MASTER

An Evaluation of the Fuel-Conservation Potential of Truck Aerodynamic-Drag-Reduction Devices

Prepared by
The Mobile Systems Group
Environment and Energy Conservation Division
THE AEROSPACE CORPORATION
El Segundo, California 90245

AT03-76SF76003

30 June 1976

Prepared for
U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Transportation Energy Conservation Division
Washington, D. C.

Contract No. E(04-3)-1101, PA-3

ltr. dtd. 7/30/76 filed 1101/8-2

THE AEROSPACE CORPORATION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

**AN EVALUATION OF THE FUEL-CONSERVATION POTENTIAL
OF TRUCK AERODYNAMIC-DRAG-REDUCTION DEVICES**

Prepared by

The Mobile Systems Group
Environment and Energy Conservation Division
THE AEROSPACE CORPORATION
El Segundo, California, 90245

30 June 1976

Prepared for

U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Transportation Energy Conservation Division
Washington, D. C.

Contract No. E(04-3)-1101, PA-3

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ACKNOWLEDGMENTS

Appreciation is acknowledged for the guidance and assistance provided by Mr. Graham Hagey of the Energy Research and Development Administration, Transportation Energy Conservation Division, who served as Program Manager for this study.

Mr. Gene Mascetti and Mr. Kaye Swan of The Aerospace Corporation made valuable contributions to the study.

James J. Donnelly, Jr.
Study Manager

Approved by

Merrill G. Hinton, Group Director
Mobile Systems
Environment and Energy
Conservation Division

Joseph Meltzer, General Manager
Environment and Energy
Conservation Division

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

FOREWORD

This report, prepared by The Aerospace Corporation for the U. S. Energy Research and Development Administration (ERDA), Transportation Energy Conservation Division, presents the results of a study made to assess the fuel conservation potential of truck aerodynamic drag reduction devices.

The results of the study are presented in seven sections. An overview of the basic study results is given in the Summary Section, and a brief introduction to the general nature of the truck drag problem and the study scope is contained in Section 1. Section 2 provides a more detailed discussion of the aerodynamic drag problem and the characteristics of specific retrofit aerodynamic drag reduction devices which are in the production or prototype status. The results of a survey of fleet owners utilizing aerodynamic drag reduction devices and their experience with regard to fuel savings and operational factors are given in Section 3. Section 4 contains the results of economic analyses made to determine the cost-benefit effects of drag reduction devices. An analysis of the U.S. truck population to which such drag reduction devices may be applicable and the fuel savings potential attendant to their use is given in Section 5. The significant elements of a program structured to encourage the utilization of aerodynamic drag reduction devices on trucks are defined in Section 6.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

ACKNOWLEDGMENTS	iii
FOREWORD	v
SUMMARY	xi
1. INTRODUCTION	1
2. RETROFIT AERODYNAMIC DRAG REDUCTION DEVICES	3
2.1 The Aerodynamic Drag Problem	3
2.2 Classes of Devices in Production or Prototype Status	10
2.2.1 Cab Roof-Mounted Devices	11
2.2.2 Van-Mounted Devices	12
2.2.3 Gap Crossflow Reducers	20
2.3 Devices Under Development or Partially Evaluated	22
2.3.1 Cab-Mounted Air Flow Turning Vanes	22
2.3.2 Tractor-to-Trailer Fairings	22
2.3.3 Wind-Positioned Combination Air Flow Deflector and Crossflow Reducer	25
2.4 Summary	25
3. SURVEY OF FLEET OWNERS	27
4. COST-BENEFIT ANALYSES FOR COMMERCIALY AVAILABLE SYSTEMS	33
5. ANALYSIS OF U.S. TRUCK POPULATION AND FUEL SAVINGS POTENTIAL	37
6. RECOMMENDED IMPLEMENTATION PROGRAM	47
6.1 Device Comparison Tests	49
6.2 In-Use Statistical Confidence Tests	50

CONTENTS (Continued)

6.3	Documentation and Information Dissemination	52
6.4	Wind Tunnel and Correlation Program	52
APPENDIX: LIST OF COMPANIES/ASSOCIATIONS CONTACTED		53
REFERENCES		63

FIGURES

1.	Flow Separation on a Tractor-Trailer Truck	4
2.	Cross Wind Effects on Drag for COE Rigs	6
3.	Fuel Consumption Decrease versus Drag Decrease as a Function of Weight	8
4.	Aeroboost III	13
5.	Air-Flo Wind Deflector	13
6.	Wind-Gem Air Flow Diverter	14
7.	Windbreaker	14
8.	Dragfoiler II	15
9.	Airshield Wind Deflector (Cab-Mounted) and Vortex Stabilizer (Trailer-Mounted)	15
10.	Air Deflector	16
11.	Airshield Wind Deflector with Integral Gap Sealer	16
12.	Nose Cone	18
13.	Air Vane	18
14.	Aeroboost I	19
15.	Nose Cone for Straight Trucks	19
16.	Gap Sealer	21
17.	Turning Vanes	23
18.	Full Metal Fairing	23
19.	Air Cell	24
20.	Air-Deployable Fairing	24
21.	Parametric Fuel Economy Chart	34

