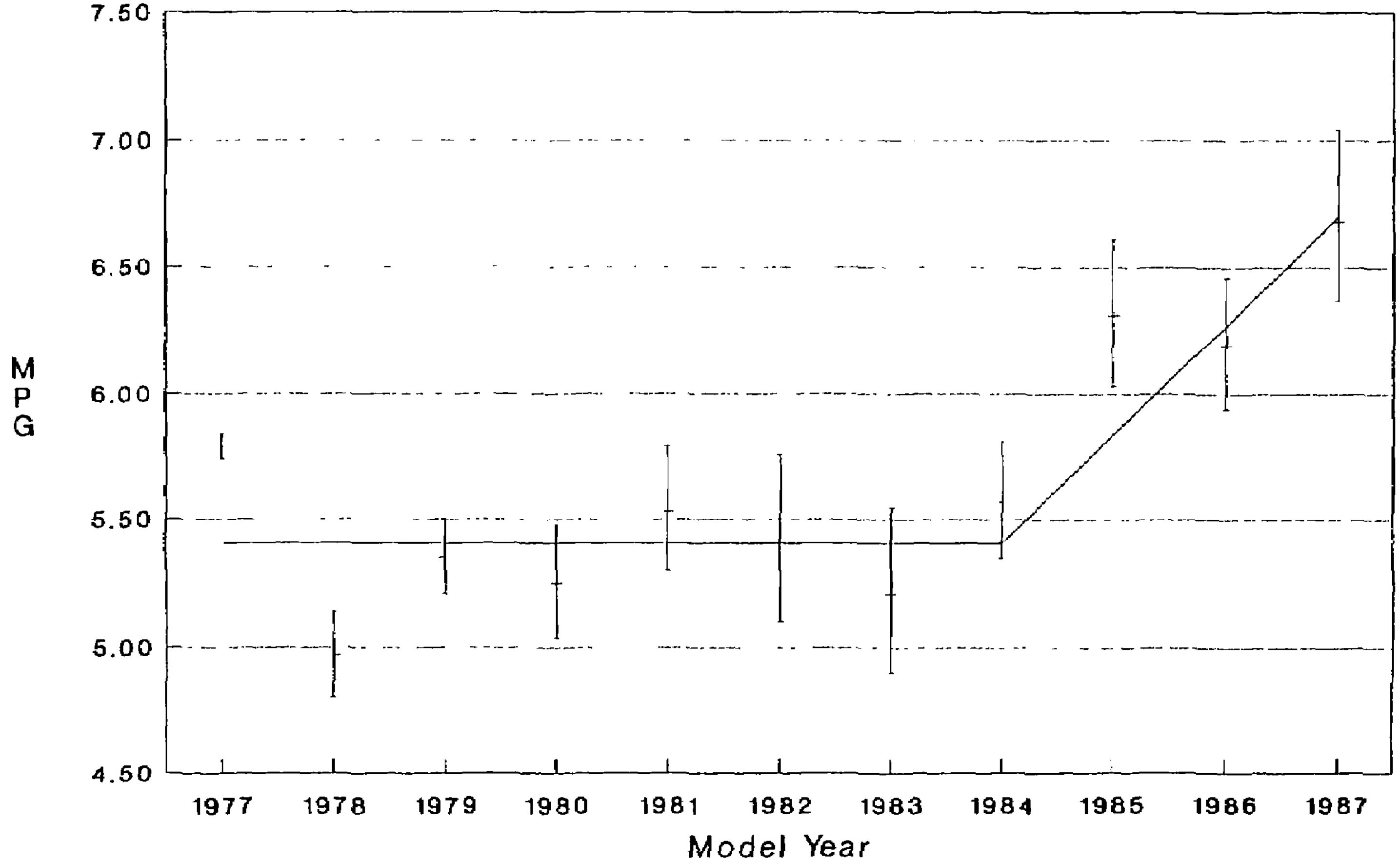


FIGURE 2-5
Average MPG By Vintage
GVW Class 6 Gasoline Trucks



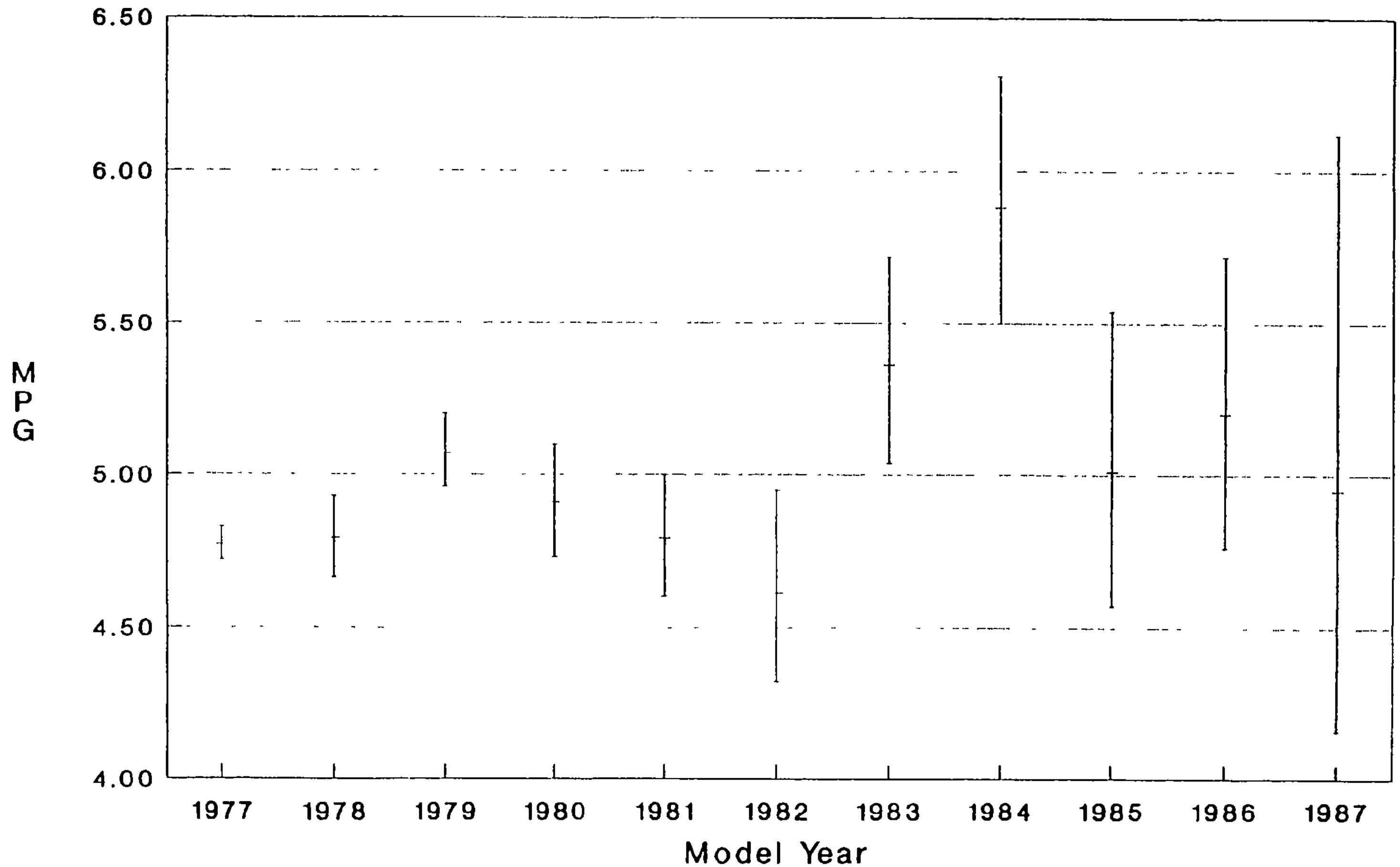

Model Year 1977 includes 1977 and pre-1977 models

## FIGURE 2-6
## Average MPG By Vintage
## GVW Class 7 Gasoline Trucks



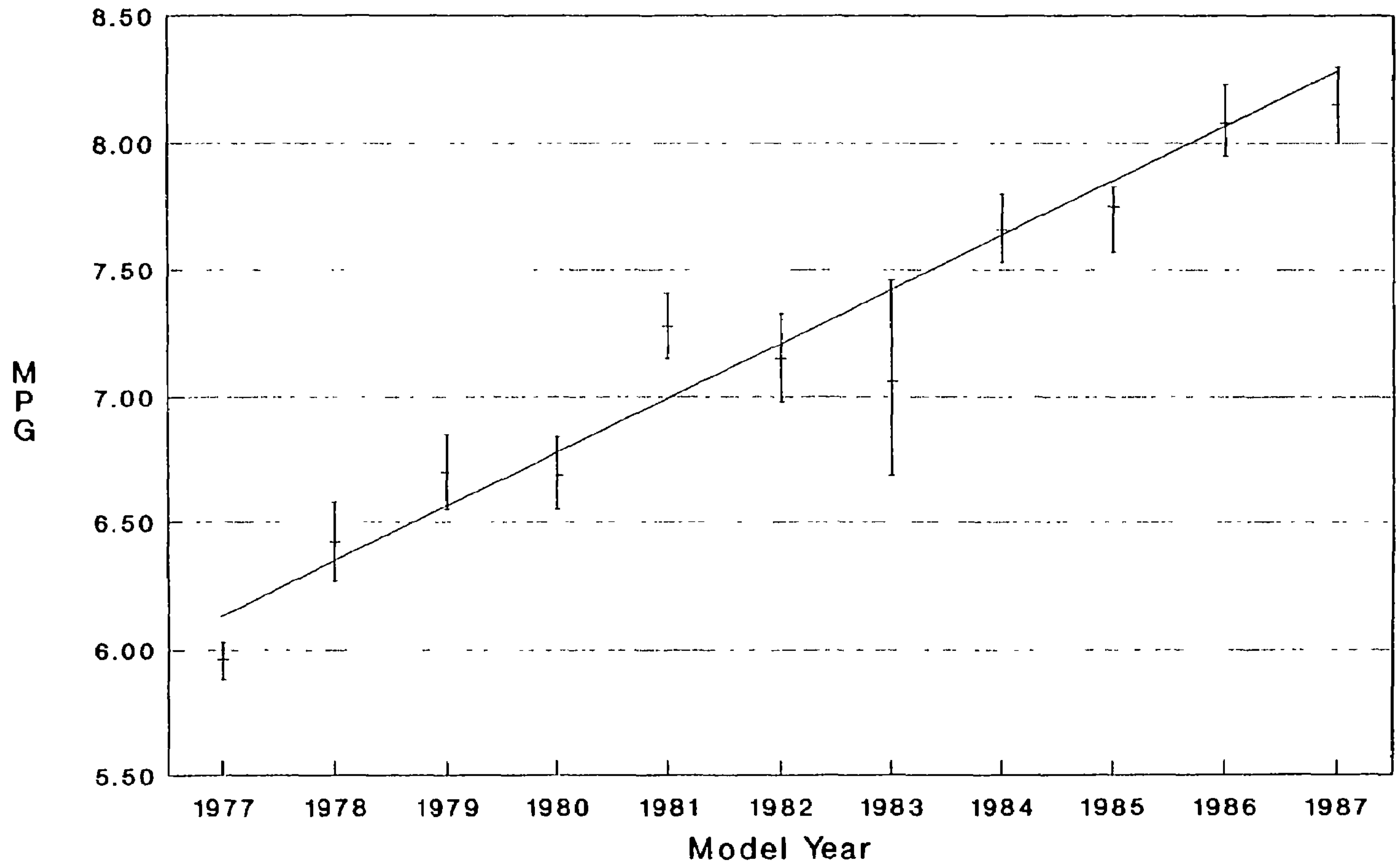

Model Year 1977 includes 1977 and pre-1977 models

FIGURE 2-7
Average MPG By Vintage
GVW Class 8A Gasoline Trucks



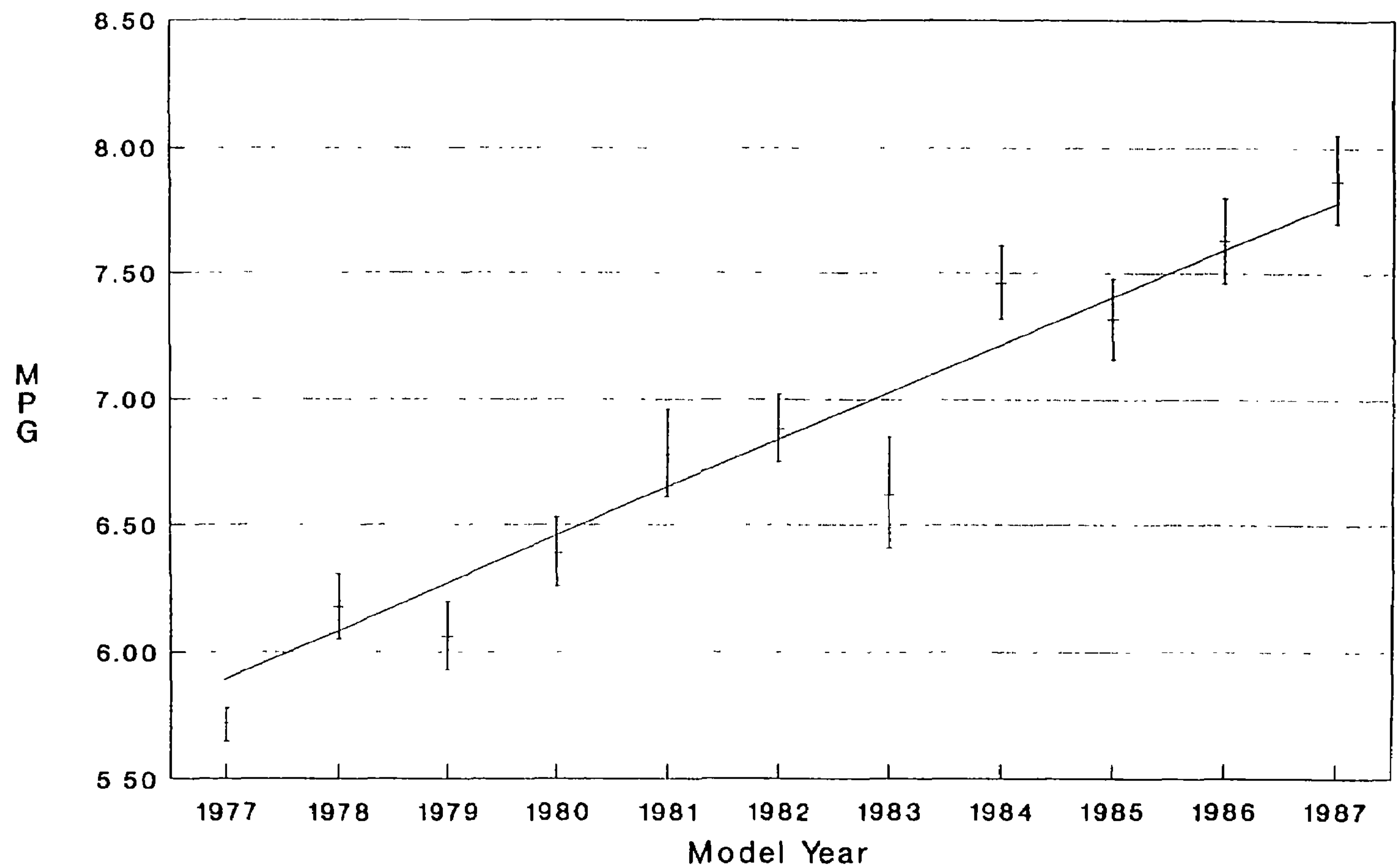

Model Year 1977 includes 1977 and pre-1977 models

FIGURE 2-8
Average MPG By Vintage
GVW Class 6 Diesel Trucks



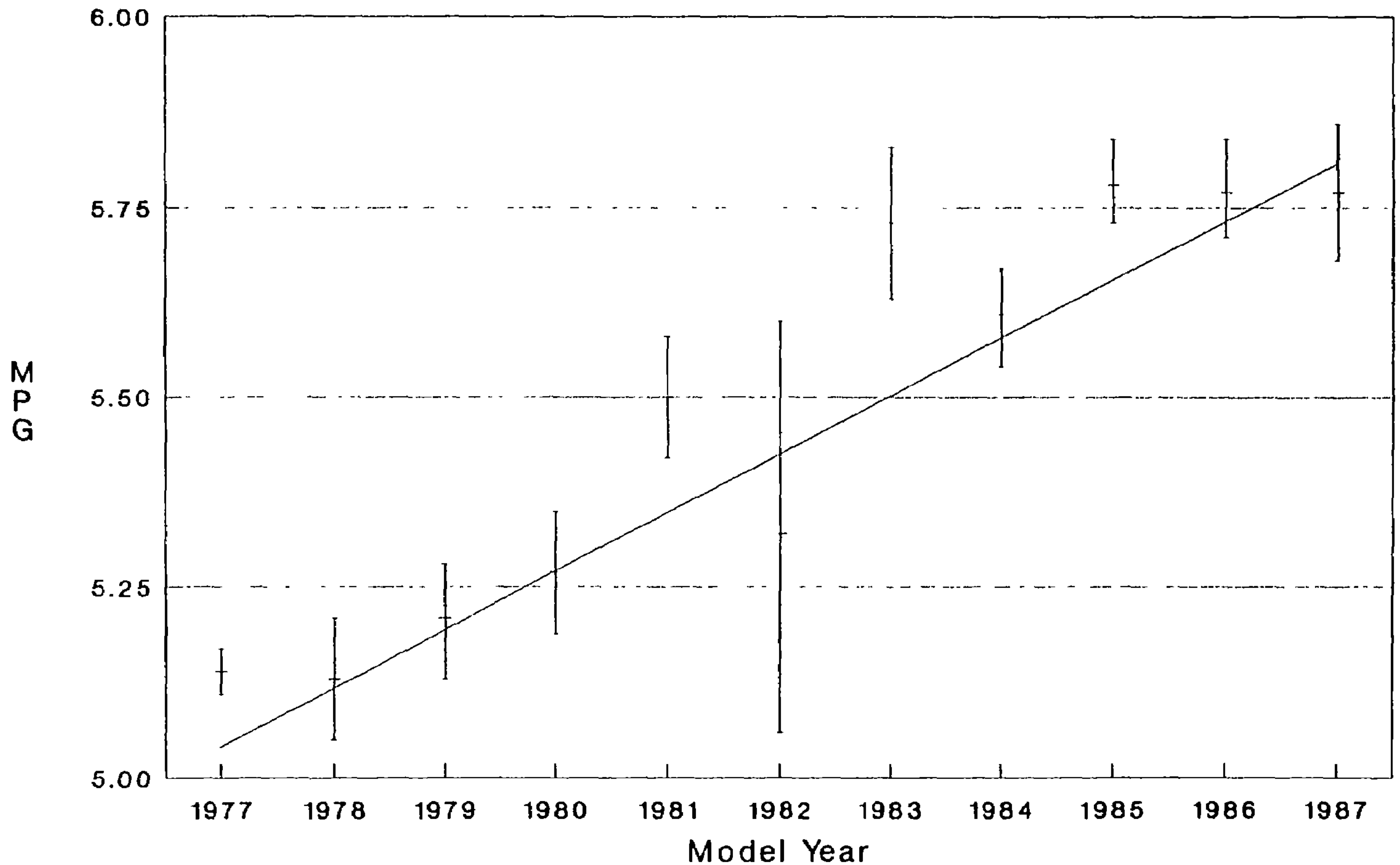

Model Year 1977 includes 1977 and pre-1977 models.