TABLES

1.	Estimated 1975 Utilization of Aerodynamic Drag Reduction Devices	25
2.	Fuel Economy of Unmodified Van Combinations in Long-Haul Fleet Operations	30
3.	Annual Mileage of Van Combinations in Long-Haul Fleet Operations	31
4.	Economic Benefit Summary - Aerodynamic Drag Reduction Devices	35
5.	Truck Number, Range, Type and Mileage Summary - 1972 Census	38
6.	Mileage Characteristics of Trucks by Weight Class - 1972 Census	39
7.	Approximate Distribution of Van Trucks by Weight Classification - 1972 Census	40
8.	Approximate Breakdown of 1972 Census Van Truck Population	41
9.	Mileage Characteristics of Van Trucks - 1972 Census.	42
10.	Potential Annual Fuel Savings: Retrofit Aerodynamic Drag Reduction Devices	44
11.	Mileage Distribution by Truck Fleet Size - 1972 Census	48
12.	Government Owned Trucks	51

SUMMARY

A study has been conducted of commercially available and prototype aerodynamic drag reduction devices which can be retrofitted onto this nation's trucks to achieve significant fuel savings by 1980. Areas of investigation were the characteristics and costs of the systems presently marketed, the experience of fleet owners who have evaluated and purchased them in significant numbers, the potential applications and fuel savings from among America's 25 million trucks, and the economic benefits to users.

The results of these investigations indicate a large and growing number of devices are available to truckers, offering substantial fuel and dollar savings potentials. The principal areas of application are the long- and short-haul vans which consumed about 6-1/2 billion gallons of fuel in 1972 (approximately 450,000 vehicles) and which are projected to consume nearly 9 billion gallons in 1980 (approximately 625,000 vehicles). However, even for this fairly specialized segment of the truck population which can utilize such devices (short- and long-haul vans), current market penetration is only about 10 percent (approximately 50,000 units); in most instances, only large fleet owners have purchased and are using the devices. Excessive fuel economy improvement claims by manufacturers and distributors, in combination with uncertainty about fuel savings that can be achieved for specific truck configurations, loads, and operating modes, are believed primarily responsible for the small sales impact on smaller-size fleets. This situation exists in spite of the fact that currently available in-use data suggest fuel economy improvements from 5 to 10 percent, and cost break-even times of 3 to 10 months. Depending upon annual average truck mileage factors, dollar savings range from 500 to 7000 dollars per truck over a 3-year period for the mileage range from 50,000 to 150,000 miles per year. Typical returns on investment are over 100 percent per year.

Suggestions are made for a program to clarify the issues and to encourage and permit owners of all sizes of truck fleets to intelligently decide upon add-on devices of maximum benefit in their operations. This program includes experimental evaluation of a representative cross section of promising aerodynamic drag reduction devices in both short and extended tests with single chassis and combination van trucks. It contemplates the acquisition of statistically meaningful fuel economy improvement data and the timely dissemination of this information to both large and small trucking fleets. Reduction in the nation's fuel consumption by these devices would be from 400 to 800 million gallons annually by 1980 if all van-type heavy-duty trucks were equipped with them. If only 70 percent of these trucks were so equipped on a voluntary basis (a more practical goal), it would still require that the current production and sales rate of approximately 1000 units per month be increased by a factor greater than 8 throughout the time interval 1976 to 1980.

1. INTRODUCTION

Large trucks operating at highway speeds expend a large fraction of their horsepower in overcoming the resistance of air to their motion. The energy dissipated by aerodynamic forces for all automotive applications has been estimated at 7 percent of all the energy consumed for all purposes in the United States^{(1)*}. Because of the size, shape, operating speed, and annual mileage characteristics of trucks over 10,000 lb in gross weight, it is appropriate to consider the potential fuel savings if trucks were equipped with suitable aerodynamic drag reduction devices. There is currently a fairly wide variety of commercially available add-on or retrofit devices for this purpose. Newer designs are being developed and evaluated. In addition, aerodynamic improvements are being made in tractor shape and road testing has shown this to be very effective in saving fuel⁽²⁾. This study is confined to consideration of retrofit aerodynamic drag reduction devices, the vehicles on which they can be prudently used, performance experience to date, projections of potential fuel savings, and the economic benefits to the users of the devices. As described and discussed in Sections 2 through 5, it is evident that the commercially available devices work sufficiently well when properly employed to save a large and growing quantity of fuel, and offer a generally very high rate of return on capital invested. Therefore, a program is outlined in Section 6 to implement a more rapid and complete utilization of these devices through further experimentation, demonstration, and dissemination of resulting information to the trucking industry.

*Numbers in parentheses indicate references which are summarized at the end of the report.

THIS PAGE
WAS THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

2. RETROFIT AERODYNAMIC DRAG REDUCTION DEVICES

2.1 THE AERODYNAMIC DRAG PROBLEM

Through wind tunnel tests conducted on many truck configurations it has been found that the total aerodynamic drag on trucks at highway speeds in the absence of winds is divided roughly as follows: approximately 70 percent dependent upon the forebody geometry which establishes the amount of pressure increase above ambient on the surface, approximately 10 percent produced by frictional drag along the top, sides and bottom of the truck, and approximately 20 percent resulting from turbulent wake losses at the blunt aft end⁽³⁾. These figures are very approximate in that they are dependent upon many details of truck shape; further, they do not consider treatment of such matters as the aero-drag on wheels and axles and the flow through the radiator. However, these figures are indicative of the reasons for past and present concern for study of front-end shape parameters. Furthermore, there are few changes of significance which can be made on the underside or aft end of a truck which do not adversely affect truck operations and maintenance.

The front-end geometry of the truck, whether it be a single-chassis unit or a combination vehicle (tractor with semitrailer or two trailers) establishes the basic flow pattern around the vehicle and the pressure forces on it. It also establishes the sensitivity to winds which add vectorially to the vehicle road velocity vector to produce a resultant wind magnitude and direction. Figure 1 depicts the air stream lines and flow separation zones on a simple representation of a tractor/van-type semitrailer under conditions of no wind and a lateral wind. The bluntness indicated for the truck components is a consequence of legal limitations on overall vehicle length and trailer length and economic pressures to maximize van internal cargo volume for a given length. Typical of such rigs and van-type, single-chassis trucks (so called straight trucks) is a large flat surface on the front end of the van

above the cab and extending to the van roof line. On this surface, normal to the vehicle velocity vector, aerodynamic stagnation conditions (maximum pressure rise) occur and flow emanates in all lateral directions. Depending upon the shape of the edges at the periphery of the front end of the van, flow separation can occur, most typically at the roof edge. This condition produces unsteady, turbulent energy dissipation which ultimately requires increased horsepower and fuel consumption to overcome. Many trailer vans have rounded or chamfered vertical corners for improved maneuverability (at the expense of cargo volume) with a side benefit of reduced tendency toward flow separation. However, few straight truck vans have this redeeming feature and almost no trucks have significantly rounded roof or floor edges. On the contrary, the economics of maintenance on lights located just below the roof line have caused most vans to have a sharp-edged channel at the roof edge to provide recessed protection of the lights from tree branches and other hazards.

Figure 1. Flow Separation on a Tractor/Trailer Truck⁽⁴⁾

Under conditions of lateral winds it is seen in Figure 1 that the shape of the front corners of the tractor are as important as those of the van body since they can induce flow separation which may not reattach over the length of the van. Even if the front end of a tractor were ideally streamlined to prevent flow separation, the aerodynamic crossflow through the gap between the rear of the cab and the front of the trailer would not be prevented. This flow is capable of inducing flow separation from the trailer's lee vertical corner unless the corner is generously curved or the flow about the corner is controlled.

The aerodynamic drag force acting on a vehicle is given by

$$D = \frac{C_D \rho A V^2}{2}$$

where

D = body axis drag, lb

C_D = body axis drag coefficient

ρ = air density, slugs/ft³

A = reference frontal area, ft²

V = velocity of air relative to vehicle, ft/sec

For typical trucks, the drag coefficient at highway speeds is relatively independent of velocity magnitude but strongly dependent upon the angle of the resultant wind and the separation distance between the cab and the van body. Figure 2 presents wind tunnel data for models of a cab-over-engine (COE) tractor/semitrailer combination with gaps of 25.5 and 73.5 in. between the two portions of the rig. Observe that the drag coefficient increases sharply with yaw or net crosswind angle, particularly for the larger clearance. Clearly, both the zero angle drag coefficient and its increase with crosswind angle are important.