# FIGURE 2-9
## Average MPG By Vintage
## GVW Class 7 Diesel Trucks



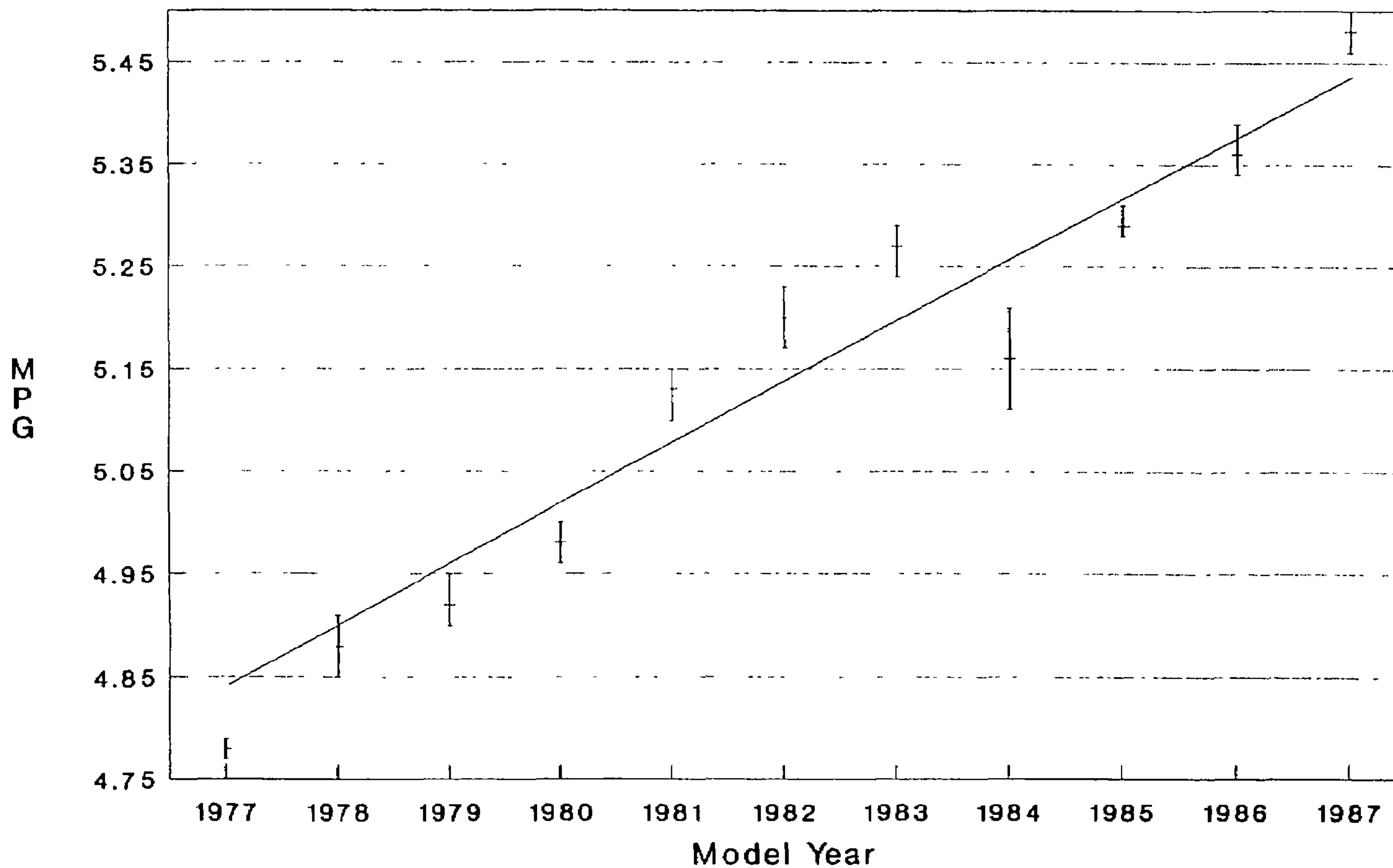

Model Year 1977 includes 1977 and
pre-1977 models

FIGURE 2-10
Average MPG By Vintage
GVW Class 8A Diesel Trucks




Model Year 1977 includes 1977 and pre-1977 models

FIGURE 2-11
Average MPG By Vintage
GVW Class 8B Diesel Trucks




Model Year 1977 includes 1977 and pre-1977 models

## 3. OPERATIONAL FACTORS TO IMPROVE FUEL EFFICIENCY

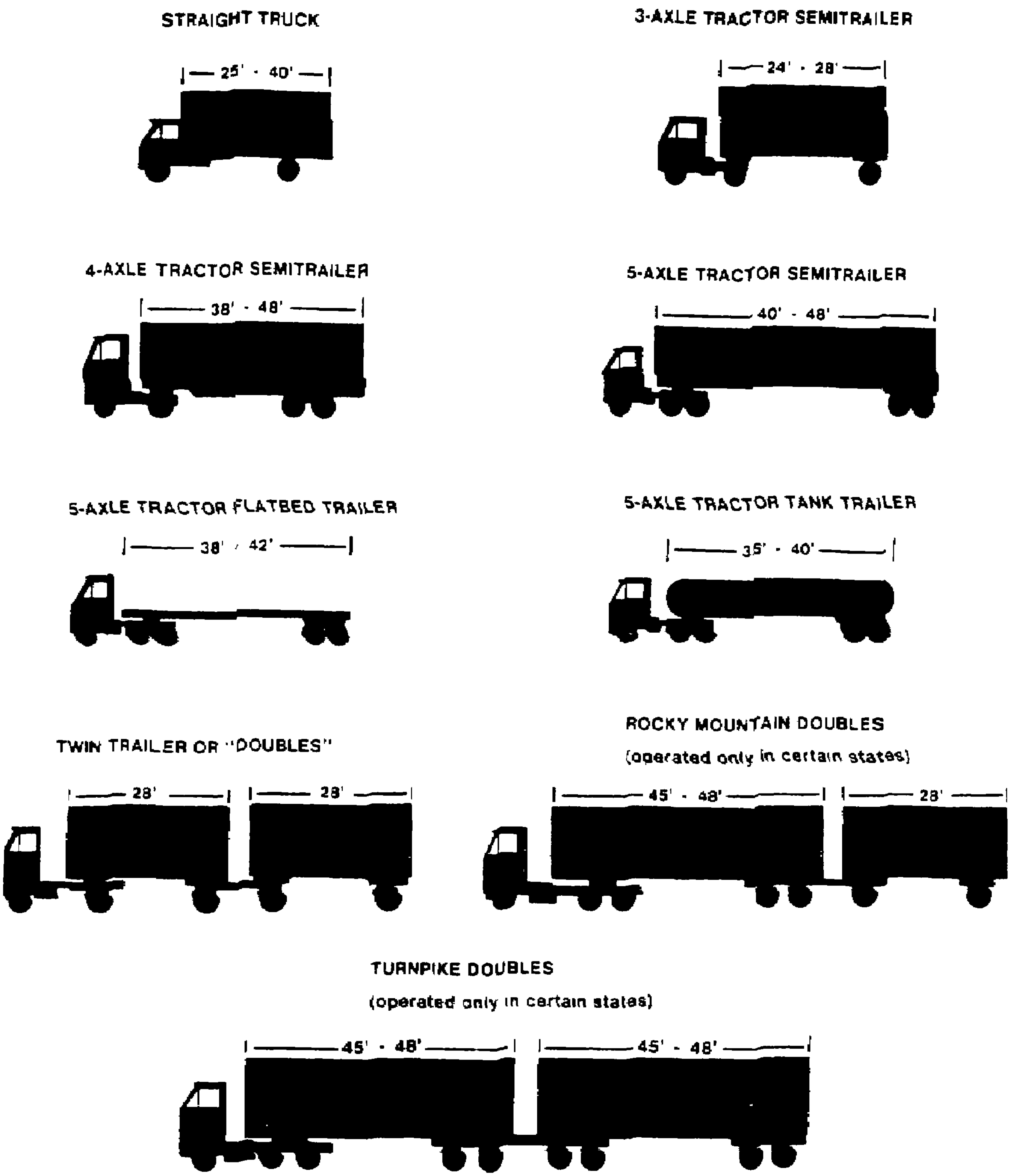
### 3.1 INTRODUCTION

Transportation facilitates the exchange of goods and services. For a given level of freight transportation demand, many combinations of the capital stock and modal share (truck, ship, or airplane) can be used to satisfy that level of demand. Each vehicle type within a mode has an average energy efficiency (BTUs per vehicle mile), a characteristic load factor (freight ton-mile per vehicle mile), and intensity of use (vehicle miles traveled per year). Therefore, given a level of demand, energy conservation in transporting freight by truck can be accomplished by reducing the energy input through operational and technological improvements, and/or by increasing the number of freight ton-miles traveled per unit of energy that is consumed (i.e., increasing fuel productivity) This section of the report provides a quantitative description of the factors that influence fuel productivity

Fuel productivity in the movement of freight by truck largely depends on the type of truck that is being used. Each vehicle type has physical and operational characteristics that are unique. Typical vehicle types are shown in Figure 3-1. Straight trucks are vehicles with the cargo body and tractor mounted on the same chassis and usually consist of 2-, 3-, or 4-axle configurations. Two-axle straight trucks are most often used in urban areas where maneuverability is important and operate between 19,500 lbs and 33,000 lbs gross vehicle weight (GVW). Three and 4-axle straight trucks are principally used in construction or other 'rough-duty' uses Combination trucks are vehicles that have a power unit (tractor) that is separate from the trailer(s), and are generally used for interstate freight movement. Although combination trucks may have 3 to 9 axles, the most common types are 5-axle combinations with one 48 ft long semi-trailer and 5-axle double trailer combinations with two 28 ft trailers (i e , 5-axle Twin 28s). Five-, 6-axle tractor semitrailers, and 5-axle Twin 28s commonly operate between 60,000 lbs

Figure 3-1

# TRUCK TYPES




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

Source: ATA, American Trucking Trends, 1989 and 80,000 lbs GVW. Seven-axle, 8-axle, and 9-axle Twin 28s generally operate beyond 80,000 lbs GVW (the current legal maximum) under special permit in accordance with applicable state laws. A double trailer combination with one or both trailers longer than 28 ft is defined as a Longer Combination Vehicle (LCV). The definition of LCVs is not consistent within the trucking industry. Some define 7-axle, 8-axle, and 9-axle Twin 28s as LCVs, since these configurations hardly ever operate below 80,001 lbs GVW Others, including EEA, consider only those double trailer combinations with one or both trailers longer than 28 ft operating at weights that exceed 80,000 lbs (under special permit) as LCVs In this context, the most common types of LCVs are Rocky Mountain Doubles and Turnpike Doubles. Rocky Mountain Doubles are 7-axle double trailers commonly having one trailer that is 28 ft long and another that is 48 ft long. Turnpike Doubles are 9-axle double trailers whose trailers are usually both 48 ft long. Triple trailer combinations (i.e , a tractor unit with three 28 ft trailers) are also common in some states, operating under special permit. However, because of their specialized applications and physical characteristics, an analysis of triples is beyond the scope of this report.

One way to change fuel productivity is to increase the payload capacity of a truck Payload capacity is determined by the difference between a vehicle's empty weight and a vehicle's maximum gross vehicle weight (GVW). A vehicle's maximum practical GVW is defined by a carrier's needs and by state and federal regulations on truck size and weight. Truck weight limits constrain GVW by restricting a vehicle's maximum operating weight, while truck size limits constrain GVW by restricting a vehicle's volumetric carrying capacity

Liberalizing weight limits to allow trucks to operate at higher GVWs directly influences fuel productivity. A vehicle's empty weight does not increase in step with GVW, so a more liberal weight limit increases the payload capacity of the vehicle. Increasing payload capacity compromises fuel economy (as defined by miles traveled-per-gallon of fuel that is consumed, or MPG) since the added weight requires more energy input to propel the vehicle into motion However, in the context of fuel productivity, the potential payload capacity benefit is expected to be greater than the loss in fuel economy. Fuel economy losses will be relatively small because aerodynamic forces do not closely scale with added vehicle weight and because heavier vehicles have larger engines that can be more fuel efficient. On the other hand, changes in weight limits affect not only the operating weights of today's trucks, but also the types of equipment that motor carriers will operate in the future. If weight limits are liberalized, some motor carriers will switch to vehicle configurations that have higher empty weights. The difference in empty weights between these new configurations and those used previously are small relative to the difference in payload capacities. Seven-, eight- and nine-axle double-trailer trucks with trailing units that are longer than 28 ft - defined as Longer Combination Vehicles (LCVs) that are currently not allowed to operate in most states - have empty weights between 30,000 and 40,000 lbs. These vehicles operate at weights of well over 100,000 lbs, often carrying payloads of over 70,000 lbs Conventional five-axle tractor semi-trailer trucks, on which most freight is currently transported, are limited by law to a maximum GVW of 80,000 lbs These vehicles usually have empty weights of 25,000 lbs and often carry payloads that weigh below 65,000 lbs Even if changes in the weight limits induce a shift toward vehicles with higher empty weights, the fuel productivity gain of the added payload capacity can be significant Increasing payload capacity will also increase the cost productivity of the vehicle's driver At a given driver cost more payload can be carried.

Policies that liberalize weight limits are expected to increase fuel productivity and operational productivity in the movement of freight by truck. Weight limits are imposed at both the state and federal level However, current federal regulations supersede many state limits, at least as they apply to the interstate highway system on which a significant portion of fuel is consumed.[1] Due to this, and because state regulations for non-interstate roads vary from one state to the other, this report quantifies the effect on fuel productivity of a change in the **federal** weight limit. Throughout the analysis, size limits are assumed to remain unchanged.

Another way to increase fuel productivity is to decrease the mileage when a truck is operating empty. Empty operation takes place when a truck carries a load in one direction but travels empty in the other. During empty mileage fuel productivity (ton-miles per gallon) is equal to zero. Therefore, to the extent that carriers can minimize empty backhaul, fuel productivity gains can be realized. This section also quantifies the influence of empty mileage on fuel productivity and investigates what can be done from a policy perspective to minimize empty mileage.

The organization of this section is as follows: Section 3.2 outlines current federal weight regulatory constraints in the maximization of fuel productivity and presents the policy change that is investigated in this report, Section 3.3 describes the analytical methodology that was used to develop quantitative estimates of fuel productivity, Section 3.4 quantifies the effect of empty mileage on fuel productivity, and Section 3.5 quantifies the effect of a change in the federal weight limit and the effect of LCV operations.

## 3.2 FEDERAL REGULATIONS ON WEIGHT

Truck weight regulations, at the federal and state level, are motivated by concern for protecting pavements and bridges from the effects of heavy loads. For a given truck, increasing the number of freight ton-miles traveled per unit of fuel that is consumed implies a heavier operation weight, since the payload weight increases and empty weight remains constant or does not proportionately increase with payload The introduction of heavier trucks has a direct effect on pavement wear and the safety margin for bridges, thus increasing the cost to a highway agency of maintaining its road network

During the 1970s one of the major issues of concern to the trucking industry was uniform truck weight regulations. Although previous federal regulation had increased the allowable weight of trucks on the interstate system, it had not mandated all states to comply. As a result, six states in the Mississippi Valley and Montana retained lower limits, and truckers in interstate commerce passing through these states were forced to operate at the lower limits or operate illegally [2] In response to the need for uniform regulations the

Surface Transportation Assistance Act of 1982 (STAA of 1982) was passed into law. This act resolved the uniform weight issue and expanded the role of federal regulations to other federally-aided primary roads. Regulations brought about by the STAA of 1982 are valid today.

Under the STAA of 1982, Congress requires all states to allow on the interstate highway system and primary roads receiving federal-aid the following weights: a maximum load of 20,000 lbs on single-axles, a maximum load of 34,000 lbs on tandem-axles (a tandem-axle is a pair of closely spaced axles), and an overall gross weight on a group of two or more consecutive axles produced by application of the Federal Bridge Formula B, provided that such overall gross weight does not exceed 80,000 lbs. Bridge Formula B is specified as follows:

$$W = 500\ [LN/(N - 1) + 12N + 36]$$

where, W = maximum weight in pounds carried on any group of two or more axles,

L = the distance in feet between the extremes of any two or more consecutive axles,

N = the number of axles on the vehicle.

The intent of Bridge Formula B is to limit axle weights so that trucks do not over-stress bridges on interstates and the federal-aid highway network. Under the Bridge Formula, gross weights are allowed to increase as the number of axles and the length between axle groups increase. However, the overall gross weight of a vehicle cannot exceed 80,000 lbs, except for those vehicles carrying loads which cannot be easily divided and which have been issued special permits in accordance with applicable state laws.

State laws also determine the length of the trailing units of tractor trailer combinations. The STAA of 1982 prohibited states from limiting the length of the semitrailer of a tractor-trailer combination to less than 48 ft or each trailer of a combination with two trailers to less than 28 ft on the interstate highway system.* The federal regulation on length imposes a minimum criterion on a state's maximum length regulation. States must permit these lengths, but can set limits on semitrailer and double trailer lengths beyond 48 ft and 28 ft, respectively (see Table 3-1). These state maximum length limits are important because in the absence of the 80,000 lbs GVW cap, Bridge Formula B would allow higher GVW limits depending on the number of axles and the distance between the extremes of any two or more consecutive axles, assuming that axle-weight limits are met.

Permissible gross weights under Bridge Formula B are shown in Table 3-2. This table demonstrates that the maximum allowable GVW for a 2-axle truck is 40,000 lbs providing that the distance between the axles is 10 ft. For a 3-axle truck the GVW limit under this formula is 60,000 lbs providing that the distance between the extreme axles is 32 ft. A 4-axle truck combination can reach an overall weight of 80,000 lbs only when the distance between the vehicle's extreme axles is not less than 57 ft. However, even if distances are satisfied, these configurations will not reach the Bridge Formula B GVW maximums because axle-load limits will rarely be met This means that the maximum practical GVW for these truck configurations is actually determined by the axle-weight limits that are discussed above. Under these axle-weight limits, a 2-axle truck with a 12,000 lbs load on the steering axle and a 20,000 lbs load on the rear single-axle has a practical GVW limit of 32,000 lbs. A 3-axle truck with two single-axles and 12,000 lbs on the steering axle has a GVW limit of 52,000 lbs, while a 4-axle truck with one single-axle, one tandem-axle, and 12,000 lbs on the steering axle is limited to 66,000 lbs GVW. Likewise, a typical 5-axle tractor-semitrailer with two tandem-axles and 12,000 lbs on the steering axle is limited to a practical GVW of 80,000 lbs by the axle-weight limits, although Bridge Formula B allows for higher GVWs as the distance between extreme axles increases.

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* STAA of 1982 also required states to allow use of combinations consisting of a tractor and two trailing units on the interstates and the network of primary roads.[3]

TABLE 3-1

STATE SIZE LIMITS

| STATE | HEIGHT | WIDTH | LENGTH (FT-IN) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Tractor-Semitrailer Combinations | | | Twin Combinations | | |
| | In Feet / Inches | In inches | Truck (Single Unit) | Semitrailer on Interstate & National Network* | Semitrailer Length off National Network* | Overall Combination Length on Other Roads | Semitrailer or Trailer on Interstate & National Network | Twin Combination Length on Other Roads | Straight Truck – Trailer |
| Alabama | 13-6 | 102 | 40-0 | 53-6 | 53 | NR | 28-6 | NR | 50 |
| Alaska | 14-0 | 102 | 40-0 | 48 | 45 | 70 | 90 | 75 | 75 |
| Arizona | 14-0 | 102 | 40-0 | 57-6 | 53/NR | 65 | 28-6 | NR | NR |
| Arkansas | 13-6 | 102 | 40-0 | 53-6 | 53-6 | 75 | 28 | 65 | NS |
| California | 14-0 | 102 | 40-0 | 48/53 | NR | 65 | 28-6 | 75 | 65 |
| Colorado | 13-6 | 102 | 40-0 | 57-4 | 57-4 | 70 | 28-6 | 70 | 70 |
| Connecticut | 13-6 | 102 | 60-0 | 48 | 48 | NR | 28 | NP | 60 |
| Delaware | 13-6 | 102 | 40-0 | 53 | NR | 60 | 29 | NP | 60 |
| Dist. of Columbia | 13-6 | 102 | 40-0 | 48 | NR | 55 | 28 | NP | 55 |
| Florida | 13-6 | 102 | 40-0 | 48/57-6 | 48 | NR | 28 | NP | |
| Georgia | 13-6 | 102 | 60-0 | 53 | 48/53 | 60/67-6 | 28 | NP | 60 |
| Hawaii | 13-6 | 108 | 40-0 | 48 | 45 | 60 | 65 | 65 | 65 |
| Idaho | 14-0 | 102 | 40-0 | 48/53 | 48 | NR | 61 | 61 | 75 |
| Illinois | 13-6 | 102 | 42-0 | 53 | 53 | 55 | 28-6 | 65 | 60 |
| Indiana | 13-6 | 102 | 36-0 | 53 | 53 | NR | 28-6 | NR | 60 |
| Iowa | 13-6 | 102 | 40-0 | 53 | NR | 60 | 28-6 | 60 | 65 |
| Kansas | 14-0 | 102 | 42-6 | 59-6 | 59-6 | NR | 28-6 | NR | 65 |
| Kentucky | 13-6 | 102 | 45-0 | 53 | NR | 57-9 | 28 | NP | 57-9 |
| Louisiana | 13-6 | 102 | 40-0 | 59-6 | NR | 65 | 30 | NR | 65 |
| Maine | 13-6 | 102 | 45-0 | 48 | 48 | 65 | 28-6 | NP | 65 |
| Maryland | 13-6 | 102 | 40-0 | 48 | 48 | NR | 28 | NP | 55 |
| Massachusetts | 13-6 | 102 | 40-0 | 48 | 45/48 | 60 | 28-6 | NP | 60 |
| Michigan | 13-6 | 102 | 40-0 | 53 | 50 | NR | 58 | 58 | 59 |
| Minnesota | 13-6 | 102 | 40-0 | 53 | 53 | 65 | 28-6 | NP | 65 |
| Mississippi | 13-6 | 102 | 40-0 | 53 | 53 | NR | 30 | NR | NR |
| Missouri | 13-6 | 102 | 40-0 | 53 | NR | 60 | 28 | 65 | 65 |
| Montana | 14-0 | 102 | 40-0 | 53 | 53 | NR | 28-6 | 75 | 75 |
| Nebraska | 14-6 | 102 | 40-0 | 53 | 53 | NR | 65 | 65 | 65 |
| Nevada | 14-0 | 102 | 40-0 | 53/NR | 53/NR | 70 | 28-6/NR | 70 | 70 |
| New Hampshire | 13-6 | 102 | 40-0 | 48 | 48 | NR | 28 | NP | 65 |
| New Jersey | 13-6 | 102 | 35-0 | 48 | 48 | NR | 28 | NP | 62 |
| New Mexico | 14-0 | 102 | 40-0 | 57-6 | 57-6 | 65 | 28-6 | 65 | 65 |
| New York | 13-6 | 102 | 40-0 | 53 | 48 | 65 | 28-6 | NP | 60 |
| North Carolina | 13-6 | 102 | 40-0 | 53 | NR | 60 | 28 | NP | 60 |
| North Dakota | 13-6 | 102 | 50-0 | 53 | 53 | 75 / 88 | 53 | 75 / 88 | 75 |
| Ohio | 13-6 | 102 | 40-0 | 53 | 53 | NR | 28-6 | NR | 65 |
| Oklahoma | 13-6 | 102 | 45-0 | 59-6 | 53 | NR | 29 | NR | 70 |
| Oregon | 14-0 | 102 | 40-0 | 53 | NR | 60 | 68 | 60 | 75 |
| Pennsylvania | 13-6 | 102 | 40-0 | 53 | NR | 60 | 28-6 | NP | 60 |
| Rhode Island | 13-6 | 102 | 40-0 | 48-6 | 48-6 | NR | 28-6 | NP | NS |
| South Carolina | 13-6 | 102 | 40-0 | 53 | 48 | NR | 28-6 | NP | NR |
| South Dakota | 14-0 | 102 | 45-0 | 53 | 53 | NR | 81-6 | 81-6 | 80 |
| Tennessee | 13-6 | 102 | 40-0 | 50 | 50 | NR | 28-6 | NP | 65 |
| Texas | 13-6 | 102 | 45-0 | 59 | 59 | NR | 28-6 | NR | 65 |
| Utah | 14-0 | 102 | 45-0 | 48 /53 | 48 | NR | 61 | 61/NR | 65 |
| Vermont | 13-6 | 102 | 60-0 | 48 | 45/NR | 65 | 28 | NP | 60 |
| Virginia | 13-6 | 102 | 40-0 | 53 | NR | 60 | 28-6 | NP | 60 |
| Washington | 14-0 | 102 | 40-0 | 48 | 48 | NR | 60 | 60 | 75 |
| West Virginia | 13-6 | 102 | 40-0 | 53 | NR | 60 | 28 | NP | 60 |
| Wisconsin | 13-6 | 102 | 40-0 | 53 | NR | 60 | 28-6 | NP | 60 |
| Wyoming | 14-0 | 102 | 60-0 | 60 | 60 | NR | 60 | 60 | 85 |

Source: ATA, Size and Weight Limits, July 1990.

Table 3-2

## INTERSTATE/NATIONAL NETWORK ALLOWABLE GROSS WEIGHT
(FEDERAL BRIDGE FORMULA)

**GROSS WEIGHT LAW**

States have adopted the Federal Bridge Formula for travel on the Interstate and other public highways either by formula (Formula B) or by chart (Table B), with the exception of the states found at Table A. Variations may occur due to rounding language adopted or not adopted by the respective state. Table B appears as provided by the Federal Highway Administration.

**FORMULA B** $W = 500 (LN/N-1 + 12N + 36)$

W = maximum weight in pounds carried on any group of two or more axles computed to nearest 500 pounds

L = distance in feet between the extremes of any group of two or more consecutive axles

N = number of axles in group under consideration

**TABLE B (in 1,000 lbs.)**

| Distance in feet between the extremes of any group or 2 or more consecutive axles | Maximum load in 1000 lbs carried on any group of 2 or more consecutive axles | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2 axles | 3 axles | 4 axles | 5 axles | 6 axles | 7 axles | 8 axles | 9 axles |
| 4 | 34.0 | | | | | | | |
| 5 | 34.0 | | | | | | | |
| 6 | 34.0 | | | | | | | |
| 7 | 34.0 | | | | | | | |
| 8 and less | 34.0 | 34.0 | | | | | | |
| more than 8 | 38.0 | 42.0 | | | | | | |
| 9 | 39.0 | 42.5 | | | | | | |
| 10 | 40.0 | 43.5 | | | | | | |
| 11 | | 44.0 | | | | | | |
| 12 | | 45.0 | 50.0 | | | | | |
| 13 | | 45.5 | 50.5 | | | | | |
| 14 | | 46.5 | 51.5 | | | | | |
| 15 | | 47.0 | 52.0 | | | | | |
| 16 | | 48.0 | 52.5 | 58.0 | | | | |
| 17 | | 48.5 | 53.5 | 58.5 | | | | |
| 18 | | 49.5 | 54.0 | 59.0 | | | | |
| 19 | | 50.0 | 54.5 | 60.0 | | | | |
| 20 | | 51.0 | 55.5 | 60.5 | 66.0 | | | |
| 21 | | 51.5 | 56.0 | 61.0 | 66.5 | | | |
| 22 | | 52.5 | 56.5 | 61.5 | 67.0 | | | |
| 23 | | 53.0 | 57.5 | 62.5 | 68.0 | | | |
| 24 | | 54.0 | 58.0 | 63.0 | 68.5 | 74.0 | | |
| 25 | | 54.5 | 58.5 | 63.5 | 69.0 | 74.5 | | |
| 26 | | 55.5 | 59.5 | 64.0 | 69.5 | 75.0 | | |
| 27 | | 56.0 | 60.0 | 65.0 | 70.0 | 75.5 | | |
| 28 | | 57.0 | 60.5 | 65.5 | 71.0 | 76.5 | 82.0 | |
| 29 | | 57.5 | 61.5 | 66.0 | 71.5 | 77.0 | 82.5 | |
| 30 | | 58.5 | 62.0 | 66.5 | 72.0 | 77.5 | 83.0 | |
| 31 | | 59.0 | 62.5 | 67.5 | 72.5 | 78.0 | 83.5 | |
| 32 | | 60.0 | 63.5 | 68.0 | 73.0 | 78.5 | 84.5 | 90.0 |
| 33 | | | 64.0 | 68.5 | 74.0 | 79.0 | 85.0 | 90.5 |
| 34 | | | 64.5 | 69.0 | 74.5 | 80.0 | 85.5 | 91.0 |
| 35 | | | 65.5 | 70.0 | 75.0 | 80.5 | 86.0 | 91.5 |
| 36 | | | 66.0* | 70.5 | 75.5 | 81.0 | 86.5 | 92.0 |
| 37 | | | 66.5* | 71.0 | 76.0 | 81.5 | 87.0 | 93.0 |
| 38 | | | 67.5* | 71.5 | 77.0 | 82.0 | 87.5 | 93.5 |
| 39 | | | 68.0 | 72.5 | 77.5 | 82.5 | 88.5 | 94.0 |
| 40 | | | 68.5 | 73.0 | 78.0 | 83.5 | 89.0 | 94.5 |
| 41 | | | 69.5 | 73.5 | 78.5 | 84.0 | 89.5 | 95.0 |
| 42 | | | 70.0 | 74.0 | 79.0 | 84.5 | 90.0 | 95.5 |
| 43 | | | 70.5 | 75.0 | 80.0 | 85.0 | 90.5 | 96.0 |
| 44 | | | 71.5 | 75.5 | 80.5 | 85.5 | 91.0 | 96.5 |
| 45 | | | 72.0 | 76.0 | 81.0 | 86.0 | 91.5 | 97.5 |

* 68,000 may be carried on tandem axles spaced at least 36' apart

NOTE States that have a "table" in their law (See *Type of Restriction on other side*) may have slight weight differences for selected axles/distances due to rounding

NOTE All states applying Table B or Formula B restrict Interstate highways to 80,000 lbs

NOTE The higher 8' tandem weight is not a requirement of Formula B but rather is an interpretation by the federal government and has not necessarily been adopted by individual states

| Distance in feet between the extremes of any group or 2 or more consecutive axles | Maximum load in 1000 lbs carried on any group of 2 or more consecutive axles | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2 axles | 3 axles | 4 axles | 5 axles | 6 axles | 7 axles | 8 axles | 9 axles |
| 46 | | | 72.5 | 76.5 | 81.5 | 87.0 | 92.5 | 98.0 |
| 47 | | | 73.5 | 77.5 | 82.0 | 87.5 | 93.0 | 98.5 |
| 48 | | | 74.0 | 78.0 | 83.0 | 88.0 | 93.5 | 99.0 |
| 49 | | | 74.5 | 78.5 | 83.5 | 88.5 | 94.0 | 99.5 |
| 50 | | | 75.5 | 79.0 | 84.0 | 89.0 | 94.5 | 100.0 |
| 51 | | | 76.0 | 80.0 | 84.5 | 89.5 | 95.0 | 100.5 |
| 52 | | | 76.5 | 80.5 | 85.0 | 90.5 | 95.5 | 101.0 |
| 53 | | | 77.5 | 81.0 | 86.0 | 91.0 | 96.5 | 102.0 |
| 54 | | | 78.0 | 81.5 | 86.5 | 91.5 | 97.0 | 102.5 |
| 55 | | | 78.5 | 82.5 | 87.0 | 92.0 | 97.5 | 103.0 |
| 56 | | | 79.5 | 83.0 | 87.5 | 92.5 | 98.0 | 103.5 |
| 57 | | | 80.0 | 83.5 | 88.0 | 93.0 | 98.5 | 104.0 |
| 58 | | | | 84.0 | 89.0 | 94.0 | 99.0 | 104.5 |
| 59 | | | | 85.0 | 89.5 | 94.5 | 99.5 | 105.0 |
| 60 | | | | 85.5 | 90.0 | 95.0 | 100.5 | 105.5 |
| 61 | | | | 86.0 | 90.5 | 95.5 | 101.0 | 106.5 |
| 62 | | | | 86.5 | 91.0 | 96.0 | 101.5 | 107.0 |
| 63 | | | | 87.5 | 92.0 | 96.5 | 102.0 | 107.5 |
| 64 | | | | 88.0 | 92.5 | 97.5 | 102.5 | 108.0 |
| 65 | | | | 88.5 | 93.0 | 98.0 | 103.0 | 108.5 |
| 66 | | | | 89.0 | 93.5 | 98.5 | 103.5 | 109.0 |
| 67 | | | | 90.0 | 94.0 | 99.0 | 104.5 | |
| 68 | | | | 90.5 | 95.0 | 99.5 | 105.0 | |
| 69 | | | | 91.0 | 95.5 | 100.0 | 105.5 | |
| 70 | | | | 91.5 | 96.0 | 101.0 | 106.0 | |
| 71 | | | | 92.5 | 96.5 | 101.5 | 106.5 | |
| 72 | | | | 93.0 | 97.0 | 102.0 | 107.0 | |
| 73 | | | | 93.5 | 98.0 | 102.5 | 107.5 | |
| 74 | | | | 94.0 | 98.5 | 103.0 | 108.5 | |
| 75 | | | | 95.0 | 99.0 | 103.5 | 109.0 | |
| 76 | | | | 95.5 | 99.5 | 104.5 | | |
| 77 | | | | 96.0 | 100.0 | 105.0 | | |
| 78 | | | | 96.5 | 101.0 | 105.5 | | |
| 79 | | | | 97.5 | 101.5 | 106.0 | | |
| 80 | | | | 98.0 | 102.0 | 106.5 | | |
| 81 | | | | 98.5 | 102.5 | 107.0 | | |
| 82 | | | | 99.0 | 103.0 | 108.0 | | |
| 83 | | | | 100.0 | 104.0 | 108.5 | | |
| 84 | | | | | 104.5 | 109.0 | | |
| 85 | | | | | 105.0 | | | |
| 86 | | | | | 105.5 | | | |
| 87 | | | | | 106.0 | | | |
| 88 | | | | | 107.0 | | | |
| 89 | | | | | 107.5 | | | |
| 90 | | | | | 108.0 | | | |
| 91 | | | | | 108.5 | | | |
| 92 | | | | | 109.0 | | | |

Source: ATA, Summary of Size and Weight Limits, 1990.

On the other hand, 6-axle tractor-semitrailers and Twin 28s are limited by the 80,000 lbs GVW cap, since without the cap higher GVWs would be allowed by Bridge Formula B. A typical 6-axle tractor-semitrailer with a 48 ft trailer, a kingpin-to-rear-axle distance of 41 ft, a kingpin setting of 1 ft behind the second axle (giving a distance between extreme non-steering axles of 42 ft), and 12,000 lbs on the steering axle is allowed to 'gross-out' at 86,000 lbs under Bridge Formula B. With 3 ft between trailers and assumptions similar to those previously discussed for axle spacing, the Bridge Formula B GVW limits for Twin 28s range from 91,500 lbs for 5-axle Twin 28s to 110,000 lbs for 9-axle Twin 28s - with 7-axle and 8-axle Twin 28s 'grossing-out' at 99,500 lbs and 104,500 lbs, respectively.[4] For these tractor-semitrailer and Twin 28 configurations axle-weight limits are typically satisfied so that maximum practical GVWs are determined by the 80,000 lbs GVW cap. In practice, however, 7-axle, 8-axle, and 9-axle Twin 28s seldom adhere to the 80,000 lbs GVW cap and operate, <u>under special permit</u>, at higher weights that satisfy Bridge Formula B and axle-weight limits.

LCVs also operate beyond 80,000 lbs under special permit Where not restricted by a state's length limits, LCVs comply with GVW limits that are set by Bridge Formula B, axle-weight limits, and additional state specific requirements concerning horsepower, braking, linkage, driver training, weather restrictions, and route designation according to the type of LCV.[5] Under Bridge Formula B, a Rocky Mountain Double with 12,000 lbs on the steering axle, a 48 ft lead trailer, a 28 ft rear trailer, and 3 ft between trailers, is allowed to 'gross-out' at 108,500 lbs - assuming that the distance between extreme non-steering axles is at least 74 ft. Turnpike Doubles that have two 48 ft trailers, with 94 ft between extreme non-steering axles and 12,000 lbs on the steering axle, are allowed to operate at roughly 131,700 lbs under Bridge Formula B.

The flexibility to choose vehicles and payloads that meet their needs effectively and at the lowest cost is of great economic value to truck companies and individual truckers that transport freight to and from markets. For vehicle configurations that have 5 or more axles the maximum practical payload weight is the difference between the vehicle's empty weight and 80,000 lbs (maximum legal operating weight). This GVW limit constrains the maximization of fuel productivity for many carriers. At this, or any other, weight limit there is a freight density at which weight capacities are fully utilized. This is referred to as the **optimum density**. For finely divisible commodities, such as liquids, it is possible to load a vehicle to its optimum capacity. But for many other products, the 80,000 lbs GVW cap results in the inability to use some portion of the vehicle's potential capacity by restricting the weight of the items being shipped. To the extent that freight hauled is more than the optimum density, weighing-out situations occur. The 80,000 lbs capacity is reached before the alternative capacity can be realized. Such unused capacity is an opportunity cost that motor carriers must incur. This cost can be metered by losses in fuel productivity.

In this study, EEA investigates the fuel productivity effect of eliminating the 80,000 lbs GVW cap. Under this scenario, GVW would be controlled by weight limits set by the application of Bridge Formula B and by current axle-weight limits. It is assumed that no changes in state length limits take place. This policy would have no effect on those configurations that are limited in GVW by current axle-weight limits, such as, straight trucks, 4-axle tractor-combinations, and 5-axle tractor-combinations. Of course, other policy options are available regarding weight regulations (and have been studied extensively), such as redefining the bridge formula or changing axle-weight limits However, such proposals are more difficult to quantify in a systematic fashion and are beyond the scope of this study.

When both conventional tractor-semitrailers, 5-axle Twin 28s, and 7- to 9-axle Twin 28s are limited to 80,000 lbs, the 7- to 9-axle Twin 28s are much less productive because of their higher empty weights. Weight-limited carriers are better off operating 5-axle tractor-semitrailers since more payload can be carried, while size-limited carriers are better off operating 5-axle Twin 28s that are lighter and more fuel efficient. Under an uncapped Bridge Formula B scenario, 7-axle, 8-axle, or 9-axle Twin 28 operators would not need special permit to operate beyond 80,000 lbs GVW A policy that eliminates the 80,000 lbs cap is, therefore, expected to induce shifts from weight-limited 5-, 6-axle tractor-semitrailers and 5-axle Twin 28s to these heavier Twin 28s. Bridge Formula B GVW limits allow 7- to 9-axle Twin 28s to carry more payload and, thus, be more productive. Such a policy would not, however, affect the nationwide operation of LCVs. Even without the 80,000 lbs cap, operation of these vehicles would be restricted by most states' length limits. Given that this analysis assumes no changes in state size limits, the fuel productivity benefits of LCVs are recognized by comparing fuel productivity between LCVs and conventional configurations operating under the uncapped Bridge Formula B scenario (i.e., 5-, 6-axle tractor-semitrailers and Twin 28s).

As mentioned in the introduction to this section, EEA also analyzes the effects of empty mileage on fuel productivity. Unlike the elimination of the 80,000 lbs GVW cap, empty mileage affects all freight trucks.

### 3.3 ANALYTICAL METHODOLOGY

The fuel productivity analysis in this study requires only those trucks used for the movement of freight. As a result, GVW Classes 1, 2, 3, 4, and 5 (defined in Section 2) were not included in the analysis since vehicles in Classes 1, 2, and 3 are not predominantly used for this purpose and sales in Classes 4 and 5 are very low. The remaining classes reflect those trucks which are recognized by the trucking industry as predominantly commercial vehicles.

The analysis also excluded from the "active" data base those vehicles that are propelled by LPG or other fuels. As was shown in Section 2, on average less than half of a percent of the trucks in each GVW class have LPG or other engine types Disregarding such trucks was deemed appropriate since no statistically significant results could be drawn from analyzing them. As a result, only gasoline and diesel powered trucks are included in the fuel productivity analysis Classes 6, 7, and 8A consist of both gasoline and diesel trucks, while Class 8B consists of only diesel trucks.

Finally, those trucks whose greatest percentage of mileage was accrued off-road were also deleted from the "active" data base. Such vehicles do not operate on the interstate highway system and have physical and operational characteristics that are not consistent with commercial trucks. EEA also investigated the statistical differences between trucks that are predominantly used for agricultural services, rough use services (i e., construction, forestry and mining), and regular commercial services (such as, wholesale trade, retail trade, manufacturing, refining, or processing activities, etc). The statistical differences were not significant and a distinction in the analytical procedure was deemed inappropriate.

Fuel productivity is usually defined as ton-miles per gallon, or the number of freight ton-miles traveled per unit of fuel that is consumed. Therefore, to determine the effect of lifting the 80,000 lbs GVW cap and the effect of empty mileage on fuel productivity, it was necessary to devise models that explain the functional relationship between the rate of fuel consumption (as defined by GPM, or gallons of fuel consumed per miles traveled) and the variables that influence this rate These variables should theoretically represent actual operational and physical characteristics of a given vehicle, or vehicle class, so that when changes in these variables take place the rate of fuel consumption for that vehicle will adjust accordingly

Table 3-3 defines relevant TIUS variables used in the analysis. From these variables fuel productivity can be defined as (AVWGHT - EMWGHT) * MPG. The difference between AVWGHT and EMWGHT is the typical payload weight of a vehicle - since AVWGHT is defined as EMWGHT plus weight of cargo This difference multiplied by MPG equals, by definition, payload-miles (or ton-miles) traveled per gallon of fuel consumed. However, such an estimate of fuel productivity does not take into account the effect of empty mileage on fuel productivity or the effects of a vehicle's physical and operational characteristics on MPG [such as, the vehicle's engine size (CID) and horsepower (HRSPWR), the vehicle's age (MODELYR) and area of operation (AREAOP), or the presence of aerodynamic devices (AERODN) or a fuel economy engine (ECOENG)]

## TABLE 3-3

## DEFINITIONS OF TIUS VARIABLES

## USED IN THE ANALYSIS

| VARIABLE (TIUS) | DEFINITION |
|---|---|
| MPG | The number of miles-per-gallon that the vehicle averaged during 1987 |
| MODELYR | The model year of the vehicle, ranging from 1987 to 1976 Model year 1976 includes all pre-1976 model years as well |
| EMWGHT | The empty, or tare, weight of the vehicle expressed in tons |
| AVWGHT | The average weight (empty weight plus weight of cargo), expressed in tons, of a vehicle when carrying a typical payload |
| ANNMIL | The number of miles that the vehicle was driven during 1987 |
| PNOLOD | The approximate percentage of the vehicle's annual mileage that that no payload, or cargo, was carried |
| AREAOP | The area of operation of the vehicle AREAOP will be take on the following numbers if the particular condition is met<br><br>AREAOP=1 if the vehicle's greatest percentage of miles traveled were off-road<br>AREAOP=2 if the vehicle's greatest percentage of miles traveled were within a 50 mile radius of the vehicle's home base<br>AREAOP=3 if the vehicle's greatest percentage of miles traveled were within a 50 to 200 mile radius of homebase<br>AREAOP=4 if the vehicle's greatest percentage of miles traveled were beyond a 200 mile radius from home base |
| PCARSZ | The approximate percentage of annual miles that the vehicle carried payloads that filled its maximum cargo size This variable can be used as an index for the cube-out rate of the vehicle |
| PCARWT | The approximate percentage of annual miles that the vehicle carried payloads that filled its maximum cargo weight This variable can be used as an index for the weigh-out rate of the vehicle |
| CID | The size of the vehicle's engine, in cubic inches Rather than an actual number, a ranged coding scheme is used whereby the responder provides the range in which the vehicle's engine size falls |
| HRSPWR | The horsepower rating of the vehicle's engine As with CID, rather than an actual number, a ranged coding scheme is used whereby the responder provides the range in which the vehicle's horsepower rating falls |
| AERODN | AERODN=1 if the vehicle has aerodynamic features |
| ECOENG | ECOENG=1 if the vehicle has a fuel economy engine with low RPM, high torque rise, turbocharger, etc |

As a result, EEA used TIUS variables to define new variables that more accurately explain the factors that determine fuel productivity so that regression analysis could be employed to quantify the effect of physical and operational characteristics on a vehicle's fuel consumption rate (GPM). These EEA variables are defined in Table 3-4.

The variable WTDWGT1 is of special interest to the fuel productivity analysis. WTDWGT1 is defined as follows:

WTDWGT1 = ((AVWGHT*FRCLOAD)+(EMWGHT*FRCNLOAD))/EEAMAX,

where EEAMAX is defined as the high end of the GVW range for the vehicle in question. Therefore, WTDWGT1 describes the actual operating weight of the vehicle normalized to that vehicle's weight category The numerator of WTDWGT1 describes the weighted sum of the vehicle's average operating mass by employing as the weights the loaded to empty mileage ratio and the empty to loaded mileage ratio. The effect of WTDWGT1 on GPM is expected to be positive since the greater a mass the more energy input that is required to propel that mass into motion.

Engine control variables for engine size and horsepower were defined by EEA using TIUS variables, namely CID and HRSPWR. The purpose of EEA's CIDCTR and HPCTR variables was to recognize the effect of engine size or horsepower on a vehicle's fuel consumption rate. The expected relationship being that vehicles with large engines or high horsepower ratings have higher average GPMs

A vehicle's age is also expected to directly impact GPM, with older vehicles being relatively less efficient in the consumption of fuel than newer vehicles, given recent technological advances in engine and vehicle design that have improved fuel economy. To recognize this effect, EEA used TIUS's MODELYR variable to create MDLIDX.

## TABLE 3-4

## DEFINITIONS OF EEA VARIABLES

| VARIABLE (EEA) | DEFINITION |
|---|---|
| GPM | GPM = 1 / MPG<br>Defined as gallons-per-mile, the inverse of MPG |
| LGPM | LGPM = ln (GPM)<br>The natural log of GPM |
| MDLIDX | MDLIDX = MODELYR - 1976<br>Defined as model year index whose range of possible values is 1 to 11 |
| FRCLOAD | FRCLOAD = (100 - PNOLOD) / 100.<br>The fraction of annual mileage that the vehicle did carry a payload |
| FRCNLOAD | FRCNLOAD = PNOLOD / 100<br>The fraction of annual mileage that the vehicle did not carry a payload |
| EQUIVWT | EQUIVWT = (AVWGHT x FRCLOAD) + (EMWGHT x FRCNLOAD)<br>The equivalent weight, or average operating weight, of the vehicle accounting for empty mileage |
| EEAMAX | EEAMAX is defined as the high end of a vehicle's EEAGVW range, expressed in tons<br>EEAMAX = 13 0 for vehicles in GVW Class 5<br>EEAMAX = 16 5 for vehicles in GVW Class 6<br>EEAMAX = 30 0 for vehicles in GVW Class 7<br>EEAMAX = 40 0 for vehicles in GVW Class 8<br>EEAMAX = 70 0 for vehicles in GVW Class 9 |
| WTDWGT1 | WTDWGT1 = EQUIVWT / EEAMAX<br>The equivalent weight of the vehicle, normalized to that vehicles weight class |
| LWTWGT1 | LWTWGT1 = ln (WTDWGT1)<br>The natural log of WTDWGT1 |
| WTDWGT2 | WTDWGT2 = AVWGHT / EEAMAX<br>The average weight of the vehicle, not accounting for empty mileage, normalized to that vehicle's weight class |
| LWTWGT2 | LWTWGT2 = ln (WTDWGT2)<br>The natural log of WTDWGT2 |
| WTDWGT3 | WTDWGT3 = EMWGHT / EEAMAX<br>The empty weight of the vehicle, normalized to that vehicle's weight class |
| LWTWGT3 | LWTWGT3 = ln (WTDWGT3)<br>The natural log of WTDWGT3 |
| MIDCID | MIDCID is the midpoint of the reported CID range for a vehicle |
| MEANCID | MEANCID is the expected value, or mean, of the MIDCIDs for a give GVW class |
| CIDCTR | CIDCTR = MIDCID / MEANCID<br>A vehicle's approximate engine size, normalized to that vehicle's weight class |
| LCIDCTR | LCIDCTR = ln (CIDCTR)<br>The natural log of CIDCTR |
| MIDHP | MIDHP is the midpoint of the reported HRSPWR range for a vehicle |
| MEANHP | MEANHP is the expected value, or mean, of the MIDHPs for a given EEAGVW class |
| HPCTR | HPCTR = MIDHP / MEANHP<br>A vehicle's approximate horsepower rating, normalized to that vehicle's weight class |
| LHPCTR | LHPCTR = ln (HPCTR)<br>The natural log of HPCTR |
| DLOCAL | DLOCAL is a dummy variable that equals 1 when AREAOP equals 2 and DLOCAL equals 0 if AREAOP does not equal 2 |
| DAERO | DAERO is a dummy variable that equals 1 if AERODN equals 1 and DAERO equals 0 if AERODN does not equal 1 |
| DECO | DECO is a dummy variable that equals 1 if ECOENG equals 1 and DECO equals 0 if ECOENG does not equal 1 |

Finally, dummy variables were created to assess the impact of a vehicle's area of operation and the presence of fuel economy engines or aerodynamic devices. EEA used TIUS variables AREAOP, ECOENG, and AERODN to create dummy variables DLOCAL, DECO, and DAERO.

Various linear and log-linear model specifications, employing different combinations of the variables listed in Table 3-4, were tested to determine the most statistically significant model for each GVW class and fuel type combination. The following models were chosen based on their statistical and analytical significance:

- For gasoline powered trucks, irrespective of GVW class, the model that displayed the best statistical significance was;

  ln(GPM) = a+b*(MDLIDX)+c*ln(WTDWGT1)+d*ln(CIDCTR)+e*(DLOCAL)

- For diesel trucks with a GVW classification between 19,500 lbs and 60,000 lbs that model was;

  ln(GPM) = a+b*(MDLIDX)+c*ln(WTDWGT1)+d*ln(HPCTR)+e*(DLOCAL)+f*(DAERO)

- For diesel trucks in GVW Class 8B (60,000 lbs to 80,000 lbs) that model was;

  ln(GPM) = a+b*(MDLIDX)+c*ln(WTDWGT1)+d*ln(HPCTR)+e*(DLOCAL)+f*(DAERO)+ g*(DECO)

The significance of the coefficient of aerodynamic devices on gasoline trucks was not statistically different from zero, and thus the DAERO dummy variable was excluded from that model The coefficients displayed no statistical significance because of the small number of gasoline trucks that actually had aerodynamic devices. For example, of the gasoline vehicles in Class 5 only 1 0% had aerodynamic devices Of all gasoline trucks in Class 6 only 1 4% had aerodynamic devices, while of those in Class 7 only 0.9% had them (see Section 2). Similarly, other technology variables (such as the presence of radial tires, variable fan drives and fuel efficient axle or drive ratios) were tested but also did not display any statistical significance. Finally, note that the engine control variable that displayed the best statistical significance for gasoline powered trucks was engine displacement, rather than horsepower. The lack of variability in horsepower across a GVW class/gasoline combination explains this insignificance. The exact opposite was found to be true for diesel vehicles.

The statistical results of the chosen regression models are presented in Appendix A. The significance probabilities, or p values (shown in the output tables as Prob > |T|), indicate that the estimated coefficients are significant above the 95% significance level. The fitted models are presented in Table 3-5.

### 3.4 THE EFFECT OF EMPTY MILEAGE

Empty mileage usually takes place when a truck carries an empty backhaul (i e , carries a payload in one direction but not in the other). The 1980 Interstate Commerce Act abolished backhaul restrictions on the federal interstate highway system. Today any carrier which obtains Interstate Commerce operating authority - and does not, for example, carry food produce in one direction and hazardous waste in the other, as stipulated by the recent "Garbage Bill" - is free to carry backhaul loads and avoid empty mileage when traveling the interstate roads. However, the ability of a carrier to avoid empty mileage largely depends on logistical and managerial factors within the carrier's trucking company and on state laws regarding intra-state backhauls This section estimates the effect of empty mileage on fuel productivity and discusses possible policies that may minimize empty mileage.