Figure 2. Crosswind Effects on Drag for COE Rigs⁽⁵⁾ (University of Maryland Tests)

A national average wind speed of 9.5 mph from any direction is sometimes indicated as a condition under which short-haul and long-haul truck aero-drag should be evaluated. However, this speed was obtained from wind measurements taken at numerous sites across the country at heights approximately 30 ft above the ground⁽⁶⁾. Wind profile data indicates use of a factor of 0.6 to correct the measured wind speed to that at a height of about 10 ft which should be meaningful for truck drag evaluation⁽⁷⁾. Therefore, 5.7 mph can be considered an average wind speed for analysis. At a 55-mph road speed this corresponds to a maximum yaw angle of 5.95 deg. For the truck characterized by the 73.5-in. tractor-to-trailer clearance in Figure 2, this condition produces an aerodynamic drag about 38 percent higher than the drag in still air. If the 5.7 mph average

wind approached head on (zero degrees yaw), the drag would only be about 22 percent over that in still air. This illustrates the importance of wind speed and direction. For wind speeds above average, say 10 mph, it can be seen that the unmodified truck noted above could experience an aero-drag force approximately twice that experienced in still air. In addition, the side loads and moments on the rig would induce increased tire resistance drag.

The drag force equation indicates that drag is proportional to velocity squared. Therefore, the required horsepower and fuel consumption to overcome aerodynamic drag is basically proportional to velocity cubed. For a combination rig consisting of a COE tractor with a 12.5-ft high van semitrailer (12 in. radius vertical front corners), operating at 55 mph with a 5-deg yaw angle, approximately 88 hp is required to overcome aero-drag⁽²⁾. At 70 mph this increases to over 180 hp; therefore, speed control is very important. Another aspect of this situation is the ease with which an aerodynamic improvement can be dissipated. If engine power output were kept the same after an aerodynamic drag coefficient improvement of 20 percent were made, a vehicle speed increase of approximately 3 mph would result, including the combined effects of simultaneous increases in truck rolling resistance and driveline losses and the characteristics of the engine. The increased engine fuel consumption at this increased speed would largely negate the fuel consumption reduction afforded by the 20 percent drag reduction.

The fuel savings which can be achieved by a decrease in truck aerodynamic drag at a given speed are established by the engine's brake specific fuel consumption rate or efficiency in converting fuel to power. However, when the savings are expressed as a percentage of the truck's fuel consumption the gross weight of the truck becomes important because of the relative quantities of fuel required to overcome aerodynamic and rolling resistance forces. This relationship for a typical truck is depicted in Figure 3. It is apparent that claims of large percentage savings in fuel consumption for aerodynamic improvements measured in empty trucks must be tempered by the realities of competitive truck operations which demand near-capacity loads. A tractor/trailer combination weighs roughly 30,000 lb

empty and over 73,000 lb fully loaded, with a substantial difference in basic fuel economy values.

Figure 3. Fuel Consumption Decrease versus Drag Decrease as a Function of Weight⁽⁸⁾

The evaluation of potential aero-drag reduction devices and shape changes and investigation of the many parameters affecting overall drag are most expeditiously accomplished on scale models in wind tunnels. At the current wind tunnel state of the art, such data are most meaningful for comparisons and indications of trends. Direct usage in prediction of fuel consumption of truck fleets has been less successful and has limited credibility due to the uncertainties in wind tunnel testing (such as adequacy of ground plane representation, nonrotating wheels, simulation of flow through radiator, and accuracy of corner radii) and the number of things which are not simulated (such as weather, road turbulence, and gusts). When an aerodynamic feature is found attractive in comparative wind tunnel investigations a prototype unit may be evaluated on a truck in a brief period of coast-down tests or hill rolling tests. Coast-down tests with an instrumented truck on a level surface provide data which can be analyzed to deduce aerodynamic drag coefficient. However, careful analysis of the data and

measurement of rolling resistance and driveline resistances as functions of velocity are also required⁽⁹⁾. The opportunities for error are great and significant controversy exists over the results of a test series which did not reflect truck fleet experience⁽¹⁰⁾. Hill-rolling of a truck at terminal velocity can be a somewhat better indicator of aero-drag than coast-down testing because of a narrower speed range but suffers from the availability of suitable constant, curve-free grades, the need for negligible winds and traffic, and introduces the probability of speeds beyond the U. S. legal limit. Track tests, if run long enough, can give a good indication of aerodynamic fuel savings with averaged wind effects. If fuel meters are employed for continuous monitoring, great care is required since the difference between engine inlet fuel flow and return flow to the tank must be related to the aerodynamic force difference experienced in consecutive runs. Some track evaluations of devices have been very misleading⁽¹¹⁾.

Road tests over long distances (hundreds to thousands of miles) with a control truck and a modified truck, and with careful procedures and accurate measurements, can give an accurate evaluation of the fuel savings potential of a drag-reducing device^(12, 13). They are obviously expensive to conduct and tend to give results somewhat higher than can be experienced in normal fleet operations. Their higher fuel-saving values stem from rigorous control of speeds, driving techniques and choice of terrain, and a limited spectrum of weather.