The effect of empty mileage on fuel productivity can be estimated using the variables and regression models that were developed by EEA and explained in Section 3 3 If a vehicle experiences empty mileage in a given trip, then the vehicle's operating weight is represented by AVWGHT, or empty weight plus typical cargo weight. However, a vehicle on any given trip will incur some empty mileage and some loaded mileage. In such situations, the vehicle's operating weight will equal EQUIVWT, which is defined as the weighted sum of AVWGHT and EMWGHT WTDWGT3 must be used to estimate fuel consumption (GPM) when a truck operates empty, since it reflects a vehicle's operating weight when empty WTDWGT2 should be used to estimate fuel consumption when a truck

TABLE 3-5

LISTING OF FITTED MODELS

Model 1. GVW Class 6 (Gasoline Trucks)

LGPM = -1.7801 - 0.0049*MDLIDX + 0.2346*LWTWGT1 + 0.4403*LCIDCTR + 0.0503*DLOCAL
(0.0165) (0.0019) (0.0247) (0.0391) (0.0133)

Model 2: GVW Class 6 (Diesel Trucks)

LGPM = -1.7854 - 0.0278*MDLIDX + 0.2209*LWTWGT1 + 0.0966*LHPCTR + 0.0337*DLOCAL - 0.0691*DAERO
(0.0181) (0.0017) (0.0343) (0.0512) (0.0123) (0.0227)

Model 3: GVW Class 7 (Gasoline Trucks)

LGPM = -1.6990 - 0.0092*MDLIDX + 0.1963*LWTWGT1 + 0.5560*LCIDCTR + 0.0180*DLOCAL
(0.0235) (0.0025) (0.0316) (0.0602) (0.0193)

Model 4: GVW Class 7 (Diesel Trucks)

LGPM = -1.7435 - 0.0300*MDLIDX + 0.2336*LWTWGT1 + 0.0930*LHPCTR + 0.0635*DLOCAL - 0.0415*DAERO
(0.0172) (0.0017) (0.0314) (0.0522) (0.0125) (0.0228)

Model 5: GVW Class 8A (Gasoline Trucks)

LGPM = -1.5181 - 0.0102*MDLIDX + 0.1492*LWTWGT1 + 0.5729*LCIDCTR + 0.0416*DLOCAL
(0.3344) (0.0040) (0.0387) (0.0985) (0.0223)

Model 6: GVW Class 8A (Diesel Trucks)

LGPM = -1.6020 - 0.0112*MDLIDX + 0.1743*LWTWGT1 + 0.0630*LHPCTR + 0.0509*DLOCAL - 0.0573*DAERO
(0.0085) (0.0009) (0.0123) (0.0099) (0.0061) (0.0096)

Model 7: GVW Class 8B (Diesel Trucks)

LGPM = -1.5546 - 0.0112*MDLIDX + 0.0426*LWTWGT1 + 0.1113*LHPCTR + 0.0255*DLOCAL - 0.0181*DAERO - 0.0275*DECO
(0.0032) (0.004) (0.0058) (0.0072) (0.0029) (0.0043) (.0047)

---

Standard errors of the coefficients are shown in parenthesis.

For definitions of the variables see Table 3-4 carries a typical load, since it reflects a vehicle's operating weight when carrying cargo.

The potential gain in fuel productivity from eliminating empty mileage is calculated as follows:

$$G_{ij} = \left( \frac{MPG_C \times [AVWGHT - EMWGHT]}{[(FRCLOAD \times MPG_C) + (FRCNLOAD \times MPG_E)] \times [EQUIVWT - EMWGHT]} - 1 \right) \times 100$$

where,

$G_{ij}$ = Percent gain in fuel productivity for the average fuel type j truck in class i,
$MPG_C$ = Estimated MPG when carrying cargo,
$MPG_E$ = Estimated MPG when operating empty.

Payload when no empty mileage is incurred on an average trip is given by [AVWGHT - EMWGHT], and payload when some empty mileage is incurred is given by [EQUIVWT - EMWGHT]. Therefore, the numerator of the expression in parenthesis represents fuel productivity when empty mileage is not incurred in a given trip, while the denominator represents fuel productivity when some empty mileage is incurred.

Before MPG can be estimated under either definition, it is first necessary to determine the appropriate values for all the variables in a corresponding regression model Table 3-6 presents the statistical means by GVW class and engine type combination for some of the variables that were discussed in Section 3.3. These means can be interpreted as the average characteristics of a typical truck in a GVW class and engine type combination The mean for each regression variable can, therefore, be plugged into the corresponding model to estimate $GPM_E$ and $GPM_C$. For example, average $GPM_E$ for GVW Class 8B is calculated from Model 7 in Table 3-5 as:

TABLE 3-6

STATISTICAL MEANS OF SELECTED

VARIABLES BY GVW CLASS AND ENGINE TYPE COMBINATION

| | - GVW Class 6 - | | - GVW Class 7 - | | - GVW Class 8A - | | GVW Class 8B |
|---|---|---|---|---|---|---|---|
| | Gasoline | Diesel | Gasoline | Diesel | Gasoline | Diesel | Diesel |
| # of Obs | 5,159 | 2,425 | 2,401 | 2,238 | 2,166 | 8,973 | 19,974 |
| ANNMIL | 7,160 | 19,320 | 7,720 | 20,235 | 8,230 | 27,725 | 65,750 |
| MPG | 5.96 | 6.94 | 5 68 | 6.58 | 4.83 | 5.32 | 5.05 |
| EMWGHT[1] | 5 53 | 6.70 | 6.58 | 7.85 | 8 44 | 10.94 | 13.75 |
| AVWGHT[1] | 11.15 | 11.32 | 14.34 | 14.62 | 21 43 | 23.11 | 35.95 |
| FRCNLOAD | 0.36 | 0.29 | 0.36 | 0 28 | 0.41 | 0.33 | 0.31 |
| EQUIVWT[1] | 9.00 | 9.95 | 11.34 | 12.68 | 16.00 | 18.91 | 28.93 |
| MDLIDX[2] | 2 21 | 5.45 | 2 39 | 5.33 | 1 84 | 3.80 | 5.16 |
| % w/DLOCAL=1 | 84 40 | 66.10 | 86.20 | 66.40 | 86.30 | 63.40 | 25.40 |
| % w/DAERO=1 | 1 00 | 6.30 | 1.40 | 6.40 | 0 90 | 9.80 | 22.50 |
| % w/DECO=1 | 0.10 | 2.80 | 0.80 | 3.00 | 0.20 | 5.60 | 15.90 |
| LHPCTR | - | -0.0099 | - | -0.010 | - | -0.0485 | -0.0127 |
| LCIDCTR | -0.0077 | - | -0.0081 | - | -0 0027 | - | - |
| LWTWGT1 | -0.3863 | -0.2817 | -0.3967 | -0 2793 | -0 6499 | -0.4865 | -0.3444 |
| LWTWGT2 | -0 1633 | -0 1478 | -0.1483 | -0.1287 | -0.3510 | -0.2801 | -0.1200 |
| LWTWGT3 | -0.9035 | -0.7085 | -0.9781 | -0.7936 | -1 312 | -1 0604 | -1.1034 |

[1] Expressed in tons.

[2] This second block of variables give regression values used in estimating GPM.

$$LGPM_E = -1.5546 - 0.0112*(5.16) + 0.0426*(-1.1034) + 0.1113*(-0.0127) + 0.0255*(0.2540) - 0.0181*(0.2250) - 0.0275*(0.1590) = -1.6628$$

where, MDLIDX = 5.16, LWTWGT3 = -1.1034, LHPCTR = -0.0127, DLOCAL = 25.4%, DAERO = 22.5%, and DECO = 15.9% (see Table 3-6).

Taking the anti-log of -1.6628 gives 0.1896, or the estimate of average $GPM_E$. The inverse of 0.1896 defines $MPG_E$, which in this case equals 5.2743.

The same procedure can be used to estimate $MPG_C$ for GVW Class 8B under the WTDWGT2 definition of vehicle weight. Using LWTWGT2 instead of LWTWGT3, and assuming that all other variables remain constant, $MPG_C$ is estimated to be 5.0582.

Having estimated $MPG_E$ and $MPG_C$, $G_{ij}$ can be calculated from Class 8B's data in Table 3-6. Simply, payload when empty mileage is not incurred equals 22.20 tons. Payload when empty mileage is incurred equals 15.18 tons. It follows that fuel productivity is 112.29 ton-miles per gallon under no empty mileage and 77.81 ton-miles per gallon with empty mileage. As a result, $G_{8B,D}$ is estimated at 44.31%.

This procedure was performed for each GVW class and engine type combination. The results are presented in Table 3-7. It is clear that empty mileage has a severe detrimental effect on fuel productivity. Avoiding empty mileage can potentially increase fuel productivity by 33 to over 60 percent. However, there are many reasons why these increases will not be achieved. The ability of a carrier to avoid empty mileage greatly depends on logistical and managerial factors. First, a carrier may not have perfect information regarding the availability of a load, and miss the opportunity to carry it Even if perfect information exists, a carrier may choose to return empty rather than wait for the next available load if time restrictions are a concern. Second, irregular route, specific commodity carriers may never encounter traffic for which a corresponding backhaul exists within the constraints of commodity and point-to-point restrictions. Third, backhaul

TABLE 3-7

THE EFFECT OF EMPTY MILEAGE

ON FUEL PRODUCTIVITY

| GVW Class | Fuel Productivity[1] With Empty Mileage (WTDWGT1) | Fuel Productivity[1] Without Empty Mileage (WTDWGT2) | Potential Gain From Eliminating Empty Mileage |
|---|---|---|---|
| Class 6 Gasoline | 22.95 | 33 67 | 51 33% |
| Class 6 Diesel | 23.77 | 32.56 | 36.98% |
| Class 7 Gasoline | 28.82 | 44.17 | 53.26% |
| Class 7 Diesel | 33.65 | 45.04 | 33.80% |
| Class 8A Gasoline | 38.06 | 61.51 | 61.61% |
| Class 8A Diesel | 44.37 | 64.63 | 45.66% |
| Class 8B Diesel | 77 53 | 112.29 | 44.31% |

[1] Ton-miles per gallon

restrictions at the state level may not allow certain carriers to avoid empty mileage. Currently, approximately 30 states have economic regulations that prohibit intra-state backhauls For example, a carrier originating in Chicago with destination to San Antonio is not allowed (under Texas law) to transport a load from San Antonio to Houston on his/her return to Chicago. Such restrictions are of particular significance in larger states Finally, backhaul restrictions stemming from the "Garbage Bill" limit some carrier's ability to minimize empty backhauls. The "Garbage Bill" does not, for example, allow carriers who haul food produce in one direction to haul hazardous waste in the other For these reasons only a fraction of the potential benefit from eliminating empty mileage will be recoverable.

Trucking companies can alleviate the detrimental effects of empty mileage by introducing managerial and logistical techniques that identify available loads and better manage a carrier's route. For example, innovation has led some firms to find market niches where empty mileage can be minimized, while computerization has allowed managers to better coordinate routes and identify available loads Individual truckers, on the other hand, may not be able to implement innovative management processes or computerize their operations because of cost constraints and practical reasons. These truckers are specially hurt by empty mileage since fuel costs often account for a large portion of their total cost. Individual trucking practices are usually one-man operations that operate at small profit margins and cannot incur the additional cost of computerization or innovation.

From a policy perspective, a federal mandate that eliminates or relaxes backhaul restrictions at the state level may prove worthwhile Such a policy is likely to have a significant impact in large states, like Texas and California, where distances between markets are greater and trucks are often forced to incur empty backhauls for many miles Also, government sponsored clearinghouses that locate and inform individual truckers on an on-time basis about the availability of backhaul loads may prove to be helpful in eliminating the information problem. These clearinghouses would specifically help individual truckers and small trucking companies that have not computerized their operations. Such a program would be cost effective if a fee structure is designed that is economical to users and a revenue source to government.

### 3.5 FUEL PRODUCTIVITY UNDER AN UNCAPPED BRIDGE FORMULA B

This section quantifies fuel productivity gains from eliminating the 80,000 lbs GVW cap. Under this scenario, GVW would be controlled by existing axle-weight limits and by Bridge Formula B. As was shown in Section 3.2, allowable GVWs under the Bridge Formula are determined by the number of axles on a vehicle and the distance between the extremes of any group of 2 or more axles. Eliminating the 80,000 lbs GVW cap would not affect conventional 5-axle tractor-semitrailers, since these configurations cannot exceed 80,000 lbs without violating current axle-weight limits However, 6-axle tractor-semitrailers and Twin 28s would be directly affected by this policy. Under the uncapped Bridge Formula B scenario, 6-axle tractor-semitrailers would typically be allowed to operate at 86,000 lbs GVW, while 5-axle Twin 28s would be allowed to 'gross-out' at 91,500 lbs. Seven-axle, 8-axle, and 9-axle Twin 28s would be allowed to operate, without special permit, at 99,500 lbs, 104,500 lbs, and 110,000 lbs, respectively. The analysis assumes that no changes in state length limits will take place, and fuel productivity calculations are based on 48 ft semitrailers for tractor-semitrailer configurations and 28 ft trailers for double trailer configurations to assure that the benefits reflect nationwide operation. The nationwide operation of LCVs will not be affected. By definition these configurations are double trailers that have at least one trailer longer than 28 ft violating most states' length limits (see Table 3-1). The fuel productivity benefits of LCVs are recognized later in the section through fuel productivity comparisons with 5-axle, 6-axle tractor-semitrailers and Twin 28s operating under the uncapped Bridge Formula B scenario.

Fuel productivity changes resulting from the elimination of the 80,000 lbs GVW cap can be estimated by employing the regression model for GVW Class 8B that is specified in Section 3 3 Because GVW Classes 6, 7, and 8A do not include 5-axle or greater vehicle configurations, trucks in these classes are not affected by a policy that eliminates the 80,000 lbs GVW cap. Moreover, not all vehicles in GVW Class 8B will be affected by a policy that eliminates the 80,000 lbs GVW cap. Carriers that often carry light-density freight will rarely be weight-limited. These carriers will be limited by volumetric capacity and restrictions on the vehicle's size.** On the other hand, those vehicles in GVW Class 8B that carry high-density freight are often weight-limited by the 80,000 lbs cap.

To distinguish between the operational and physical characteristics of weight-limited vehicles versus all vehicles in GVW Class 8B, EEA employed TIUS' PCARWT variable Those vehicles in GVW Class 8B that exhibited a PCARWT value of greater than 75% were identified as being weight-limited by the GVW cap. Out of 19,974 vehicles in this class 3,276 met this criteria. However, TIUS data for GVW Class 8B does not distinguish between 5-axle, 6-axle, 7-axle, 8-axle, and 9-axle vehicle configurations To get around this problem EEA assumed the following:

- MDLIDX to be 11 and DAERO to be 1 for all configurations so that fuel productivity comparisons are made only between new vehicles equipped with drag reduction devices.
- For all configurations, the values for DLOCAL and DECO can be approximated from the statistical frequencies of weight-limited vehicles in GVW Class 8B (i e., those 3,276 trucks that met the PCARWT greater than 75% criterion).
- Horsepower ratings under the uncapped Bridge Formula B scenario increase by the same percentage as GVW for increasing axle configurations.

Table 3-8 presents the average physical and operational characteristics for these vehicle configurations under both the capped and uncapped Bridge Formula B scenarios (LCV data is shown for later reference). Statistical analysis was performed on weight-limited vehicles in Class 8B to determine the values for

** Volumetric capacity restrictions are not relevant in the immediate analysis since size limits remain constant But such restrictions are relevant when comparing fuel productivity between LCVs and conventional configurations Carriers that are currently transporting light density freight with Twin 28s will be able to increase payload by shifting to LCVs that have longer trailers

TABLE 3-8

PHYSICAL AND OPERATIONAL CHARACTERISTICS

OF WEIGHT-LIMITED 5-AXLE OR GREATER TRUCKS

| | 5-Axle Semi. | 6-Axle Semi. | 5-Axle Twin 28 | 7-Axle Twin 28 | 8-Axle Twin 28 | 9-Axle Twin 28 | Rocky Mt Doubles | Turnpike Doubles |
|---|---|---|---|---|---|---|---|---|
| Empty Weight (lbs)[1] | 26,800 | 28,300 | 30,000 | 34,200 | 36,700 | 39,200 | 36,000 | 45,000 |
| GVW Under 80,000 lb GVW Cap (lbs) | 80,000 | 80,000 | 80,000 | NA | NA | NA | NA | NA |
| GVW Under Uncapped Bridge Formula (lbs) | 80,000 | 86,000 | 91,500 | 99,500 | 104,500 | 110,000 | 108,500 | 131,700 |
| Payload Under 80,000 lb GVW cap (lbs) | 53,200 | 51,700 | 50,000 | NA | NA | NA | NA | NA |
| Payload Under Uncapped Bridge Formula (lbs) | 53,200 | 57,700 | 61,500 | 65,300 | 67,800 | 70,800 | 72,500 | 86,700 |
| $LHPCTR_c$[2] | 0.1068 | 0.1068 | 0.1068 | NA | NA | NA | NA | NA |
| $LHPCTR_u$[2] | 0.1068 | 0.1791 | 0 2411 | 0 3249 | 0.3739 | 0.4252 | 0.4115 | 0.6053 |
| MDLIDX | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| % w/DLOCAL=1 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 |
| % w/DAERO=1 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| % w/DECO=1 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 |

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1 Empty Weights reflect tractors pulling dry vans
Empty weight varies by trailer types and length of trailers

2 LHPCTR estimates reflect AVWGHT of 35.95 tons for Class 8B trucks (Table 3-6).

NA: Not applicable since these configurations seldom, if ever, operate below 80,001 lbs.

DLOCAL and DECO. The horsepower control variable for the uncapped Bridge Formula B scenario ($LHPCTR_u$) was scaled according to the percentage change in GVW between increasing axle configurations. Typical empty weights for different configurations were determined from conversations with staff at Jack Faucett Associates and the American Trucking Association, and reflect tractors pulling dry vans. The numbers for GVW under the uncapped Bridge Formula B are those that were derived in Section 3.2.*** Average operating GVW under the 80,000 lbs cap for 5-, 6-axle tractor-semitrailers and 5-axle Twin 28s is assumed to be 80,000 lbs since the analysis reflects weight-limited vehicles. For 7-axle, 8-axle, and 9-axle Twin 28s, GVW under the 80,000 lbs cap has no practical meaning, since these configurations seldom, if ever, operate below 80,001 lbs.

Having established the typical physical and operational characteristics of these vehicle configurations, fuel productivity estimates can be derived for both scenarios Regression Model 7 was used to calculate GPM under both GVW scenarios and, together with payloads in Table 3-8, fuel productivity estimates were derived Table 3-9 demonstrates the results of the calculations. In practice, most weight-limited carriers facing an 80,000 lbs GVW limit operate 5-axle tractor-semitrailers This is supported by the estimates in Table 3-9, which indicate that weight-limited operations of other than 5-axle tractor-semitrailers result in fuel productivity losses to the carrier. Higher empty weights of 6-axle tractor-semitrailers and 5-axle Twin 28s allow less payload to be carried when GVW is limited to 80,000 lbs.

In contrast, when the 80,000 lbs GVW cap is eliminated, Table 3-9 shows that the least productive configuration is a conventional 5-axle tractor-semitrailer. Lifting the GVW cap will result in substantial increases in the use of 6-axle tractor-semitrailers and Twin 28s, as weight-limited carriers shift away from 5-axle tractor-semitrailers to these configurations to take

*** Note that unlike the empty mileage analysis, estimating fuel productivity changes from eliminating the 80,000 lb GVW cap is not concerned with EQUIVWT since the concern is on fuel productivity differences when carrying a load.

TABLE 3-9

ESTIMATES OF FUEL PRODUCTIVITY GAINS

FROM ELIMINATING THE 80,000 lb GVW CAP

| Truck Configuration | Fuel Productivity[1] Under 80,000 lb GVW Cap | Fuel Productivity[1] Under Uncapped Bridge Formula B |
|---|---|---|
| 5-Axle Tractor-Semis | 142.86 | 142 86 |
| 6-Axle Tractor-Semis | 138.83 | 153.29 |
| 5-Axle Twin 28s | 134.27 | 161.76 |
| 7-Axle Twin 28s | NA | 169 61 |
| 8-Axle Twin 28s | NA | 174.74 |
| 9-Axle Twin 28s | NA | 181 07 |

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1 Ton-miles Per Gallon

NA: Not applicable since these configurations seldom, if ever, operate below 80,001 lbs.

advantage of higher fuel productivity. For example, the potential benefit to a weight-limited carrier of shifting from a 5-axle tractor-semitrailer to a 6-axle tractor-semitrailer is an increase in fuel productivity of about 7%. Shifts to 5-axle Twin 28s can result in a fuel productivity gains of approximately 13%, while shifts to 9-axle Twin 28s can result in a gain of roughly 27%. In the short-run, however, Twin 28s may not be practical for certain carriers because the ease of shifting to Twin configurations is constrained by the following factors:[6]

- Previous investment in expensive equipment of long life, particularly tanks, but also refrigerator units and concrete mixers,
- The extra cost of handling Twins, which increases as a proportion of total cost for short hauls,
- The extra cost of handling Twins in tightly constrained terminal areas,
- Possible capacity constraints of shippers and receivers because of limitations of space in existing facilities, particularly of van operations that serve dense urban areas with high space cost,
- Some shippers may be slow in changing production processes or modifying their facilities to take advantage of potential productivity improvements.

In the long run, the fuel productivity benefits of Twin 28s are expected to outweigh the costs of operating these configurations for those carriers that can benefit most from the added payload capacity. Terminal areas and existing facilities will be redesigned to accommodate the handling of Twin 28s, current equipment will depreciate and be replaced with Twin 28s, and shippers that were previously slow in recognizing the productivity benefits of 7-axle, 8-axle, and 9-axle Twin 28s will have reacted to potential gains

It should be noted that the analysis presented above describes maximum fuel productivity attainable under each scenario. The analysis assumes that new trucks operate at maximum payload capacity under both the capped and uncapped Bridge Formula B scenarios and that trucks incur no empty mileage on a given trip. Also, the estimated vehicle weight coefficient is lower in Model 7 than in those Models for lighter truck classes, suggesting that operating weight has less of an impact on the fuel consumption of Class 8B trucks than on the fuel consumption of trucks in lighter GVW classes. From an engineering standpoint, however, the effect of operating weight should be much higher (approximately 0.30) than the estimated value (0.0426), since this effect is expected to increases as the weight of the vehicle increases. EEA has conducted extensive analysis to identify inconsistencies inherent in the data, but must conclude that other unidentifiable compensating effects are driving Class 8B's LWTWGT1 coefficient to such a low level. With this caveat in mind, EEA is confident that the analysis does provide reliable estimates of potential fuel productivity gains from eliminating the 80,000 lbs GVW cap.

The Fuel Productivity of LCVs

Under assumptions made in this study, the nationwide operation of LCVs would not be affected by the elimination of the 80,000 lbs GVW cap because LCVs have longer trailer units that violate most state length limits. However, in those states where length restrictions allow their operation, carriers operating both size and weight-limited loads will benefit by shifting to LCVs when the 80,000 lbs GVW cap is lifted and permits are not required for their operation. This section characterizes the fuel productivity of Rocky Mountain Doubles and Turnpike Doubles through comparisons with 5-axle, 6-axle tractor-semitrailers and Twin 28s operating under the uncapped Bridge Formula B scenario.

In those states where length restrictions do not prohibit the operation of Rocky Mountain Doubles and Turnpike Doubles, lifting the 80,000 lbs GVW cap will affect carriers operating weight-limited Twin 28s and carriers operating size-limited 5-, 6-axle tractor-semitrailers or Twin 28s. As shown earlier in Section 3.5, weight-limited operators of 5- and 6-axle tractor-semitrailers benefit by shifting their operations to Twin 28s. Weight-limited carriers operating Twin 28s, on the other hand, can gain by shifting their operations to Rocky Mountain and Turnpike Doubles since these LCVs have longer distances between extreme axles and are thus allowed higher GVWs under Bridge Formula B. Size-limited carriers operating either 5-, 6-axle tractor-semitrailers or Twin

28s also benefit if allowed to switch to LCVs. Trailers pulled by LCVs are longer and have higher volumetric capacities.

Fuel productivity estimates, under a weight-limited scenario, for Rocky Mountain and Turnpike Doubles can be calculated using regression Model 7 and the physical and operational characteristics that are shown in Table 3-8 EEA estimated the fuel productivity of Rocky Mountain and Turnpike Doubles to be 185.80 and 216.42 ton-miles per gallon, respectively. Comparing these estimates to those for Twin 28s under the uncapped Bridge Formula B (Table 3-9) provides approximations of the fuel productivity gains possible from shifts to Rocky Mountain and Turnpike Doubles. Such shifts are estimated to result in increases of 2 6% to 15.0% for Rocky Mountain Doubles and of 19.0% to 33.8% for Turnpike Doubles. Of course, these benefits are not attainable on a nationwide scale, but are attainable in those states where length restrictions will not prohibit the operation of these LCVs when the 80,000 lbs GVW cap is lifted and special permits are no longer required.

Shifting from 5-, 6-axle tractor-semitrailers and Twin 28s to Rocky Mountain and Turnpike Doubles will also benefit those carriers that frequently carry size-limited cargo Size-limited carriers are constrained by the volumetric carrying capacity of the vehicle Table 3-10 shows the typical dimensions and the volumetric capacities of the hauling units of 5-, 6-axle tractor-semitrailers, Twin 28s and these LCVs The volumetric capacities of Rocky Mountain and Turnpike Doubles are greater than those of other truck configurations. For example, shifting from any Twin 28 to a Rocky Mountain Double results with a gain in volumetric capacity of 2,941 cubic ft, while a shift to Turnpike Doubles results with a gain of 5,406 cubic ft.

However, gains in volumetric capacity must be translated into fuel productivity benefits This translation requires data describing the typical freight densities at which size-limited vehicles operate These densities can then be used as a baseline to calculate the potential payload gains that result from shifts to these LCVs. Typical payloads for cube-limited tractors pulling dry vans were determined from publications by Jack Faucett Associates.

TABLE 3-10

TYPICAL DIMENSIONS AND VOLUMETRIC CAPACITIES

FOR 5-, 6-AXLE TRACTOR-SEMIS, TWIN 28s, AND LCVs

| | 5-Axle Semi. | 6-Axle Semi. | 5-Axle Twin 28 | 7-Axle Twin 28 | 8-Axle Twin 28 | 9-Axle Twin 28 | 7-Axle LCV | 9-Axle LCV |
|---|---|---|---|---|---|---|---|---|
| Trailer(s) Width (in) | 102 | 102 | 102 | 102 | 102 | 102 | 102 | 102 |
| Trailer(s) Height[1] (ft) | 13 5 | 13.5 | 13.5 | 13 5 | 13 5 | 13.5 | 14 5 | 14.5 |
| Trailer(s) Total Length (ft) | 48.0 | 48 0 | 56 0 | 56.0 | 56.0 | 56.0 | 76.0 | 96.0 |
| Estimated Volumetric Capacity (cubic ft) | 5,508 | 5,508 | 6,426 | 6,426 | 6,426 | 6,426 | 9,367 | 11,832 |

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[1] Most states limit the maximum height of the trailer(s) on tractor-semis and Twin 28s to 13 1/2 feet However, LCVs usually are allowed to pull trailers that are 14 1/2 feet high

The typical payload for cube-limited 5-, 6-axle tractor-semitrailers and Twin 28s are estimated at 24,500 lbs and 28,600 lbs, respectively.[7] At an average payload of 28,600 lbs, cube-limited Twin 28s operate with a typical freight density of 4.45 pounds per cubic ft. Recognizing that Rocky Mountain and Turnpike Doubles have volumetric capacities that are 2,941 and 5,406 cubic ft greater than Twin 28s, average payload for these LCVs can be approximated if the freight density for cube-limited Twin 28s is held constant. At a freight density of 4.45 pounds per cubic ft, a Rocky Mountain Double can carry payloads that are approximately 13,100 lbs greater than the typical Twin 28, while a Turnpike Double can approximately carry an additional 24,100 lbs when compared to cube-limited Twin 28s. Therefore, Rocky Mountain Doubles are expected to operate with an average payload of 41,700 lbs, while Turnpike Doubles are expected to operate with an average payload of 52,700 lbs.

Having determined the average payload weight of size-limited 5-, 6-axle tractor-semitrailers, Twin 28s, Rocky Mountain, and Turnpike Doubles, fuel productivity estimates can be derived for size-limited vehicles using Model 7 and the typical physical and operational characteristics presented in Table 3-11. Data for size-limited trucks in GVW Class 8B was used to determine the values for DLOCAL and DECO. LHPCTR was scaled in accordance with increasing GVWs across axle configurations. The values for MDLIDX and DAERO implicitly assume that fuel productivity comparisons are made between new vehicles.

Table 3-12 shows fuel productivity estimates for size-limited 5- and 6-axle tractor-semitrailers, Twin 28s, Rocky Mountain Doubles, and Turnpike Doubles Fuel productivity for size-limited Twin 28s slightly decreases with increasing axles. This is because at a constant freight density, Twin 28s carry the same payload weight without regard to the number of axles on the vehicle. But as the number of axles increase the empty weight and total weight of the vehicles increase without a payload gain As weight increases MPG decreases while payload remains constant. So, fuel productivity decreases as the number of axles increase. However, the fuel productivity benefits from shifting to

TABLE 3-11

PHYSICAL AND OPERATIONAL CHARACTERISTICS

OF SIZE-LIMITED 5-AXLE OR GREATER TRUCKS

| | 5-Axle Semi. | 6-Axle Semi. | 5-Axle Twin 28 | 7-Axle Twin 28 | 8-Axle Twin 28 | 9-Axle Twin 28 | Rocky Mt Double | Turnpike Double |
|---|---|---|---|---|---|---|---|---|
| Empty Weight (lbs) | 26,800 | 28,300 | 30,000 | 34,200 | 36,700 | 39,200 | 36,000 | 45,000 |
| Estimated Payload Weight (lbs) | 24,500 | 24,500 | 28,600 | 28,600 | 28,600 | 28,600 | 41,700 | 52,700 |
| GVW Under Uncapped Bridge Formula (lbs) | 51,300 | 52,800 | 58,600 | 62,800 | 65,300 | 67,800 | 77,700 | 97,700 |
| LHPCTR[1] | -0 3376 | -0.3088 | -0.2045 | -0.1353 | -0.0963 | -0.0587 | -0.0776 | -0.3066 |
| MDLIDX | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 |
| % w/DLOCAL=1 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 |
| % w/DAERO=1 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| % w/DECO=1 | 25.4 | 25 4 | 25.4 | 25.4 | 25.4 | 25.4 | 25.4 | 25.4 |

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1 LHPCTR estimates reflect AVWGHT of 35 95 tons for Class 8B trucks (Table 3-6).

TABLE 3-12

FUEL PRODUCTIVITY ESTIMATES FOR SIZE-LIMITED

VEHICLES AND POTENTIAL GAINS FROM SHIFTS TO LCVs

| Truck Configuration | Fuel Productivity[1] With Uncapped Bridge Formula | Potential Gain From Shifting to Rocky Mt Doubles | Potential Gain From Shifting to Turnpike Doubles |
|---|---|---|---|
| 5-Axle Tractor-Semis. | 70.52 | 59 7% | 94.8% |
| 6-Axle Tractor-Semis. | 70.24 | 60 4% | 95.6% |
| 5-Axle Twin 28s | 80 70 | 39.6% | 70.2% |
| 7-Axle Twin 28s | 79.84 | 41 1% | 72.1% |
| 8-Axle Twin 28s | 79.36 | 41.9% | 73.1% |
| 9-Axle Twin 28s | 78.87 | 42.8% | 74.2% |
| Rocky Mountain Doubles | 112.64 | NA | NA |
| Turnpike Doubles | 137.38 | NA | NA |

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[1] Ton-Miles Per Gallon
NA - Not Applicable

Rocky Mountain and Turnpike Doubles from Twin 28s and tractor-semitrailers are substantial to cube-limited carriers. As shown in Table 3-12, shifts to Rocky Mountain Doubles result in potential fuel productivity gains that range from 39.6% to 60.4%. Shifts to Turnpike Doubles result in gains that range from 70.2% to 95.6%. Of course, these benefits are not attainable on a nationwide scale, but only in those states where length restrictions will not prohibit the operation of these LCVs when the 80,000 lbs GVW cap is lifted and special permits are no longer required.

As in the analysis of fuel productivity gains from eliminating the 80,000 lbs GVW cap, the estimates calculated for LCVs and size-limited conventional truck configurations are derived under the assumption that trucks operate at maximum payload and cubic capacities, incurring no empty mileage. Therefore, the fuel productivity estimates presented under the discussion of LCVs are also absolute maximums. The LCV discussion also assumes that fuel consumption of Rocky Mountain and Turnpike Doubles can be estimated from the regression model for GVW Class 8B (i.e., Model 7) Given that these LCVs have distinct physical and operational characteristics than Class 8B trucks, Model 7 may not be altogether representative of LCV fuel consumption.

To account for this possibility, Model 8 using data for TIUS trucks rated at above 80,000 lbs GVW (defined as Class 9 trucks) was formulated. It is evident from the data, however, that Class 9 includes many different truck configurations and is not wholly defined by LCVs. To single out LCVs, Class 9 trucks were further disaggregated by type of use - rough, agricultural, and regular. Model 8 only uses data for regular use Class 9 trucks and, therefore, is expected to roughly represent LCVs.

Statistical results of Model 8 are presented in Appendix A, while the fitted model is shown below.

LGPM = -1.4320-0 0092(MDLIDX)+0.0616(LWTWGT1)+0 1489(LHPCTR)-0.0591(DECO).

Using this model and data from Tables 3-8 and 3-11, an alternative estimate of fuel productivity for Rocky Mountain and Turnpike Doubles can be derived. Under a weight-limited scenario, the fuel productivity of Rocky Mountain Doubles is estimated at 165.30 ton-miles per gallon and that of Turnpike Doubles is estimated at 189.8 ton-miles per gallon. Under a size-limited scenario, fuel productivity is estimated at 102.21 and 123.07 ton-miles per gallon, respectively[****] In either case, LCV fuel productivity is much lower when estimates are derived using Model 8. However, since it is not inconclusive that Class 9 (regular use) represents only LCVs, the estimates derived from Model 8 should be regarded as conservatively low, since other configurations with inefficient engines may be included.

## 3.6 SUMMARY OF RESULTS

This section of the report has investigated two factors that greatly influence fuel productivity, as defined by ton-miles per gallon of fuel consumed. These factors are. 1) the prevalence of empty mileage, or mileage incurred when a truck is not carrying payload, and 2) the effect of lifting the 80,000 lbs GVW cap that is imposed by the Federal government on trucks travelling the interstate highway system and other federally-aided roads Empty mileage affects all commercial trucks, while the 80,000 lbs GVW weight limit constrains the payload capacity of heavier trucks, usually 5-axle or greater configurations.

Empty mileage has a severe detrimental impact on fuel productivity, since when a truck operates empty fuel productivity is equal to zero EEA determined that avoiding empty mileage can potentially increase fuel productivity by 35 to over 60 percent, depending on GVW class and engine type combination. However, there are many reasons why these potential increases will not be realized; such as, the lack of perfect information regarding available hauls, time restrictions, and backhaul restrictions at the state level

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[****] Estimates for Rock Mountain Doubles using model 8 are based on a LHPCTR of 0 1371 (weight-limited) and -0.1968 (size-limited) For Turnpike Doubles they are based on a LHPCTR of 0.3309 (weight-limited) and 0 0322 (size-limited) AVWGHT for class 9 regular use trucks is 47.3 tons.

Nevertheless, there are measures that can be taken by trucking companies and government to alleviate the impact of empty mileage. These measures are:

- The introduction of managerial and logistical techniques by trucking companies that identify available loads and better manage a carrier's route.
- A federal mandate that eliminates or relaxes backhaul restrictions at the state level, which is expected to have a disproportionate impact in larger states where carriers are often forced to incur empty backhauls for many miles.
- Government sponsored clearinghouses that locate and inform individual truckers about the availability of backhaul loads

The current 80,000 lbs GVW cap results in the inability of a carrier to use some portion of the vehicle's potential capacity by restricting the weight of the items being shipped Payload capacity is determined by the difference between the truck's maximum practical GVW and it's empty (or tare) weight Carriers operating Class 8B trucks that haul high density freight are often weight-limited by the 80,000 lbs GVW cap. The weight limit does not allow the carrier to load the truck to its optimum density where weight and size capacities are fully utilized Such foregone capacity penalizes fuel productivity and translates into an opportunity cost to the carrier.

A policy that eliminates the 80,000 lbs GVW cap, and limits GVW through axle-load limits and Federal Bridge Formula B, will result in substantial increases in the use of 6-axle tractor semitrailers and Twin 28s, as weight-limited carriers shift away from 5-axle tractor-semitrailers to these configurations to take advantage of higher fuel productivity. This higher productivity results because axle-weight limits constrain the maximum practical GVW of 5-axle tractor-semitrailers to 80,000 lbs even under an uncapped Bridge Formula B scenario On the other hand, 6-axle tractor-semitrailers and Twin 28s would be allowed to operate beyond 80,000 lbs under Bridge Formula B and current axle-load limits if the GVW cap is lifted. Payload gains of shifting to these configurations are expected to be greater than the empty weight penalties that these heavier configurations impose.

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# 4. TECHNOLOGICAL IMPROVEMENTS TO TRUCKS

## 4.1 OVERVIEW

In the medium and heavy duty truck segments considered in the analysis, the diesel engine has a commanding market share. The medium-duty truck market (19,000 to 50,000 lb) is over 80 percent diesel, while the heavy-duty market has been completely dieselized for over a decade. It is widely anticipated that by the end of this decade, the gasoline engine may be limited to some small specialized niches, or be used after conversion to compressed natural gas use. This analysis concentrates primarily on diesel powered medium and heavy-duty truck technology and the potential for improvement in fuel economy. The analysis utilizes 1987 as a base year, and TIUS fuel economy data for 1987 are used for baseline fuel economy estimates.

Current diesel powered trucks are already very fuel efficient relative to their weight. For example, a fully loaded 80,000 lb truck can attain a fuel economy of 7 to 8 MPG on the highway, which translates to 280 to 320 ton-miles per gallon. In contrast, a gasoline powered car which weighs 5000 lbs or less fully loaded can attain a fuel economy of 26 to 30 MPG or 65 to 75 ton-miles per gallon. It is difficult to increase the diesel trucks fuel economy by very large amounts in the future without affecting payload capacity

Using the laws of motion and conservation of energy it is simple to show that fuel consumption (the inverse of fuel economy) is given by·

$$FC = \frac{\overline{bsfc}}{\eta_d} [E_R + E_A + E_K] + \overline{bsfc}\ E_{ac} + G(t_i + t_b).$$

Where, $\overline{bsfc}$ is the average brake specific fuel consumption of the engine,

$\eta_d$ is the transmission efficiency,

$E_R$ is the energy required to overcome rolling resistance,

$E_A$ is the energy required to overcome aerodynamic drag,

$E_K$ is the energy lost to inertia forces during acceleration or climbing gradients,

$E_{ac}$ is the energy used by accessories,

G is idle fuel consumption,

$t_i$ is time at idle,

$t_b$ is time of braking.

For large diesel trucks, $E_{ac}$ is generally small relative to $E_A$, $E_K$, and $E_R$ Depending on the cycle, the value of $G(t_i + t_b)$, which represents fuel used during periods of no useful engine output, can be quite small since G, idle fuel consumption per unit time, is low for a diesel engine.

The above equation points to methods to improve fuel consumption Improvements to bsfc can be accomplished by:

- increasing engine thermodynamic efficiency,
- reducing friction loss,
- reducing pumping loss, and
- increasing turbocharger efficiency

Fuel consumption can also be reduced by reducing the vehicle related parameters of weight, drag and rolling resistance or reducing accessory loads. Idle fuel consumption can be reduced by reducing idle time, i.e. switching off at idle, and by reducing the engine displacement. In the case of weight reduction, we are referring to the empty weight of the truck. Reduction in empty weight will reduce truck total weight, allowing either an absolute weight reduction or an increased payload capacity (when trucks are limited by the weight rather than the size of the payload).

## 4.2 FUEL CONSUMPTION SENSITIVITY

The sensitivity of fuel consumption over any specific driving cycle to a particular independent truck attribute, such as weight, can be represented as the derivative of the equation relating fuel consumption to these variables, and physically represents the percent change in fuel consumption due to a unit change in the variable (e.g., a 10 percent change in the weight results in a 'X percent' change in fuel consumption).

Volvo provided a general set of values for the energy demanded (and, hence, fuel consumed) over a typical European long haul cycle. These values are:

| | |
|---|---|
| Inertia (Weight) | 48.9 % |
| Aerodynamic Drag | 17.4 % |
| Rolling Resistance | 24.6 % |
| Drivetrain losses | 5 0 % |
| Accessories | 3.8 % |

The above figures do not explicitly refer to idling and braking energy loss. Moreover, Volvo stated that these figures are for a highly aerodynamic truck, and that average values for aerodynamic losses on a U.S. highway cycle were considerably higher. Other manufacturers suggested that, depending on the cycle, aerodynamic drag could account for 30 to 50 percent of energy loss, while inertia related losses were in the 30 to 40 percent range, at highway speeds.

Volvo and Navistar provided data from computer simulations of the same truck/engine combination loaded to different weights Volvo provided data on two trucks, a medium duty (Class 7) truck and a F12 longhaul truck rated at 100,000 lb GVW (50 tons). Class 7 trucks had a nominal fuel consumption of 30 l/100 km at 15 tons GVW and a sensitivity of 1.12 l/100 km per ton in city driving. This leads to a sensitivity coefficient of 0.55, i.e. a 10 percent weight decrease results in a 5.5 percent fuel consumption decrease. The F12 truck had a nominal consumption of 50 l/100 km at 55 tons GVW on a long haul driving cycle, and a sensitivity of 0.65 l/100 km per ton. This represents a sensitivity coefficient of 0.715, which appears to be very high relative to other opinions. However, this is consistent with the energy breakdown provided by Volvo, as weight reduction reduces both inertial and rolling resistance energy loss, which Volvo determined as being 73.5 percent of total energy.

Navistar provided data on fuel economy for a Class 6, a Class 8A, and a Class 8B truck over two driving cycles, at different loaded weights. The Navistar data is shown in Table 4-1. Using these data EEA calculated the sensitivity coefficients for different truck classes as follows:

| GVW Class | City | Highway |
|---|---|---|
| 6 | 0.307 | 0.146 |
| 7/8A | 0.369 | 0.188 |
| 8B | 0.523 | 0.298 |

These coefficients are much lower than those shown by Volvo, and are more consistent with the results from regression analysis of TIUS data. For example, TIUS data shows a weight sensitivity of roughly 22 percent for Class 6/7 trucks, which is between the city and highway coefficients shown above. However, the TIUS data shows a much lower sensitivity for Class 8B trucks that are at odds with predicted trends shown above, as well as with the absolute magnitude. Actual testing conducted on Class 8B trucks by Freightliner Corporation showed that a 80,000 lb truck with a fuel consumption of 4 MPG (0.25 GPM) had a fuel consumption decrease of 0.0029 GPM per ton weight increase, for a sensitivity of 0.46, intermediate to the city/highway values predicted by Navistar's simulation.

Aerodynamic drag reduction sensitivity factors have not yet relied on accurate measurements of $C_D$ reduction versus fuel economy on a fixed test cycle The only comprehensive data on $C_D$ reductions and fuel savings is based on study of a roof fairing for a 80,000 lb tractor trailer, conducted by GMC [2/] The measured drag coefficient for the base (no aerodynamic device) tractor trailer was a $C_D$ of 0.770. Typical reductions of $C_D$ were measured at different yaw angles with the aerodynamic device and a mean (wind averaged) value of $\Delta C_D$ was

**TABLE 4-1**

**SENSITIVITY OF FUEL ECONOMY**

**TO TRUCK LOAD**

Class 6 Truck, 155 HP 7.3 L Navistar diesel.

| Gross Weight | City F/E | Highway F/E |
|---|---|---|
| 8,000 | 9.48 | 9.50 |
| 13,000 | 8.72 | 9.14 |
| 18,000 | 8 17 | 8.79 |
| 23,000 | 7.63 | 8.50 |
| 28,000 | 7.15 | 8.24 |

Class 8A Truck, 210 HP DT 466 Navistar diesel.

| | | |
|---|---|---|
| 10,000 | 9.41 | 8.68 |
| 15,000 | 8.22 | 8 40 |
| 20,000 | 8.13 | 8.14 |
| 25,000 | 7.60 | 7 88 |
| 30,000 | 7.14 | 7.41 |
| 35,000 | 6.72 | 7 20 |
| 40,000 | 6.34 | 7 01 |

Class 8B Truck, Cummins NTC engine.

| | | |
|---|---|---|
| 30,000 | 6.59 | 8 42 |
| 40,000 | 5.99 | 8.04 |
| 50,000 | 5.49 | 7 69 |
| 60,000 | 5.05 | 7.35 |
| 70,000 | 4.68 | 7 04 |
| 80,000 | 4.35 | 6.75 |

Source: Navistar Simulation City Speed: 18.6 MPH
Highway Speed: 53.0 MPH

found to be 0.170. Fuel savings were measured on track tests conducted at 55 mph. Fuel economy increased from 6.3 mpg without the device to 6.93 mpg with the device, providing a sensitivity of 0.453 for drag reduction. Truck industry experts confirm that a 10 percent drag reduction provides about 5 percent fuel economy benefit at highway speeds closely matching the calculated coefficient. The Volvo data indicates a coefficient of only 0.25 which appears low but is consistent with the high inertial loss claimed by Volvo.

Since the sum of aerodynamic drag forces and inertial & rolling resistance forces represents the total force to be overcome, the drag sensitivity coefficient is related to the inertial & rolling resistance (weight) sensitivity coefficient. The reduced weight sensitivity coefficient translates to a higher drag sensitivity for medium-duty trucks. At highway speeds, medium-duty trucks can have a coefficient for drag as high as 0.75. This is consistent with engineering expectation since the product of drag coefficient and frontal area is nearly constant for all trucks from Class 6 to 8B while weight varies by a factor of 4. Hence, at the lightest weight, drag is a much more significant factor than weight at the same speed.

Power consumed due to aerodynamic drag scales as the cube of speed. At city speeds of 19 mph, the highway sensitivity coefficient for a Class 8 truck should decrease by the cube of the speed ratio, hence

$$\text{Sensitivity at 19mph} = 0\ 453 \times \left(\frac{19}{55}\right)^3 = 0.019$$

The small coefficient has not been verified by confirmatory testing. A similar calculation for Class 6/7 truck at 19 mph indicates a sensitivity factor of 0.031.