Fleet usage is the final proof of the effectiveness of a device. It of course requires significant capital expenditure and time to produce meaningful results. However, fuel cost savings begin to accrue immediately and customer satisfaction is generally obtained. The growing body of such fleet data can be used to modify the expected fuel savings from more sophisticated but less realistic evaluation techniques. In this study, fleet operating savings were examined for all devices in accordance with the objectives of the study. Performance claims with little or no in-use substantiation were invariably found to be excessive.

2.2 CLASSES OF DEVICES IN PRODUCTION OR PROTOTYPE STATUS

In order to alter the flow patterns around the bodies of van-type trucks, retrofit devices began appearing on the U.S. market in 1967. The variety of devices and the number of manufacturers have grown substantially in the last few years. Over 50,000 units are now installed on U.S. heavy-duty trucks. The devices available at this time may be grouped according to their basic function and mounting location. Significant performance, cost, and experience differences exist within the classes. For the purposes of this study, a range of performance and cost parameters is presented for each class of device. The performance improvements represent effective applications of the units; i.e., use on trucks where van body height and/or width significantly exceed the dimensions of the cab, van leading edges are not all generously rounded, and the truck is primarily employed in intercity trucking operations at normal highway speeds.

Virtually all truck aerodynamic drag reduction devices were conceived to improve operation of large intercity combination van trucks. Such trucks are numerous and consume large quantities of fuel because of their heavy loads and large annual mileage. Drag reduction devices have been applied in substantial numbers and fuel economy data are readily obtained. Some devices have been modified slightly and offered for use on intercity single chassis van trucks as well. These applications came later in time and affect a much smaller population of trucks. Some such devices have been unwisely applied to straight trucks in local operations where performance gains are slight and annual mileage too low for cost payoff.

Limited data are available on application of aerodynamic drag reduction devices to single chassis trucks in short- and long-haul service. However, where such data exist the percentage improvement in fuel economy is generally indicated to be significantly greater than when the same types of drag reduction devices are applied to combination vehicles. There appear to be good reasons for this observation. The total van height and width are often as great for the straight van truck as for typical van trailers and the cabs are usually smaller. The same construction is usually employed in the

van body roof line (usually a sharp-edged channel protecting lights) but the vertical corners are almost invariably sharper than those on most trailers (usually a 10-in. radius or a 45-deg chamfer to accommodate turning without tractor/trailer mechanical interference). Therefore the single chassis van truck presents a physically larger flat surface to the relative wind and one that is more conducive to flow separation and high drag coefficient. Equally important, the single chassis truck is typically equipped with a gasoline engine of marginal horsepower considering the unfavorable aerodynamics and the load capacity of the truck. When fully loaded and operated at highway speeds the engines of these trucks operate at or near full output. When such trucks are equipped with effective aerodynamic drag reduction devices the horsepower reductions are large, as evidenced by substantially higher attainable speeds on level roads and on hills, and for a given road speed the engine is enabled to operate in a more efficient region of its performance map. Although owners of such trucks report fuel economy improvements of 20 to 35 percent when equipped with van body-mounted aerodynamic devices, it is assumed in this report that 15 percent is a representative improvement for the best devices.

2.2.1 Cab Roof-Mounted Devices

The greatest variety and widest usage of drag reduction devices are found in this category. Included are air flow deflectors, partial fairings and diffusers. These devices seek to alter the airstream over the top of the cab so as to eliminate the direct impingement of the airstream upon the flat upper front end of the van body and to cause instead the flow to pass over the roof and around the sides.

- (a) Tractors. For use on combination trucks, the available devices produce a range of fuel economy improvements from 4 to 9 percent. Installed cost of the units, neglecting discounts for quantity purchases and optional illumination provisions for display of corporate logos, range from 160 to 427 dollars. The manufacturers of the devices and their product names are listed below. Illustrations are presented in Figures 4 through 10.

- (1) Aerovironment, Inc. - Aeroboost III (one fixed model)
 - (2) Air-Flo Co. - Air-Flo Wind Deflector (two fixed heights and one fold-down)
 - (3) Black & Lee Mac Associates - Wind-Gem Air Flow Diverter (two fixed heights)
 - (4) CBF Industries - Windbreaker (seven fixed widths)
 - (5) General Motors Corp. - Dragfoiler II (one fixed model)
 - (6) Rudkin-Wiley Co. - Airshield Wind Deflector (sixteen heights with fold-down)
 - (7) Uniroyal Plastic Products - Air Deflector (one adjustable model)
- (b) Single Chassis Trucks. Some of the tractor-mounted devices, with modification, are suitable for straight trucks as well. Limited data indicate a fuel economy improvement of approximately 10 percent. Installed costs range from 287 to 327 dollars. The manufacturers and their products are listed below. The first unit is a larger version of the unit shown in Figure 5. A picture of the second unit is presented in Figure 11.
- (1) Air-Flow Co. - Air-Flo Wind Deflector (one fixed model)
 - (2) Rudkin-Wiley Co. - Airshield Wind Deflector (thirty-six fixed models)
 - (3) Uniroyal Plastic Products - Air Deflector (one adjustable model)

2.2.2 Van-Mounted Devices

These devices are used to eliminate relatively sharp edges on van bodies and to smooth the flow over and around them. Stagnation conditions may be experienced on the van face, but the flow-turning provisions can minimize flow separation from the van sides and roof.