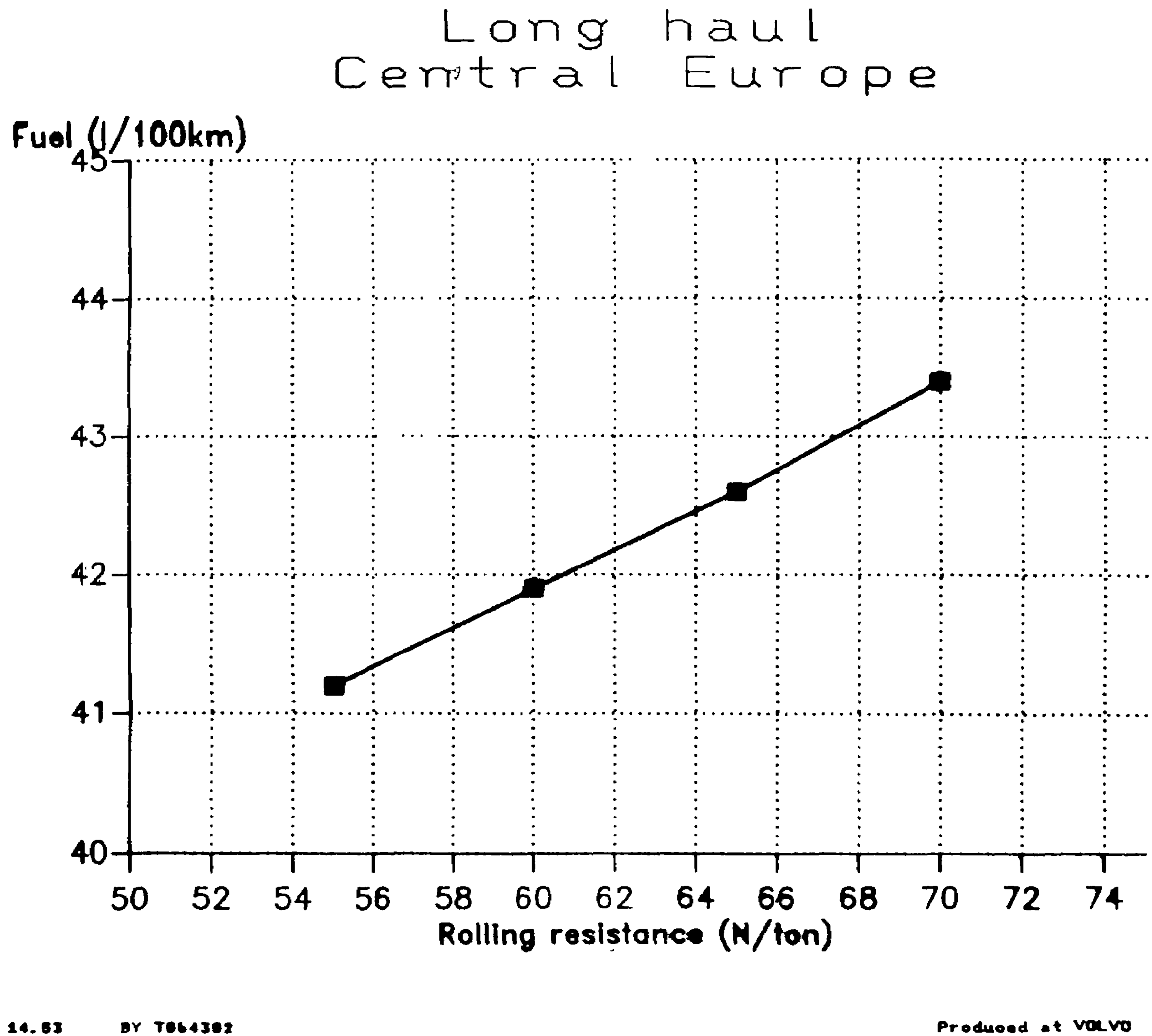
Tire rolling resistance changes have a large effect on fuel economy It should be noted that total rolling resistance is a function of both truck weight and the tire rolling resistance coefficient. The weight effect calculated includes both the rolling resistance effect and the reduced inertia loss effect, while the change in the rolling resistance coefficient effects only the tire losses. A study by Goodyear[3/] on the correlation between tire rolling resistance and fuel economy provided data on the sensitivity to the rolling resistance coefficient. The study was performed on a 78,700 lb GVW tractor trailer at 60 mph. The study showed the following relationship between the rolling resistance coefficient and fuel economy:

| | Rolling Resistance | | Fuel Economy | |
|---|---|---|---|---|
| | Value | % Change | Value | % Change |
| Bias ply | 43.9 | Base | 4.10 | Base |
| Radial A | 39.9 | -9.1 | 4 27 | 4 2 |
| Radial B | 37.7 | -14.1 | 4.34 | 5.8 |

The factors indicate an average rolling resistance sensitivity of 0.4. Volvo provided data on a 80,000 lb tractor-trailer on a long haul European cycle with tires of different rolling resistance, and the data is shown in Figure 4-1. The data indicates a sensitivity of 0.237. This lower figure is also indicated in the Goodyear study cited above, as the sensitivity to tire rolling resistance decreases with decreasing speed and weight. For example, an empty truck was cited as having a sensitivity of 0.17 to 0.2 at 60 mph Coefficients in the range of 0 25 to 0.35 are cited by many experts. The sensitivity factors scaling with speed or weight are not well studied. It is also likely that the rolling resistance of drive tires that transmit torque to the road have a greater impact on fuel economy than those used in axles that do not transmit torque Unfortunately, there is no data to support separate or independent analysis of those effects.

There is general and widespread agreement that typical driveline efficiencies are 93 to 95 percent (i.e., 5 to 7 percent of engine torque is lost in the driveline) for manual transmission equipped vehicles. Automatic transmissions are currently sold in some medium duty trucks and in buses, which may have higher Losses.

Figure 4-1



Long haul
Central Europe
Fuel (l/100km)
45
44
43
42
41
40
50
52
54
56
58
60
62
64
66
68
70
72
74
Rolling resistance (N/ton)
1991-02-01 14.53
BY T864302
Produced at VOLVO

Lastly, accessory drive losses for engines equipped with a variable fan drive are typically in the 4 to 6 percent range for medium duty trucks, and somewhat lower (3 to 5 percent) range for Class 8B trucks. Truck manufacturers suggest that variable fan drives are used in over 90 percent of diesel engine powered trucks.

## 4.3 WEIGHT REDUCTION

Weight reduction measures are actively being undertaken by truck manufacturers in both medium-duty and heavy-duty truck classes. In most cases, the weight reduction is largely due to two specific reasons:

- the substitution of plastic and aluminum components for steel components
- the use of more modern, high BMEP engines that weigh much less than older engines of the same power rating.

Weight reduction by material substitution has been widely introduced by all major manufacturers in the last three or four years The cab (for non-sleeper type cabs) is generally a common design used across all trucks from Class 5 to 8B, and plastic hoods and fenders have been introduced by Freightliner, Paccar, and Ford. For example, Ford uses a Reaction Injection Molded (RIM) hood in their new Aeromax trucks. The items are considered to be cost-effective based only on production cost and have been introduced regardless of the fuel savings potential. Aluminum is, however, a relatively expensive option The Aluminum Association has conducted a study of weight savings in certain load bearing parts as shown in Table 4-2, and this study indicates a weight saving of up to 900 lbs on a Class 8 tractor Currently, none of these parts are made from aluminum, although Navistar offers special truck models with aluminum frame rails as an option. The estimates in Table 4-2 may be optimistic, as is the usual case with supplier provided data.

Navistar, however, does offer an aluminum cab that offers a weight saving of 160 to 200 lb over a steel cab, depending on the model The cost for this option is about $2000, equivalent to $10 to $12 per pound saved Navistar indicated that aluminum frame rails were appropriately the same cost as a per

## TABLE 4-2

## WEIGHT SAVINGS FOR SPECIFIC ALUMINUM PARTS

| Part | Weight Savings Per Vehicle, Lbs |
|---|---|
| Front Bumper | 37 |
| Front and Rear Hubs | 220 |
| Front Wheels | 22 |
| Drive Axle Wheels | 90 |
| Rear Axle Carrier Housing | 71 |
| Rear Axle Carrier Housing | 110 |
| Rear Axle Carrier Housing | 131 |
| Frame Rails | 200 |
| Fuel Tank (100 gallons) | 30 |
| Air starter with aluminum air reservoir | 47 |

pound saved basis. The high prices are, to a degree, a function of the limited sales volume of these options. In general, neither Volvo nor Navistar expected or had specific programs for (large) weight reduction through material substitution, but expected 100 to 200 lbs in weight savings over the next ten years. Volvo stated the weight reduction potential was 500 kg (1100 lbs) for the tractor, and up to 500 kg for the trailer for a Class 8B combination truck. Volvo stated that Class 6/7 trucks had only a 200 kg weight reduction potential. However, it was not clear that these potential reduction levels could be obtained in a cost-effective manner.

Weight reduction by the use of lightweight engines of high specific output is already occurring A detailed listing of engines by horsepower category and their weights is provided in Table 4-3. The 350 to 450 HP range is unlikely to see any major weight reduction except in certain specific cases, as, for example, by replacement of the Mack EM-9 V-8 engine with six cylinder engines Engines in the 350 to 450 HP range are widely used in the Class 8B truck market by owner operators and fleet owners who need extra power to negotiate the steep gradients in many Western states. The 290 to 350 HP range is more commonly specified by fleets in Eastern states that are concerned about fuel costs. In 1990/91 Caterpillar and Cummins introduced the so called '10 litre' engines that weigh 1900 to 2050 lb with ratings of 300 to 350 HP The engines can directly replace the popular Cummins NTC Series and Caterpillar 3406 engines, with a weight savings of 500 to 600 lbs. However, these engines have only about 30 percent of the Class 8B market in 1991, but can be expected to increase market share in the future. The 240 to 290 HP segment is usually specified for 60,000 lb Class 8B trucks or by the 'supermedium' 50,000 lb Class 8A trucks In this class, weight savings may be significant only if owners choose the more traditional 'medium-duty' engines such as the DTA466, or high output versions of the Caterpillar 3116 These engines will have lower durability than.the L10 and 3176, and also have lower efficiency so that the weight reduction will not be a major factor affecting fuel economy. Similar concerns are valid for the 190-240 HP engines used in Class 7 and some Class 8A trucks where moving from a Cummins C-series engine to a B-series may

**TABLE 4-3**

**COMPARISON OF ENGINE WEIGHTS**

**1987 vs 1991**

**(Selected Examples)**

| HP Range | 1987 Engine Models Model | Weight (lb) | 1991 Engine Models Model | Weight (lb) |
|---|---|---|---|---|
| 350 to 450 | Cum NTC (400) | 2530 | Cum NTC (400) | 2530 |
| | Cat 3406 (400) | 2840 | Cat 3406B (425) | 2840 |
| | DDC 8V-92TTA | 2415 | DDC Series 60 (450) | 2670 |
| | Mack EM-9 (400) | N/A | Mack E7 (400) | 2165 |
| 290-350 | Cum NTC (315) | 2520 | Cum L10 (330) | 1870 |
| | Cat 3406 (310) | 2760 | Cat 3176 (325) | 1945 |
| | DDC 6V-92TTA (300) | 2020 | DDC Series 60 (350) | 2630 |
| | Mack EM-6 (335) | 2165 | Mack EM-7 (350) | 2165 |
| 240-290 | Cum L10 (270) | 1950 | Cum L10 (270) | 1950 |
| | Cat 3306 (270) | 2040 | Cat 3176 (275) | 1945 |
| | DDC 6V-71TA (270) | 2175 | | |
| | Mack EM-6 (275) | 2160 | Navistar DTA 466 (270)* | 1475 |
| 190-240 | Cat 3208N (210) | 1340 | Cat 3116 (250) | 1198 |
| | Cum 6CT 8.3 (210) | N/A | Cum BTA 5 9 (230)* | 880 |
| | GM 8.2T (205) | 1120 | | |
| | Nav. DTI466 (210) | 1475 | Nav. DT466 (210) | 1475 |
| | Ford 7.8L T (210) | 1395 | Ford 7 8L (210) | 1395 |
| <190 HP | Ford 6.6T (170) | 1310 | Ford 6.6T (170) | 1310 |
| | | | Cum BTA 5.9 (180)* | 880 |
| | Nav DTA310 (175) | 1235 | Nav. 7 3L (175) | 790 |
| | GM 8.2N (170) | 1095 | Cat 3116 (185) | 1190 |

Engine HP in parentheses

* Engines do not have the same durability as others in this class

be impractical due to the reduced durability. The Caterpillar 3116 and the Cummins C series engines are replacing the older Navistar DT466 and Caterpillar 3208 models in the medium-duty Class 6 and 7 trucks. In the lower than 190 HP engine range used in Class 6, trucks can shift to some of the new light-heavy-duty engines such as the Cummins BT 5.9 litre, also with some loss in durability. On a class average basis, industry experts anticipate that engine changes (from the 1987 baseline) will contribute to the following weight reduction by class:

- Class 8B - 250 lbs
- Class 8A - 200 lbs
- Class 7/6 - 150 lbs

The reductions are in addition to the reductions forecasted for material substitution.

## 4.4 AERODYNAMIC DRAG

Aerodynamic drag coefficients of heavy-duty trucks for a tractor trailer combination are usually quite high, historically, the drag coefficient ($C_D$) has been in the 0.75 to 0.8 range While the simple wind deflector mounted on the cab roof or the trailer nose cone has been available since the late-1970's, more modern integrated cab/roof fairing designs have become available from many manufacturers in the mid-to-late 1980's. The new aerodynamic cabs were pioneered by Kenworth, and most manufacturers have since followed suit. New models in Navistar's popular 9000 series (Class 8B) have 30 percent lower drag than the earlier trucks of 1980-1985 vintage when equipped with the full aerodynamic package and a 102 ft trailer. In the medium-duty segment, Navistar has also introduced more aerodynamic cabs that have 7 to 12 percent lower drag, mostly from the change in the shape of the hood.

Navistar's simulation handbook provides a guide to the relative changes in drag coefficients achieved by the different aerodynamic devices in a Class 8B tractor trailer combination. The 9600 series is a 'cabover' design while the 7100 is a conventional tractor, and with a high van trailer, the device specific drag reduction from the basic cabs (which are already lower drag designs) are as follows:

| | 9600 | 7100 |
|---|---|---|
| Cab roof fairings | 12% | 10% |
| Side fairings | 3.5% | 3.7% |
| Roof and Side fairings | 13.5% | 19% |
| Full roof and side fairings | 18% | N/A |

Typically, the full roof and side fairing 'aero package' costs $1400 to $1500 for trucks without sleeper cabs, and about $2300 for trucks with a sleeper cab. Navistar offers a highly aerodynamic 8300 cabover model that, when equipped with the same aero package, is about 10 percent more efficient than the 9600 and 7100 models listed above. In general, these drag reductions are typical for industry average and special 'aerodynamic' trucks, respectively

Potential for further improvements in Class 8B truck aerodynamics exist Navistar has displayed a prototype truck called 'IDEA' that has 15 percent lower drag than the current best truck (the 8300 series). Navistar identified the potential for drag improvements in the tractor alone of up to 25 percent, while an integrated tractor-trailer can have the potential for up to a 40 percent reduction over the current new truck fleet average. However, many of the features required, such as tractor-trailer gap seals, tractor skirts and rounded van corners are not popular due to the payload reduction potential incurred, as well as the lack of flexibility in switching tractors to different trailers. Volvo agreed with Navistar's assessment, and believed that tractor related reductions are more likely to be realized by 2001. Navistar suggested that a 15 to 20 percent additional drag reduction would occur due to market forces by 2001. These values refer only to Class 8B trucks with van bodies, which account for about ⅔ of sales. In other truck types such as flat-beds, stake-beds, livestock haulers, petroleum tankers, etc., drag reductions are likely to be in the 7 to 10 percent range.

Smaller reductions in drag are forecast for medium duty trucks. Currently, most medium duty trucks do not even feature rounded corners for the van body

Navistar's simulation analysis suggests significant potential for drag reduction simply by introducing a radius of curvature for the top and vertical corners in a van. A rounded corner van body was found to have a 30 percent drag reduction relative to a square corner van body. Roof fairings for medium-duty trucks can produce drag reductions of up to 4 percent, but are difficult to 'tune' due to the lack of space to mount the deflector. Problems with consumer acceptance of rounded van bodies, as well as lack of development of van aerodynamics suggests these improvements are unlikely to be realized. Navistar suggested that 5 to 8 percent additional aerodynamic drag reduction would be realized from market forces alone.

Volvo and Navistar suggested that the van aerodynamics problem had not been well addressed because van bodies were independently manufactured by small manufacturers, who did not have the resources to develop low drag designs. Tractor-trailers integration was another area where manufacturers' representatives believed that further scope for cost-effective improvement was available, but market forces were insufficient to cause these improvements to occur

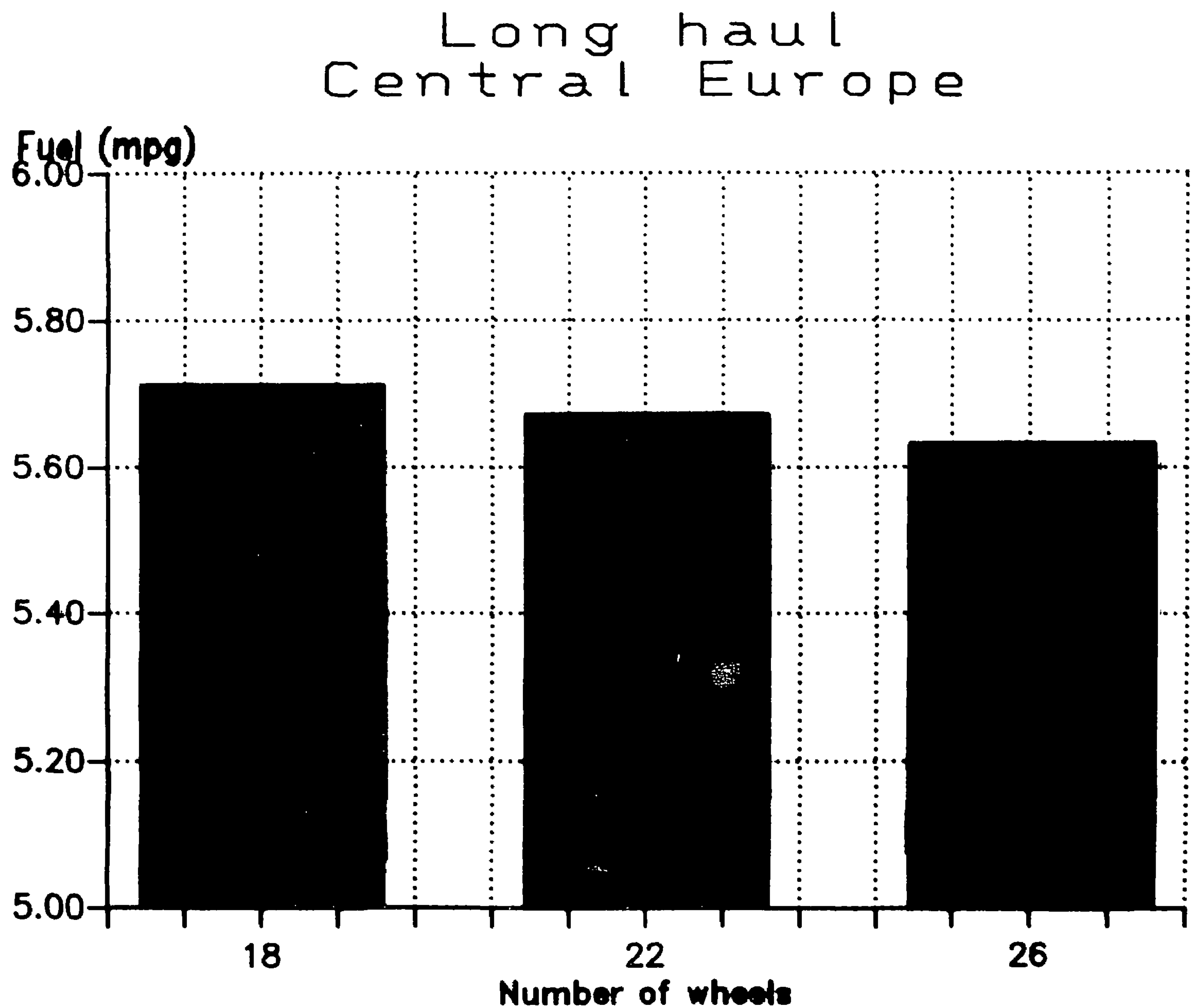
## 4.5 ROLLING RESISTANCE REDUCTION

The advent of radial tires brought about significant decreases in rolling resistance, and a large majority of trucks now use radial tires Bias-ply tires are limited to some rough terrain applications (construction) or in garbage haulers where there is potential for sidewall damage. Low profile radials were the next improvement available in tires, and currently have about 35 percent of the market. Low profile radials have 8 to 10 percent lower rolling resistance than conventional radials, and reduce the operating height of the truck. Low profile radials also have lower weight, and hence a tax advantage as tires are taxed by weight. These factors suggest that low profile radials will essentially displace conventional radial tires over the next 5 years.

Additional advances in rolling resistance reduction will come about from improved rubber formulations, new tire cord materials and the development of new tread designs. Based on confidential data received from the manufacturers, Navistar estimated that rolling resistance reduction of 20 to 25 percent was possible for tractor tires in the Class 8B long haul trucks For trailer tires, or non-traction tires, they estimate a reduction in the range of 10 percent. The 10 percent figure was also estimated as likely for medium duty truck applications. Some tires have already shown significantly greater reductions already, but these tires have compromised durability and/or handling properties. For example, Continental sold a special tire in the European market that had a 28 percent reduction in rolling resistance coefficient in comparison to a similarly sized standard tire, but had to discontinue sales due to problems with heat buildup. Future improvements are, however, not expected to impact durability.

The tread depth and number of wheels also impact tire rolling resistance. Tire rolling resistance has been found to vary inversely with tread depth; many special fuel economy prototypes often used 'shaved' tires to maximize fuel economy. Hence, special snow tires or traction tires tend to have significantly higher rolling resistance compared to standard tires. Volvo also found that the increasing number of wheels increases total tire rolling resistance. Data for a 78,000 lb GVW tractor-trailer, shown in Figure 4-2, suggests that increasing the number of wheels from 18 to 26 decreased fuel economy by one percent. The popular Class 8B tractor-trailer typically uses 18 tires, and some tire manufacturers have sought to replace the 4 tires on each of 4 axles with 2 tires, called 'super single' tires, with significant improvements in fuel economy. However this has not been popular since a tire blowout causes an unacceptable loss in payload capacity and driveability In Europe, where three axle trailers are more common, the super single tire has received greater acceptance. Manufacturers do not foresee substantial increases in market penetration for super single tires to 2001 in the U.S..

Figure 4-2




Produced at VOLVO

## 4.6 IMPROVEMENTS TO THE ENGINE

As noted in Section 4.1, improvements to the diesel engine can be accomplished by improving thermodynamic efficiency and turbocharger efficiency or by decreasing friction and pumping loss. The net effect of these improvements is to reduce the brake specific fuel consumption, or bsfc. While bsfc can be measured at specific load/speed points, EEA has utilized bsfc as measured over the EPA transient test cycle, which is designed to replicate engine speeds and loads over a city and highway driving schedule. As a matter of interest, the engine manufacturers association (EMA) provided estimates of bsfc by engine type to the year 2002. Table 4-4 reproduces the EMA submission.

It is instructive to compare the actual bsfc attained in 1991 under the prevalent 5.0 g/BHP-hr $NO_x$ standard with EMA's projections for 1992 EEA obtained detailed data from several select engine manufacturers and the data is tabulated in Table 4-5. The bsfc of engines is a function of both the horsepower rating and the rated RPM of the engines Increased horsepower ratings result in lower bsfc as frictional and pumping losses become a smaller fraction of total output. Lowering the rated RPM results in decreases in friction loss. It can be seen from Table 4-5 that most manufacturer's products are similar, although some very modern designs such as Caterpillar's 311b and 3176 models appear to have lower bsfc relative to older engines at similar HP/RPM ratings It also appear that the EMA projections for 1992 are very close to the actual values attained in 1991, with the medium-heavy-duty engines currently at about 0 420 lb/BHP-hr compared to a predicted 0.413 value, and the heavy-heavy at about 0.365 lb/BHP-hr compared to a predicted 0.353. The light-duty engines are split between the older IDI design Navistar with high bsfc relative to the more modern, turbocharged/aftercooled DI engine from Cummins With the expected conversion of Navistar's 7.3 L to DI, the EMA bsfc projection of 0.466 lb/BHP-hr could easily be attained.

Given the relative accuracy of the EMA projection, it is interesting to examine the projection to 2002. Between 1992 and 2002, no improvement is

TABLE 4-4

ENGINE MANUFACTURERS ASSOCIATION

BRAKE SPECIFIC FUEL CONSUMPTION

HEAVY-DUTY DIESEL ENGINES

(AS MEASURED ON TRANSIENT TEST CYCLE)

| Truck Class | $NO_x$ Standard | 1977 | 1982 | 1987 | 1992 | 1997 | 2002 |
|---|---|---|---|---|---|---|---|
| IIB | 10 7 | - | .527 | .524 | .451 | .451 | .451 |
| thru | 7.0 | - | .527 | .524 | .453 | .453 | .453 |
| IV | 5 0 | - | .527 | 524 | 466 | 465 | .464 |
| V | 10.7 | .467 | 457 | .412 | .382 | 373 | .367 |
| thru | 7.0 | .482* | .472* | .418* | .386 | 377 | 370 |
| VIII A | 5.0 | .516* | .507* | 454* | .413 | .401 | .398 |
| | 10.7 | .429 | .400 | .343 | .321 | 310 | .308 |
| VIII B | 7 0 | .438* | .407* | .348* | 330 | .319 | 316 |
| | 5.0 | .491* | .432* | .374* | .353 | .340 | .336 |

* Based on less than total production.

Source· EMA, 1983

TABLE 4-5

BSFC FOR SELECTED

1991 ENGINES (LB/BHP-HR)

| Class | Model | HP | RPM | BSFC |
|---|---|---|---|---|
| Light Heavy | Navistar 7.3L | 185 | 2800 | 0 550 |
| | Cummins 5 1L | 100 | 2500 | 0.400 |
| Medium Heavy | Ford 6.6L | 170 | 2300 | 0 440 |
| | Navistar DTA 360 | 185 | 2700 | 0 445 |
| | Caterpillar 3116 | 185 | 2600 | 0 396 |
| | Ford 7.8L | 210 | 2300 | 0.404 |
| | Navistar DTA 466 | 230 | 2400 | 0.418 |
| Heavy-Heavy (<350 HP) | DDC Series 60 (11.1L) | 275 | 1800 | 0.372 |
| | DDC 68-92 | 300 | 1800 | 0.448 |
| | Cummins L10 | 310 | 1800 | 0.378 |
| | Caterpillar 3176 | 325 | 1800 | 0 344 |
| Heavy-Heavy (>350 HP) | Caterpillar 3400 PEEC | 460 | 1900 | 0 358 |
| | DDC Series 60 (12.7L) | 450 | 2100 | 0.367 |

forecast for the light-heavy duty class of trucks, a 3.6 percent for the medium-duty class and a 4.8 percent improvement for the heavy-heavy-duty class. Our analysis, described below, shows that the EMA projections are relatively reasonable

As noted, engine bsfc improves with increasing the brake mean effective pressure (bmep) of the engine since friction and pumping loss do not increase in proportion to bmep, while output does. Some of the advantage of the newer, small displacement engines is due to the increased BMEP. For example, Caterpillar's 3176 rated at 325 HP has a peak torque BMEP of 300 psi which is 10 to 15 percent more than the BMEP of the typical 14 litre engine, and it displays one of the lowest bsfc ratings of all engines for which data was obtained.

There are obvious structural and durability limits to the increases possible in BMEP and Caterpillar believed that the 3176 had reached the limits of the high BMEP strategy. Volvo and Mercedes were in general agreement that this strategy produced some fuel economy benefit, but Cummins did not subscribe to this view, as it believed its 14 litre and 10 litre engines had near identical bsfc at the same rated HP.

Current thermodynamic efficiency of diesel engines is about 40% at the optimum bsfc point. Volvo suggested the following improvements were possible to current engines:

- improved charge air cooling,
- electronic control of engine timing,
- improved air utilization,
- adjustments to compression ratio, and
- variable geometry turbocharging

Air-to-air charge cooling is now (1991) available in virtually all heavy-duty diesels except in the light-heavy category and further improvements to change air cooling will result in very small benefits to fuel economy, probably less than 0.5 percent. Between 1987 and 1991, however, a very large fraction of the medium-heavy-duty engine segment began utilizing intercooling with a fuel economy benefit of 5 percent.

Electronic control of fuel injection allows optimization of injection timing and "shaping" of the "torque rise" curve. Some of the 1991 engines have electronic injection timing control offered as an option, such a Caterpillar's PEEC model, while it is standard on some engines such as the Detroit Diesel Series 60. Comparison of bsfc data from mechanically controlled and electronically controlled engines do not consistently support a fuel economy advantage, but the effect of the controls can be to change driving practices and allow the incorporation of speed control, which are discussed in Section 4.9 and 4.10.

Improvements to air utilization can be achieved by moving the piston top ring closer to the upper edge of the piston and by optimizing valve lift and duration. At this point, no manufacturer is considering variable valve timing, but it is a possibility only for the post-2000 time frame. Improved air utilization will help in reducing particulate emissions, but is expected to provide very little benefit to fuel economy.

Compression ratio (CR) increases are possible for the future, according to some manufacturers. Caterpillar and Volvo believed that CR could increase by 0.5 to 0.8 over the next decade, providing a 1/2 percent increase in bsfc. Cummins and Mercedes believed that $NO_x$ emissions would limit further CR increases and no benefit would result.

Improvements to turbochargers can arise from better matching of turbochargers as well as variable geometry turbocharging. Most of today's engines select "off-the-shelf" turbochargers that compromise peak efficiency and matching of characteristics over the load/RPM range. Variable geometry turbochargers have the capability to improve the matching characteristics over the operating RPM range, and improvements to turbine and compressor efficiency could add 1.5 to 2 percent in fuel efficiency at operating points that are not close to the peak efficiency point. The net effect over the transient cycle is estimated to be 1/2 to 1 percent benefit in bsfc. In urban driving conditions where the engine spends much of its time at conditions where current turbochargers are inefficient, the full 1.5 to 2 percent benefit may be realized.

Hence, the net benefit from improved thermodynamic efficiency is quite small The most optimistic estimates place the benefit at about 3 percent while the least optimistic at less than 1 percent.

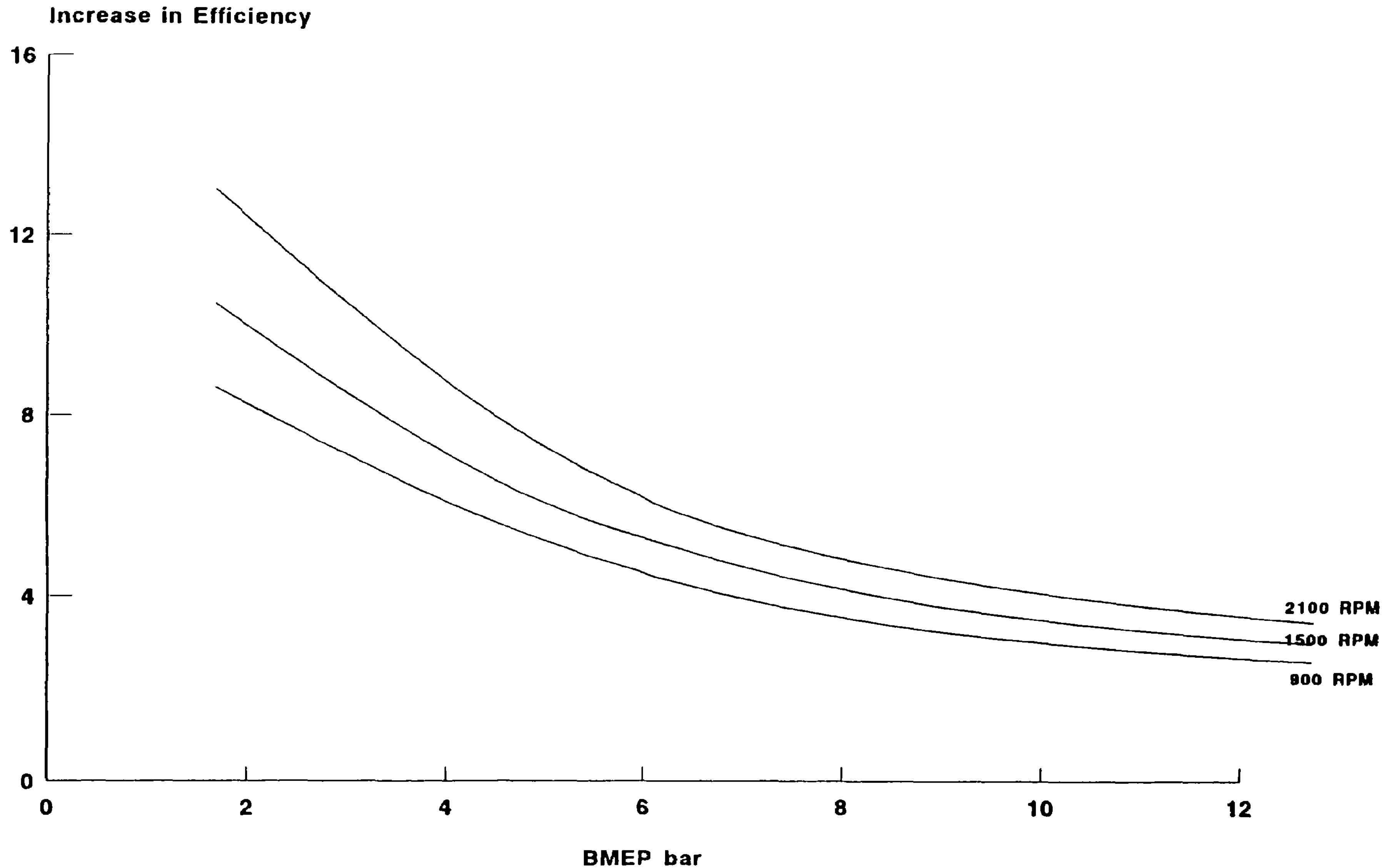
Friction reduction in diesel engines is expected to occur by:

- improved component design,
- reduction of oil and cooling water flow, and
- reduction of governed RPM.

Current levels of friction in diesel engines relative to engines output is already quite low. Mercedes provided data showing that a turbocharged diesel engine rated at 285 HP had a total loss from friction, pumping and accessory loads of 70 HP. Of this total, only about 30 HP was in friction loss. Hence, the complete elimination of all friction, a practical impossibility, would result in output increasing to 305 HP, and bsfc decreasing by 10 percent at full load. However, the particular values cited are for a low BMEP engine (135 psi). At a BMEP of 200 psi, complete elimination of friction will not increase bsfc by even 7 percent at full load. However, at part load, the friction loss (which stays nearly constant in absolute terms) becomes a much larger percent of output, and friction reduction has a bigger effect on fuel economy. An illustrative effect of friction of engine efficiency is shown in Figure 4-3 for the Mercedes engine discussed above.

Actual friction reduction and internal loss reduction potential is quite small. Mercedes has been experimenting with a special naturally aspirated engine using a 2-ring piston, special fuel efficient oils, a low flow water pump and a low flow oil pump, which reduced friction and accessory power loss

# Figure 4-3
# Effect of Reducing Friction on Engine Efficiency



by 5.2 HP (or about 10 percent). Some of the changes are inappropriate for turbocharged engines, such as the 2-ring piston. Other friction reduction technologies include roller-cam followers, that are widely used in most domestic engines, but can be adopted for some medium duty engines, and improvements to the fit and shape of the piston and cylinder liner by improved manufacturing technologies. Most of the manufacturers interviewed for this study suggested that 5 percent reduction in friction was likely by 2001, while a 10 percent change was the highest conceivable limit of friction reduction. A 5 percent reduction in friction translates into a 0.75 to 1 percent fuel economy benefit averaged over a range of load/speed conditions

Friction increases rapidly with engine RPM, and 10 percent decrease in RPM will bring about a proportionally larger reduction in friction, as the dependence is non-linear. Most heavy-heavy duty engines already operate in the 1800-1900 RPM range, although models rated to 2100 RPM are still available. Models rated at 1600 RPM as special "economy" models have been available since the early 1980's but have not been very popular since the driveability of these engines saves fuel both by friction reduction and by limiting truck speed. The new electronic controls in most engines make the 1600 RPM engine redundant, as these new engines shape the torque curve to permit the driver to cruise at 1500 RPM, while retaining the benefits of an 1800 RPM engine during acceleration or in city traffic.

In the medium-duty applications, ratings at 2800 RPM or 2600 RPM were traditionally popular, but new models rated at 2300 RPM or 2400 RPM have become available in the last few years. These models have higher torque than their 2600/2800 RPM counterparts, and require transmissions and axles with higher ratings. The lack of availability and increased cost of transmissions and axles has held back the market penetration of these lower RPM rated engines Electronic controls have not yet been adopted, and are likely to increase penetration in the future Reductions in the peak RPM to 2300/2400 RPM from 2600 RPM can result in fuel economy increases of 3 to 4 percent with no change in vehicle speed.

Pumping loss is not a large fraction of total output for diesel engines, Mercedes estimated pumping loss to be equivalent to half of friction loss at full load. At a given RPM, engine absolute pumping loss is not a strong function of load, and therefore is a larger factor at light loads, much like friction. Pumping loss can be reduced by controlling airflow through the engine to prevent "excess" air due to turbocharger mismatch at different speeds and loads. In addition, the use of pulse-tuned intake manifolds and tuned exhausts can reduce pumping loss at specific load/speed points. These technologies provide very small benefits in fuel economy, and have been widely adopted in most heavy-heavy engines. Variable volume intake and exhaust systems have not been considered for heavy-duty diesels, due to their poor cost/benefit.

The use of 4-valve heads reduces the pressure drop across the valve orifice, and is common in many of domestic heavy-heavy engines However, most of the engines rated below 270 HP, and most imports of all horsepower ratings, use 2-valve engines. Conversion to 4-valve aids in reducing the pumping loss, and also in increasing the bmep of a specific engine. BMEP increases are, however, accounted for separately in the analysis.

Reductions in pumping loss in total over the next 10 years are likely to be less than 5 percent in medium-heavy duty engines. This translates into a half percent increase in fuel economy

The net benefit from all improvements to conventional diesel engines will vary by engine type, as the heavy-duty diesels (used in Class 8B trucks) already incorporate technology that the lighter engines do not. A summary of the potential gains is provided in Table 4-6. In 1991, virtually all of the heavy-heavy-duty engines feature air-to-air intercooling and some already are of the high BMEP design As shown in Table 4-6, a 7.5 percent improvement to bsfc is forecast over the period 1987-2001 relative to a 1987 baseline, at constant emission standards. The imposition of the 5 0 g/BHP-hr standard in

**TABLE 4-6**

**IMPROVEMENTS TO ENGINE**

**BSFC, 1987-2001**

| | Light-Heavy | | Medium-Heavy | | Heavy-Heavy | |
|---|---|---|---|---|---|---|
| | Mkt. Pen. | F/E Gain | Mkt. Pen. | F/E Gain | Mkt. Pen. | F/E Gain |
| Conversion to DI | 80 | 12.0 | 0 | 0 | 0 | 0 |
| 10% Governed speed reduction | 80 | 4.0 | 50 | 2.5 | 20 | 1.0 |
| High BMEP design | 0 | 0 | 50 | 1.5 | 80 | 2.4 |
| Improved turbocharger matching | 80 | 8.0* | 100 | 0.5 | 100 | 0.5 |
| Air-to-Air intercooling | 100 | 5.0 | 80 | 4.0 | 30 | 1.5 |
| Improved Thermodynamic efficiency | 100 | 1 0 | 100 | 1.0 | 100 | 1.0 |
| Friction reduction | 100 | 1.5 | 100 | 1.0 | 100 | 1.0 |
| Pumping loss reduction | 100 | 1.0 | 100 | 0.5 | 20 | 0.1 |
| Total bsfc Benefit | | 32 5 | | 11.0 | | 7.5 |
| Effect of 5.0 $NO_x$ Std. | | 0 | | -2.0 | | -2 0 |
| Effect of 1998 $NO_x$ Std. | | -3.0 to -5.0 | | -3.0 to -5.0 | | -3 0 to -5.0 |

* Conversion from naturally aspirated.

1991 reduced fuel economy by about 2.0 percent, approximately counterbalancing the gain achieved through the introduction of air-to-air intercoolers. Hence, net gain of 5.5 percent is forecast at the 5.0 g/BHP-hr $NO_x$ standard between 1987 and 2001. However, the 1998 $NO_x$ standard of 4.0 g/BHP-hr could impose significant bsfc reduction, and it is possible that the loss could be as large as 5.0 percent, negating all of the technology benefits. This forecast closely corresponds to the opinions of most manufacturers of heavy-duty diesels. Starting from a 1987 bsfc of 0.365, the bsfc at a 5 0 $NO_x$ standard will be 0.346 lb/BHP-hr in 2001.

Larger improvements will be available for the medium and light diesels. In 1987, most medium duty diesels were not intercooled, but the new emissions standards for 1991/94 have forced a large majority of these engines to adopt air-to-air intercooling. In addition, the adoption of lower governed speeds will result in more engines moving to the 2300-2400 RPM ratings from the current 2500-2600 RPM ratings, with some engines moving to 2100 RPM A net bsfc reduction of 9.0 percent relative to 1987, at a 5.0 $NO_x$ standard is forecast. This implies that bsfc will decline from 0.425 lb/BHP-hr in 1987 to 0.390 lb/BHP-hr in 2001.

The largest gains in fuel efficiency will occur for the light-heavy engines that are used only in a few Class 5/6 trucks and school buses. This largely stems from the conversion of the IDI diesels in this segment to Direct Injection (DI) Currently, these engines are mostly indirectly injected V-8 designs rated at 2800 to 3000 RPM. By 2001, it is anticipated that they will be replaced by turbocharged and aftercooled, direct injection diesels, with a 32.5 percent decrease in bsfc for the segment as a whole Starting from an average bsfc of 0.540 lb/BHP-hr, the average bsfc will decline to 0.408 lb/BHP-hr. This forecast is the only one that differs significantly from the 1983 EMA forecast; yet, the presence of the new Cummins BT5.9 engine with a bsfc of 0 400 lb/BHP-hr in this class suggests that the forecast is conservative.

At this point, it is difficult to estimate the effect of the 4.0 g/BHP-hr $NO_x$ emissions standard required by the revised Clean Air Act for 1998 and beyond. Many diesel engine manufacturers believe that further $NO_x$ reduction from current levels would be very difficult to achieve without timing retard. Timing retard would result in significant reduction in fuel economy of 3 to 5 percent. However, Navistar was an exception, and its staff stated that fuel economy effects of the 4.0 $NO_x$ standard would be relatively small. Manufacturers need not use any timing retard if several new technologies under investigation prove successful. Among these technologies, the new zeolite catalysts appear promising in that tests with diesels have shown $NO_x$ reduction sufficient to meet even a 3.0 g/BHP-hr standard. Of course, these test results are preliminary and the durability of these catalysts is unknown. Nevertheless, there is potential to meet the 4.0 g/BHP-hr $NO_x$ standard with no fuel economy penalty. Other technologies, such as incorporation of exhaust gas recirculation, reduced compression ratio and/or variable valve timing may be used singly or in combination to attain the 4 0 g/BHP-hr standard with less fuel economy penalty than if the standard was obtained by timing retard alone.

## 4.7 TURBOCOMPOUND DIESEL ENGINES

Turbocompound diesel engines were extensively researched by the Department of Energy (DOE) in the late 1970's and early 1980's. Despite a successful technology development program that suggested significant fuel efficiency benefit, the technology was not commercialized. The DOE-Cummins joint development program that was essentially complete in 1982 involved the assembly of a 450 HP turbocompound diesel that met the 6.0 g/BHP-hr $NO_x$ standard. The turbocompound engine provided a fuel consumption reduction of 15 to 16 percent over a production 1982 NTC-400 horsepower engine used as a reference. However, the turbocompound engine used a number of component refinements, and Cummins determined that the benefit of turbocompounding alone was 4.2 to 5.3 percent. Additional advances in the exhaust manifold design, and insulation of the exhaust flow path resulted in an additional 6 percent improvement over the initial turbocompound design. A minimum bsfc of 0.298 lb/BHP-hr was attained at 1500 RPM.

At meetings with manufacturers held in conjunction with this analysis, most engineers contested the large values of fuel economy benefit initially reported by Cummins. Mercedes stated that their tests had shown a 2 percent benefit in fuel efficiency with heat insulation of the exhaust manifolds and ports. Caterpillar was more optimistic, and cited recent development showing a 4.7 percent lower specific fuel consumption at rated speed and a 3.3 percent benefit at peak torque RPM. Cummins engineers also stated that a 4 percent benefit for turbocompounding may be representative over a typical driving cycle.

Turbocompounding has other benefits. Since the turbine obtains power from waste heat, the engine emissions per unit of useful work are decreased Typically, the turbine output is in the range of 10 to 12 percent of reciprocator output. If absolute engine-out emissions stay constant with and without turbocompounding, a proportional 10 to 12 percent reduction in brake specific emissions is implied. Indeed, Caterpillar found that at 4 0 g/BHP-hr $NO_x$, the turbocompound engine had 8.0 percent lower bsfc at rated RPM and 3 5 percent lower bsfc at peak torque RPM.

It has also been suggested that heat insulation of the cylinder would be particularly useful with turbocompounding. Proponents of ceramic components have discussed the heat insulation of the cylinder head, piston top, and cylinder liners as a means to recover the heat wasted to the coolant Performance assessments of ceramic components for low heat rejection engines completed in the 1985-1988 time frame suggested additional fuel efficiency benefits of 3 to 4 percent at full load, and 'up to 13 percent' at part load for high swivel engines. Tests conducted by heavy-duty diesel engine manufacturer have failed to produce such benefits. In fact, most of the manufacturers interviews had very negative perceptions of ceramics for use as heat insulation for the cylinder. Mercedes stated that the very high temperatures of the ceramics had the following negative effects·

- decreased volumetric efficiency,
- increased $NO_x$ emissions,

- potential increase in brake specific particulate emissions due to lowered intake airflow,

- and no significant reduction in heat transfer.

While Cummins was in general agreement with Mercedes and saw no benefit to ceramic "hot internal parts" at a 4.0 g/BHP-hr standard, Caterpillar was notably more optimistic. Caterpillar suggested that a ceramic cylinder head was a distinct possibility even without turbocompounding, and that with turbocompounding, ceramics could increase the total bsfc benefit from 5 to 7 or 8 percent at rated speed.

All manufacturers stated that some turbocompound engines would be introduced in 1994/1995 but this technology would not have high market penetration by 2001.

## 4.8 DRIVETRAIN OPTIMIZATION

The drivetrain parameters are selected for a given truck gross weight and engine combination to meet a variety of performance requirements, such as fuel economy, 'on-grade' startability, capability to negotiate a grade at a selected speed and vehicle top speed requirements. Once a customer has selected an engine with a specific peak torque and RPM rating, the transmission and drive axles must be selected to optimize among the various requirements. The selection is based on the power/torque rating of their components, the ratio coverage of the transmission, the number of gears, and the axle ratio. Historically, the choice was sometimes constrained by availability of transmissions, and parameters were selected to optimize overall "performance", even at some slight loss of fuel efficiency.

In Class 8B trucks, inefficient drivetrain parameters were chosen by fleet operators to limit driver top speed rather than match for best efficiency. At highway cruising speed on level roads (e.g., 55 to 60 mph), it is most fuel efficient to operate the engine closer to peak torque RPM, which is typically 60 percent of rated RPM. However, selection of gear and axle ratios to achieve this RPM results in a truck with a capability to exceed 70 mph at rated RPM. Many fleet operators specify a numerically high axle ratio to prevent overspeeding. A more fuel efficient axle ratio selection with additional road speed control can provide 3 to 5 percent improvement at the same reference speed. This improvement is possible for the portion of the feel where, currently, axle ratios are misspecified. Anecdotal information suggests that about 30 to 50 percent of Class 8B trucks may have unoptimized drive-trains.

In medium-duty trucks, greater scope exists for drivetrain optimization, since the choices of gear ratios, gearbox torque capability and axles were supply limited. For example, virtually no transmissions were available with a rating between 650 ft-lbs of torque and 1000 ft-lbs. This situation has been changing with the introduction of transmissions from Spicer and Fuller with ratings of 750 ft-lb and 975 ft-lbs, for example. As a result, the medium duty truck customer can choose the low RPM, high torque engine models without paying a very large cost penalty for transmissions and driveshafts with ratings substantially higher than required. However, the fuel economy benefit associated with using lower governed speed engines is accounted for in Section 4.7

Other improvements to the transmission include the incorporation of single-plate rather than double plate clutches. New cerametallic materials allow single plate clutches to effectively replace double plate clutches, resulting in a small (0 5 percent) increase in city cycle fuel economy More recently, Eaton has introduced a new automated 9-speed transmission called 'Econoshift' that automates the shifting in the top two gears so that the correct gear will be chosen automatically at speeds above 45 mph. Eaton stated that the Econoshift would cost $1500 more than a traditional transmission but pay for itself in 18 months, suggesting a fuel economy improvement as large as 5 percent in Class 8B trucks. It is not clear how Eaton arrived at this benefit, as the benefit would depend on the reference baseline.

Increased levels of market penetration are forecasted for automatic transmissions in the lightest medium-duty trucks and bus markets. Although the automatic transmission can be less efficient than a manual transmission that is shifted correctly, actual driver behavior may make the automatic transmission more efficient in certain applications.

Drivetrain component suppliers are also integrating their axle and transmission/clutch offering, partly in response to a narrowing of the supplier base for each manufacturer. In the past, consumers could specify clutch, transmission and axles from different suppliers with some loss of configuration optimization. The bundling of those components could result in an improvement in drivetrain optimization.