Figure 4. Aeroboost III.

Figure 5. Air-Flo Wind Deflector

Figure 6. Wind-Gem Air Flow Diverter.

Figure 7. Windbreaker.

Figure 8. Dragfoiler II.

Figure 9. Airshield Wind Deflector (Cab-Mounted) and Vortex Stabilizer (Trailer-Mounted)

Figure 10. Air Deflector.

Figure 11. Airshield Wind Deflector with Integral Gap Sealer

(a) Trailers. For use on semitrailers or full trailers the available devices produce fuel economy improvements of 8 to 12 percent. Installed cost per trailer ranges from 136 to 390 dollars. An important consideration is the number of trailers which would be equipped per tractor. The number of trailers registered in the U. S. is somewhat over twice the number of tractors. Fleet owners may have up to 6 or 7 times as many trailers as tractors because of the nature of their operations and the extent of their dual trailer usage (doubles). For this study trailer-to-tractor ratios of 1:1 and 3:1 will be considered. The manufacturers of the drag reduction devices and their products are listed below; illustrations are presented in Figures 12 and 13.

- (1) Nose Cone Manufacturing Co. - Nose Cone (two fixed heights)
- (2) Systems, Science and Software - Air Vane (two fixed lengths for roof edge and sharp vertical corners)

(b) Single Chassis Trucks. Devices for straight trucks provide 9 to 15 percent fuel economy improvements. Installed costs range from 272 to 390 dollars. Manufacturers and their products are listed below. The first two units are shown in Figures 14 and 15. The third unit is presented in Figure 13.

- (1) Aerovironment, Inc. - Aeroboost I (variable length fixed model)
- (2) Nose Cone Manufacturing Co. - Nose Cone (two fixed heights)
- (3) Systems, Science and Software - Air Vane (two fixed lengths for roof edge and vertical corners)

Figure 12. Nose Cone.

Figure 13. Air Vane.

Figure 14. Aeroboost I.

Figure 15. Nose Cone for Straight Trucks.

2.2.3 Gap Crossflow Reducers

When a wind yaw angle exists, a crossflow of air will pass through the gap between a tractor and a trailer or between a cab roof-mounted flow deflector and a van body. Vertically oriented, centrally located planar devices have been developed to be used in combination with cab roof-mounted devices to reduce or eliminate this lateral gap flow. This reduces the tendency for flow separation from the lee side of the van and therefore provides additional fuel savings.

- (a) Tractors. For combination trucks, a tractor-mounted extendible plastic gap sealer is available which can be anchored to a lightweight bracket on the front end of a van trailer. When combined with the same manufacturer's wind deflector, fuel economy can be improved approximately 10 percent for a total initial cost of approximately 515 dollars. The manufacturer and his product are identified below and his assembly is shown in Figure 16.

- (1) Rudkin-Wiley Co. - Gap Sealer (one extendible model)

- (b) Single Chassis Trucks. For these trucks, an integral feature of the air flow deflector of one manufacturer is a vertical longitudinal planar member which extends aft above the cab roof virtually to the front surface of the van body. Gap flow, at least in this region, is virtually eliminated. The assembly provides a fuel economy improvement of approximately 10 percent for an initial cost of 287 dollars. The manufacturer and his product are identified below. The unit is presented in Figure 11.

- (1) Rudkin-Wiley Co. - Airshield Wind Deflector (thirty-six fixed models)

(c) Trailers. For combination trucks, a trailer-mounted, vertically oriented planar device is available which projects forward from the center of the trailer and reduces the gap cross-flow under yawed conditions. When combined with the same manufacturer's wind deflector fuel economy is improved approximately 7 percent. The total initial costs are approximately 400 and 660 dollars for trailer-to-tractor ratios of 1:1 and 3:1, respectively. The manufacturer and his product are identified below. The assembly is shown in Figure 9.

(1) Rudkin-Wiley Co. - Vortex Stabilizer (two fixed models)

Figure 16. Gap Sealer

2.3 DEVICES UNDER DEVELOPMENT OR PARTIALLY EVALUATED

A number of prototype systems of potential future interest have been partially developed and evaluated. Several are evidently in low-level development or evaluation phases. Since they are not commercially available and data have proven difficult to obtain, these devices are merely noted for completeness.

2.3.1 Cab-mounted Air Flow Turning Vanes

Figure 17 depicts a rack of vanes capable of deflecting a longitudinal airstream upward and over a van roof edge. Fabricated by Blair-Lefler, Inc. of Wichita, Kansas, the unit was in-service road tested for over 16,000 miles, indicating a fuel economy improvement of 3 to 6 percent⁽¹⁴⁾.

2.3.2 Tractor-to-Trailer Fairings

- (a) Hinged Metal Plate Assembly. Figure 18 shows a rig equipped with a sheet aluminum full fairing which was used in a series of deceleration, hill rolling and road tests. The unit was fabricated by Aerovironment, Inc. of Pasadena, California. For the empty rig, indicated fuel savings were 17.6 percent at 55 mph⁽¹⁵⁾.
- (b) Ram Air Inflated Bags. Tractor-mounted, self-inflating fabric bags which seal the upper portion of the gap between tractor and trailer and create a fairing from the front end of the cab roof to the trailer roof edge have been fabricated and subjected to road tests. Two prototype units fabricated by Clenet Design of Santa Barbara, California are being evaluated in routine long-haul operations in different sections of the country. A picture of one of these units is presented in Figure 19⁽¹⁶⁾. Evidently similar units fabricated by Creative Engineering Consultants and Associates of Bellbrook, Ohio have been road tested to some extent.

Figure 17. Turning Vanes.

Figure 18. Full Metal Fairing.

Figure 19. Air Cell

Figure 20. Air-Deployable Fairing.

2.3.3 Wind-Positioned Combination Air Flow Deflector and Crossflow Reducer

Several prototypes have been tested of a tractor-mounted, spring-loaded assembly of panels which remain folded against the aft end of a tractor until sufficient speed is attained to aerodynamically position the panels for airstream deflection and gap flow retardation. The units were designed and fabricated by Aero Van, Inc. of Smyrna, Georgia. The first prototype was tested over 40,000 miles and indicated 6 to 7 percent fuel savings. Three prototypes of a later design, shown in Figure 20, are understood to be installed on trucks in normal operations⁽⁵⁾.

2.4 SUMMARY

A substantial number of commercial aerodynamic drag reduction devices are presently available which afford a choice for various van truck applications. They are moderate in cost and provide significant fuel savings. Table 1 indicates the approximate number of units of different type which have been installed since 1967. Present sales somewhat exceed 1000 units per month. The bulk of the units sold to date have been to owners of large fleets who have conducted their own evaluations. These evaluations provide the most meaningful data on effectiveness of the devices.

Table 1. Estimated 1975 Utilization of Aerodynamic Drag Reduction Devices

	Primary Device Mounting Location		
	<u>Cab Roof</u>	<u>Van Body Front</u>	
Tractor	45,050		
Single Chassis Unit	1,500	1,000	
Trailer		3,000	
Total Truck Installations	46,550	4,000	<u>50,550</u>

Note: Gap Sealers and Vortex Stabilizers are used in conjunction with primary devices and are included in total number of installations.

3. SURVEY OF TRUCK FLEET OWNERS

In addition to the literature search and direct contact with all identified designers or manufacturers of aero-drag reduction equipment, as well as some of their distributors, a survey was made of truck fleet operators. There were several purposes for this investigation. The primary purpose was to determine what aerodynamic and other drag reduction devices they have evaluated, their evaluation techniques, descriptions of their trucks and modes of operation, and the results of their evaluations. The principal results sought were fuel savings experience, but operational factors such as road handling, potential cab damage, and dirt accumulation were also of interest. A secondary purpose of the survey was to obtain data on average truck fuel economy without drag reduction improvements and on average annual truck mileage.

The trucking organizations contacted by telephone and selected from Reference 17 included some of the largest fleet owners from each section of the country. When the purposes of the survey were briefly explained, the representatives of these companies were very cooperative in providing details of their operations and experience. Details of these conversations are not included in this report, but the companies are identified in Appendix A.

It was found that virtually all large fleets contacted had made experimental evaluations of one or more aerodynamic drag reduction devices. They typically had evaluated radial tires, modulated radiator fans, derating of engines, and some were evaluating new "high torque rise" diesel engines. As a result of their evaluations of aerodynamic drag reduction devices, 8 out of 10 companies had equipped 10 to 100 percent of their line haul tractors with such devices. Since large numbers of units have been in use for some time, the data obtained is invaluable in putting manufacturers' performance claims in perspective. The fuel economy improvements associated with the devices described in Section 2 reflect, where possible, the cumulative experience of these fleet users.

Naturally, not all devices identified in Section 2 were found in the field because of the limited nature of the survey. Consequently, it was necessary to follow up leads and testimonials offered by device manufacturers and distributors. Some of these contacts corroborated the manufacturers' fuel economy claims, but all too often the trucker's experience was sharply at odds with the stated or implied fuel savings.