It is difficult to estimate the benefits of drivetrain optimization, as the current extent of misspecification is not well understood. In addition the benefit of some improvements is dependent on driver behavior that is common now, not on what it will be in the future. We have relied on manufacturer opinions to estimate the fleet average benefits by truck class and city-highway cycle, as follows, in terms of percent improvements to MPG

| | City | Highway |
|---|---|---|
| Class 6/7 | 2 0 | 2 0 |
| Class 8A | 1.5 | 1.5 |
| Class 8B | 1.5 | 2.0 |

These benefits do not include any benefit associated with low RPM engines for Class 6/7/8A trucks

## 4.9 ELECTRONIC CONTROL

Electronic controls are being widely incorporated into trucks, partly in response to new emission standards that are easier to meet with these controls. In 1987, very few trucks had any electronic controls, but in 1990 industry experts stated that about 20 percent of Class 8B trucks and 5 percent of medium duty (Class 6/7/8A) trucks had electronic control As noted, electronic controls of fuel injection does not improve the bsfc of the engine on the EPA test cycle significantly. However, the principal benefits of the electronic systems are associated with:

- shaping of the torque curve to allow drivers to operate at lower RPM in top gear,
- gear shift indications,
- road speed governor functions,
- engine shutdown and protection systems,
- extended idle shutoff,
- driver monitoring,
- and engine/vehicle diagnostics.

An example of such an electronic system is Mack Trucks' VMAC computer control system. The system is optional at a cost of $3000, and is available for Mack's Class 8B trucks.

The benefits of the system are dependent on the baseline. If a driver maintains speeds at or below legal limits and selects the appropriate gear for cruise, the system provides benefits only from torque curve shaping. Larger benefits will be obtained relative to the average driver who may be overspeeding on the highway. Proper shifting during city driving can also save fuel, and shutting the engine off rather than subjecting it to extended idle will also save fuel. These benefits are difficult to estimate as there are no detailed analysis of current inefficiencies in driver behavior that are publicly available. Estimates of fleet average impacts are largely based on anecdotal evidence, and not though any actual analysis.

Benefits were estimated by industry experts for electronic injection timing shaping the torque rise of the engine, speed control to 65 mph, shift control and extended idle shutdown. Total benefits are as follows:

| | City | Highway |
|---|---|---|
| Class 6/7/8A | 3 0 | 5.0 |
| Class 8B | 2.5 | 6 0 |

These benefits are percentage increases in MPG for the fleet as a whole due to adoption of electronic control.

### 4.10 OTHER IMPROVEMENTS

Small improvements in engine and drivetrain related components will occur due to evolutionary changes in design, leading to small improvements in fuel economy. The use of synthetic lubricants in the engine, gearbox and axle lead to small decreases in drivetrain friction, that also can benefit fuel economy.

The largest power drain from accessories comes form the cooling fan. Thermostatically activated cooling fans operate only when required by the engine and can improve fuel economy significantly; however, most new trucks already incorporated this device by 1978. Modest improvements can be made to the air compressor, water pump and power steering hydraulic pump For example, Eaton has recently unveiled a variable assist power steering system that cuts the pump's power absorption by up to 50 percent. Currently all of the accessory loads take up 7 to 10 percent of total engine power output, and a slightly larger share of fuel consumption While gains from improvements to existing accessories will improve fuel economy in the range of 0.5 to 1.0 percent, there is a tendency to increase the level of accessories to improve driver comfort and safety These considerations can lead to an increase in accessory loads from demands for air suspension, antilock brakes and other interior power equipment. As a result, net accessory power decrease is unlikely to decrease and could actually increase over the next decade

Synthetic lubricants have been available for over 10 years but have not achieved significant market penetration. Lubricant manufacturer sponsored testings showed significant benefits in fuel economy from their use - up to 4 percent - but truck industry experts suggest that 1 to 2 percent benefits are more appropriate Improvements to conventional lubricants have also occurred through the use of friction modifications and viscosity under improvements. Such improved non-synthetic oils are more likely to find widespread acceptance due to their lower price. A fuel economy gain if 1 percent in city driving and 0.5 percent on the highway is expected to result from lubricant improvements to 2001.

## 4.11 TOTAL IMPROVEMENT IN FUEL EFFICIENCY

In order to predict the total impact of all technological improvements to fuel economy, it is necessary to obtain a penetration weighted estimate of each technology's contribution to fleet fuel economy. If, between 1987 and 2001, the market penetration of technology i increases by $m_i$, and $r_i$ is the percent fuel economy gain associated with the application of that technology to an individual truck, then $m_i.r_i$ is the percent gain in fuel economy for the fleet as whole. The total fuel economy improvement is·

$$T = \sum_i m_i r_i$$

This assumes that there are no favorable or unfavorable synergies across all technologies. The equations governing fuel consumption demonstrate the fact that some fuel economy improvements are additive, and others are multiplicative so that the above equation is conservative.

Table 4-7 summarizes the derivation of total fuel economy benefit for Class 8B trucks. Since the sensitivities for city and highway driving are so different, the benefit over each cycle is computed separately. For Class 8B trucks, the largest benefits on the highway come from the combination of aerodynamic improvement, and the use of electronic road speed governors/high torque rise engines. Net benefits in city driving are much smaller since aerodynamic benefits are negligible and road speed governors have no effect at these speeds Nevertheless, in the absence of a 1988 $NO_x$ standard, the net fuel economy improvement for these trucks is 22 percent (assuming a 70/30 highway/city weighting) If the $NO_x$ standards penalty is as high as 3 to 5 percent, the net increase to 2001 will be only 17.5 percent, corresponding to 1 2 percent increase per year that is nearly identical to the historical experience between 1978 and 1987.

Table 4-8 shows that same calculations for Class 6/7 medium-duty trucks

**TABLE 4-7**

**IMPROVEMENTS TO CLASS 8B**

**TRUCKS, 1987 - 2001**

**(Percent Improvements in Fuel Economy)**

| Technology | | Market Penetration Increase | City F/E | Highway F/E |
|---|---|---|---|---|
| Weight Reduction (0.75%) | | 100 | 0.40 | 0.25 |
| Drag Reduction | Van Bodies | 50 | 0.28 | 6.75 |
| | Other | 35 | 0.07 | 1.60 |
| Rolling Resistance | | 65 | 1.85 | 2.90 |
| Engine Improvements | | 100 | 5.50 | 5.50 |
| Turbocompound | | 10 | 0.30 | 0.50 |
| Drivetrain Optimization | | N/A | 1.50 | 2.00 |
| Electronic Control | | 100 | 2.50 | 6.00 |
| Lubricants | | 100 | 1.00 | 0.50 |
| | | | 13.00 | 26.00 |
| Potential Effect of $NO_x$ Standard | | | (-3.00) | (-5.00) |

TABLE 4-8

IMPROVEMENTS TO CLASS 6/7

TRUCKS, 1987 - 2001

| Technology | | Market Penetration Increase | City F/E | Highway F/E |
|---|---|---|---|---|
| Weight Reduction | | 100 | 0.35 | 0.15 |
| Drag Reduction: | Van Body | 45 | 0.15 | 3.35 |
| | Other | 55 | 0.07 | 1.69 |
| Rolling Resistance | | 45 | 0.90 | 1 35 |
| Engine Improvements* | | 100 | 12.00 | 12.00 |
| Drivetrain Optimization | | 100 | 2 00 | 2.00 |
| Electronic Control | | 100 | 3.00 | 5 00 |
| Lubricants | | 100 | 1.00 | 0 5 |
| | | | 19 47 | 26 04 |
| Potential Effect of $NO_x$ Standards. | | | (-2 5) | (-4 00) |

* Weighted for light-heavy diesels in Class 6

The highway MPG improvement is as large as the one calculated for Class 8B trucks, but the source of the improvement is quite different; in this case, engine improvements are the main contributor. These engine improvements are also available in the city cycle, and the net benefit at city speeds is also quite large. The city/highway composite improvement is 21.4 percent, using a weighting of 70 percent city/30 percent highway, without any emission penalty and 18.5 percent if the penalty is as large as anticipated without any breakthroughs in technology. This translates to an annual rate of growth of 1.3 percent, which is again in good agreement with the historic rate of growth experienced in the 1978-1987 time frame.

In conclusion, it appears that technology is available to continue the historic growth rates or even exceed them slightly with no government intervention in the markets.

# Appendix A

## Statistical Results of the Regression Models to Estimate GPM

MODEL 1

Dependent Variable: LGPM

EEA GVW Group=19,500-26,000 lbs Type of fuel used by vehicle=Gasoline

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 4 | 24 94020 | 6 23505 | 64 346 | 0 0001 |
| Error | 4133 | 400 48378 | 0 09690 | | |
| C Total | 4137 | 425 42397 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0 31129 | R-square | 0 0586 |
| Dep Mean | -1 84409 | Adj R-sq | 0 0577 |
| C V. | -16 88020 | | |

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0 Parameter=0 | Prob > \|T\| |
|---|---|---|---|---|---|
| INTERCEP | 1 | -1 780058 | 0 01654815 | -107 568 | 0 0000 |
| MDLIDX | 1 | -0 004928 | 0 00193149 | -2 552 | 0 0108 |
| LWTWGT1 | 1 | 0 234598 | 0 02474108 | 9 482 | 0 0001 |
| LCIDCTR | 1 | 0 440347 | 0 03908487 | 11 266 | 0 0001 |
| DLOCAL | 1 | 0 050265 | 0 01325301 | 3.793 | 0 0002 |

Correlation of Estimates

| CORRB | INTERCEP | MDLIDX | LWTWGT1 | LCIDCTR | DLOCAL |
|---|---|---|---|---|---|
| INTERCEP | 1 0000 | -0 4183 | 0 5877 | -0 0409 | -0 6863 |
| MDLIDX | -0 4183 | 1 0000 | -0 1040 | -0 2122 | 0 1158 |
| LWTWGT1 | 0 5877 | -0 1040 | 1 0000 | -0 1311 | 0 0250 |
| LCIDCTR | -0 0409 | -0 2122 | -0 1311 | 1 0000 | 0 0649 |
| DLOCAL | -0 6863 | 0 1158 | 0 0250 | 0 0649 | 1 0000 |

# MODEL 2
## Dependent Variable: LGPM

----------------- EEA GVW Group=19,500-26,000 lbs Type of fuel used by vehicle=Diesel -----------------------

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 5 | 24 00105 | 4 80021 | 71 665 | 0 0001 |
| Error | 2006 | 134 36455 | 0 06698 | | |
| C Total | 2011 | 158 36559 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0 25881 | R-square | 0 1516 |
| Dep Mean | -1 99331 | Adj R-sq | 0 1494 |
| C V | -12 98381 | | |

### Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0 Parameter=0 | Prob > \|T\| |
|---|---|---|---|---|---|
| INTERCEP | 1 | -1 785384 | 0 01805094 | -98 908 | 0.0000 |
| MDLIDX | 1 | -0 027829 | 0 00174202 | -15 975 | 0 0001 |
| LWTWGT1 | 1 | 0 220867 | 0 03427740 | 6 444 | 0 0001 |
| LHPCTR | 1 | 0 096602 | 0 05121991 | 1 886 | 0 0594 |
| DLOCAL | 1 | 0.033743 | 0 01226845 | 2 750 | 0 0060 |
| DAERO | 1 | -0 069142 | 0 02273189 | -3 042 | 0 0024 |

### Correlation of Estimates

| CORRB | INTERCEP | MDLIDX | LWTWGT1 | LHPCTR | DLOCAL | DAERO |
|---|---|---|---|---|---|---|
| INTERCEP | 1 0000 | -0 6522 | 0 5693 | -0 0283 | -0 5189 | -0 0076 |
| MDLIDX | -0 6522 | 1 0000 | -0 0820 | 0 1331 | 0 1532 | -0 1641 |
| LWTWGT1 | 0 5693 | -0 0820 | 1 0000 | 0 0176 | 0 0207 | 0 0090 |
| LHPCTR | -0 0283 | 0 1331 | 0 0176 | 1 0000 | 0 0106 | -0 0453 |
| DLOCAL | -0 5189 | 0 1532 | 0 0207 | 0 0106 | 1 0000 | 0 0286 |
| DAERO | -0 0076 | -0 1641 | 0 0090 | -0 0453 | 0 0286 | 1 0000 |

# MODEL 3
## Dependent Variable: LGPM

--- EEA GVW Group=26 000-33,000 lbs Type of fuel used by vehicle=Gasoline ---

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 4 | 12 78172 | 3 19543 | 35 439 | 0 0001 |
| Error | 2015 | 181 68901 | 0 09017 | | |
| C Total | 2019 | 194 47073 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0 30028 | R-square | 0 0657 |
| Dep Mean | -1 78895 | Adj R-sq | 0 0639 |
| C V | -16 78527 | | |

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0 Parameter=0 | Prob > \|T\| |
|---|---|---|---|---|---|
| INTERCEP | 1 | -1 698965 | 0 02354247 | -72 166 | 0 0000 |
| MDLIDX | 1 | -0 009167 | 0 00253633 | -3 614 | 0 0003 |
| LWTWGT1 | 1 | 0 196288 | 0 03159836 | 6 212 | 0 0001 |
| LCIDCTR | 1 | 0 555994 | 0 06024826 | 9 228 | 0 0001 |
| DLOCAL | 1 | 0 018047 | 0 01933636 | 0 933 | 0 3508 |

Correlation of Estimates

| CORRB | INTERCEP | MDLIDX | LWTWGT1 | LCIDCTR | DLOCAL |
|---|---|---|---|---|---|
| INTERCEP | 1 0000 | -0 4401 | 0 5451 | -0 0227 | -0 7205 |
| MDLIDX | -0 4401 | 1 0000 | -0 1326 | -0 1493 | 0 1339 |
| LWTWGT1 | 0 5451 | -0 1326 | 1 0000 | -0 1237 | 0 0369 |
| LCIDCTR | -0 0227 | -0 1493 | -0 1237 | 1 0000 | 0 0202 |
| DLOCAL | -0 7205 | 0 1339 | 0 0369 | 0 0202 | 1 0000 |

# MODEL 4
## Dependent Variable: LGPM

EEA GVW Group=26,000-33,000 lbs Type of fuel used by vehicle=Diesel

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 5 | 28 90499 | 5 78100 | 87 187 | 0 0001 |
| Error | 1950 | 129 29585 | 0 06631 | | |
| C Total | 1955 | 158.20084 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0 25750 | R-square | 0 1827 |
| Dep Mean | -1 93881 | Adj R-sq | 0 1806 |
| C V | -13 28129 | | |

### Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0 Parameter=0 | Prob > \|T\| |
|---|---|---|---|---|---|
| INTERCEP | 1 | -1 743511 | 0 01716069 | -101 599 | 0 0000 |
| MDLIDX | 1 | -0 030025 | 0 00169165 | -17 749 | 0 0001 |
| LWTWGT1 | 1 | 0 233573 | 0 03138824 | 7 441 | 0 0001 |
| LHPCTR | 1 | 0 093002 | 0 05222425 | 1 781 | 0 0751 |
| DLOCAL | 1 | 0 063464 | 0 01246407 | 5 092 | 0 0001 |
| DAERO | 1 | -0 041537 | 0 02278786 | -1 823 | 0.0685 |

### Correlation of Estimates

| CORRB | INTERCEP | MDLIDX | LWTWGT1 | LHPCTR | DLOCAL | DAERO |
|---|---|---|---|---|---|---|
| INTERCEP | 1 0000 | -0 6271 | 0 5381 | -0 0377 | -0 5342 | -0 1007 |
| MDLIDX | -0 6271 | 1 0000 | -0 0712 | 0 1390 | 0 1155 | -0.1037 |
| LWTWGT1 | 0 5381 | -0 0712 | 1 0000 | 0 0174 | 0 0337 | -0 0320 |
| LHPCTR | -0 0377 | 0 1390 | 0 0174 | 1 0000 | 0 0229 | -0 0158 |
| DLOCAL | -0 5342 | 0 1155 | 0 0337 | 0 0229 | 1.0000 | 0 0940 |
| DAERO | -0 1007 | -0 1037 | -0 0320 | -0 0158 | 0.0940 | 1 0000 |

# MODEL 5
## Dependent Variable: LGPM

------------------------------------------ EEA GVW Group=33,000-60,000 lbs Type of fuel used by vehicle=Gasoline ------------------------------------------

### *Analysis of Variance*

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 4 | 6 33916 | 1 58479 | 17 240 | 0 0001 |
| Error | 1639 | 150 66181 | 0 09192 | | |
| C Total | 1643 | 157 00096 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0 30319 | R-square | 0 0404 |
| Dep Mean | -1 60008 | Adj R-sq | 0 0380 |
| C V | -18 94826 | | |

### Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0: Parameter=0 | Prob > \|T\| |
|---|---|---|---|---|---|
| INTERCEP | 1 | -1 518136 | 0 03343680 | -45 403 | 0 0001 |
| MDLIDX | 1 | -0 010200 | 0 00398049 | -2 562 | 0 0105 |
| LNTWGT1 | 1 | 0 149245 | 0 03873395 | 3 853 | 0 0001 |
| LCIDCTR | 1 | 0 572893 | 0 09850945 | 5 816 | 0 0001 |
| DLOCAL | 1 | 0.041550 | 0 02234609 | 1 859 | 0 0631 |

### Correlation of Estimates

| CORRB | INTERCEP | MDLIDX | LNTWGT1 | LCIDCTR | DLOCAL |
|---|---|---|---|---|---|
| INTERCEP | 1 0000 | -0 3066 | 0 7354 | -0 1225 | -0.5635 |
| MDLIDX | -0 3066 | 1 0000 | -0 0498 | 0.0839 | 0 0683 |
| LNTWGT1 | 0 7354 | -0 0498 | 1 0000 | -0 1552 | 0 0453 |
| LCIDCTR | -0 1225 | 0 0839 | -0 1552 | 1 0000 | -0 0092 |
| DLOCAL | -0 5635 | 0 0683 | 0 0453 | -0 0092 | 1 0000 |

## MODEL 6
## Dependent Variable: LGPM

--- EEA GVW Group=33,000-60,000 lbs Type of fuel used by vehicle=Diesel ---

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 5 | 33 98442 | 6 79688 | 113.184 | 0 0001 |
| Error | 7770 | 466 60260 | 0 06005 | | |
| C Total | 7775 | 500 58702 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0 24505 | R-square | 0 0679 |
| Dep Mean | -1 70807 | Adj R-sq | 0 0673 |
| C.V | -14 34692 | | |

### Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0: Parameter=0 | Prob > \|T\| |
|---|---|---|---|---|---|
| INTERCEP | 1 | -1 602002 | 0 00851730 | -188 088 | 0 0000 |
| MDLIDX | 1 | -0 011171 | 0 00088888 | -12 568 | 0 0001 |
| LWTWGT1 | 1 | 0 174341 | 0 01225588 | 14 225 | 0 0001 |
| LHPCTR | 1 | 0 063006 | 0 00986089 | 6 389 | 0 0001 |
| DLOCAL | 1 | 0 050868 | 0 00611715 | 8 316 | 0 0001 |
| DAERO | 1 | -0 057297 | 0 00964660 | -5 940 | 0 0001 |

### Correlation of Estimates

| CORRB | INTERCEP | MDLIDX | LWTWGT1 | LHPCTR | DLOCAL | DAERO |
|---|---|---|---|---|---|---|
| INTERCEP | 1 0000 | -0 4700 | 0 6884 | -0 0830 | -0.4481 | -0 1543 |
| MDLIDX | -0 4700 | 1.0000 | -0 0625 | 0 1124 | 0 1175 | -0 2512 |
| LWTWGT1 | 0 6884 | -0 0625 | 1 0000 | -0 0381 | 0 0979 | -0 0628 |
| LHPCTR | -0 0830 | 0 1124 | -0 0381 | 1 0000 | 0.1675 | -0 0517 |
| DLOCAL | -0 4481 | 0 1175 | 0 0979 | 0 1675 | 1 0000 | 0 1960 |
| DAERO | -0 1543 | -0 2512 | -0 0628 | -0 0517 | 0.1960 | 1 0000 |

# MODEL 7
## Dependent Variable: LGPM

--- EEA GVW Group=60,000-80,000 lbs Type of fuel used by vehicle=Diesel ---

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 6 | 50.93586 | 8.48931 | 379.903 | 0.0000 |
| Error | 17075 | 381.55802 | 0.02235 | | |
| C Total | 17081 | 432.49388 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0.14949 | R-square | 0.1178 |
| Dep Mean | -1.63480 | Adj R-sq | 0.1175 |
| C V | -9.14399 | | |

### Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0 Parameter=0 | Prob > \|T\| |
|---|---|---|---|---|---|
| INTERCEP | 1 | -1.554636 | 0.00315592 | -492.609 | 0.0000 |
| MDLIDX | 1 | -0.011201 | 0.00036188 | -30.953 | 0.0001 |
| LWTWGT1 | 1 | 0.042623 | 0.00575790 | 7.402 | 0.0001 |
| LHPCTR | 1 | 0.111280 | 0.00723494 | 15.381 | 0.0001 |
| DLOCAL | 1 | 0.025469 | 0.00293003 | 8.692 | 0.0001 |
| DAERO | 1 | -0.018088 | 0.00426924 | -4.237 | 0.0001 |
| DECO | 1 | -0.027505 | 0.00473327 | -5.811 | 0.0001 |

### Correlation of Estimates

| CORRB | INTERCEP | MDLIDX | LWTWGT1 | LHPCTR | DLOCAL | DAERO | DECO |
|---|---|---|---|---|---|---|---|
| INTERCEP | 1.0000 | -0.6330 | 0.6619 | -0.0542 | -0.2244 | -0.0881 | 0.0459 |
| MDLIDX | -0.6330 | 1.0000 | -0.1001 | -0.0351 | 0.1615 | -0.1792 | -0.0987 |
| LWTWGT1 | 0.6619 | -0.1001 | 1.0000 | -0.1050 | 0.1805 | -0.0624 | 0.0106 |
| LHPCTR | -0.0542 | -0.0351 | -0.1050 | 1.0000 | 0.1011 | 0.0392 | 0.0157 |
| DLOCAL | -0.2244 | 0.1615 | 0.1805 | 0.1011 | 1.0000 | 0.0812 | 0.0073 |
| DAERO | -0.0881 | -0.1792 | -0.0624 | 0.0392 | 0.0812 | 1.0000 | -0.7230 |
| DECO | 0.0459 | -0.0987 | 0.0106 | 0.0157 | 0.0073 | -0.7230 | 1.0000 |

## MODEL 8
## Dependent Variable LGPM

------------------------------------------ EEA GVW Group=Over 80,000 lbs Type of fuel used by vehicle=Diesel USETYPE=1 ------------------------------------------

### Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Prob>F |
|---|---|---|---|---|---|
| Model | 4 | 1 20481 | 0 30120 | 10 398 | 0 0001 |
| Error | 551 | 15 96073 | 0 02897 | | |
| C Total | 555 | 17 16554 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0 17020 | R-square | 0 0702 |
| Dep Mean | -1 53473 | Adj R-sq | 0 0634 |
| C V | -11 08968 | | |

### Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | T for H0 Parameter=0 | Prob > \|T\| |
|---|---|---|---|---|---|
| INTERCEP | 1 | -1 431978 | 0 02528792 | -56 627 | 0 0001 |
| MDLIDX | 1 | -0 009221 | 0 00216618 | -4 257 | 0 0001 |
| LWTWGT1 | 1 | 0 061648 | 0 02673900 | 2 306 | 0 0215 |
| LHPCTR | 1 | 0 148885 | 0 04555618 | 3 268 | 0 0011 |
| DECO | 1 | -0 059064 | 0 02693986 | -2 192 | 0 0288 |

### Correlation of Estimates

| CORRB | INTERCEP | MDLIDX | LWTWGT1 | LHPCTR | DECO |
|---|---|---|---|---|---|
| INTERCEP | 1 0000 | -0 5083 | 0 8567 | 0 0091 | 0 0312 |
| MDLIDX | -0 5083 | 1 0000 | -0 1071 | -0 0817 | -0 2626 |
| LWTWGT1 | 0 8567 | -0 1071 | 1 0000 | -0 0781 | 0 0076 |
| LHPCTR | 0 0091 | -0 0817 | -0 0781 | 1 0000 | -0 0312 |
| DECO | 0 0312 | -0 2626 | 0.0076 | -0 0312 | 1 0000 |