Fleet owners contacted were generally satisfied with the devices they had bought. In addition to fuel savings, improved handling characteristics in crosswinds, reduced buffeting when exiting underpasses, higher acceleration and higher speed under strong headwinds and up grades were typically mentioned. One owner reported fewer tickets from the highway patrol since fewer wood chips are now being blown out of his fully loaded open-top van. Individual negative comments which were made on cab roof-mounted devices included: aluminum COE tractor roofs being torn off by the high air loads; rainwater entering through cab roof mounting holes due to roof flexing; smoke and fumes entering the cab; increased dirt accumulation in the engine air cleaner; and rear view mirrors on certain tractors becoming completely obscured in rainy weather. Trailer-mounted devices were criticized for physical interference problems when a tractor's exhaust stack contacted the device when making a sharp turn (apparently at the bottom of a ramp) and when different tractor/trailer configurations are employed. It is evident that refrigeration units, almost invariably mounted on the upper front ends of vans, preclude the use of certain drag reduction devices, present physical interference problems to others, and introduce uncertainty regarding the adequacy of the environment for the refrigeration unit where cab roof-mounted devices are used. The latter is a significant deterrent since such units represent a nominal 6000 dollars investment.

The fleet owners appear anxious to comply with the 55 mph speed limit and to save fuel. They are well aware of the tendency of drivers to overspeed and the possibility that various drag reduction measures may result in reduced trip times with a smaller than expected fuel saving. To offset this

tendency, in addition to directives, some have derated their engine's horsepower and reduced governed speed and installed tachographs to enable speed to be monitored. One operator indicated the nature of the resistance of drivers by referring to the practice employed by some drivers whereby engine derating is offset by clamping a vice grip wrench on the fuel return line.

Other significant results of the survey are presented in Tables 2 and 3. Table 2 indicates that for typical, large long-haul truck fleets which use van combination vehicles extensively, if not exclusively, the average year-round fuel economy without drag reduction improvements is approximately 4.5 miles per gallon. This is significantly lower than the national average of 5.42 mpg reported for all combination trucks⁽¹⁸⁾ or the 5.7 mpg reported for all heavy duty diesel trucks^(19,20). The limited sampling of annual mileage per tractor in Table 3 indicates a considerable spread in values and an average over 100,000 miles per year. This is significantly greater than the national average of 71,900 miles for all long range trucks, 30,900 miles for all vans and 35,100 miles for all heavy-heavy trucks⁽²¹⁾ ($\geq 26,000$ lb gross vehicle weight). Thus it is seen that the van-type vehicles for which aerodynamic drag reduction devices are suitable tend to travel farther with less fuel efficiency than other vehicles with which they are usually classified.

Table 2. Fuel Economy of Unmodified Van Combinations
in Long-Haul Fleet Operations

<u>Typical Reports from Limited Survey</u>	<u>MPG</u>
Aero Mayflower Transit Company	4.93
Associated Transport, Inc.	5.0
Campbell Sixty-Six Express	4.2
Carl Subler Trucking, Inc.	4.75
Consolidated Freightways Corp.	4.1
E. I. DuPont de Nemours and Company	4.8
Garrett Freightlines, Inc. (80% doubles)	4.6
Globe Union, Inc.	4.67
Hennis Freight Lines	4.5
Lee Way Motor Freight, Inc.	4.5
Northwest Agricultural Cooperative Assoc., Inc.	4.35
ONC Freight Systems Company	4.28
Stalcup Trucking, Inc.	4.37
Standard Trucking Company	4.3
Tom's Foods, Ltd.	5.0
AVERAGE	4.56
<u>Other Reports:</u>	
United Parcel Service	
Trailers 12.5 ft high, closed coupled, high torque rise engines, 5-speed transmissions, fan clutches, radial tires on trailers	5.9 (5.5 for twin trailer)

Table 3. Annual Mileage of Van Combinations in
Long-Haul Fleet Operations

<u>Typical Reports from Limited Survey</u>	<u>Average Tractor Miles per Year</u>
Beatrice Foods Company	135,000
Carl Subler Trucking, Inc.	100,000
E.I. DuPont de Nemours and Company	160,000
Global Van Lines	150,000
Globe Union, Inc.	55,000
IML Freight, Inc.	120,000
Northwest Agricultural Cooperative Assoc., Inc.	167,000
ONC Freight Systems Company	120,000
Standard Trucking Company	120,000
Tom's Foods, Ltd.	105,000
	<hr/>
AVERAGE	123,000

4. COST-BENEFIT ANALYSES FOR COMMERCIALLY AVAILABLE SYSTEMS

The annual economic benefit to the user of drag reduction equipment is related directly to his annual mileage, baseline fuel economy, fuel cost per gallon, and the percentage improvement in fuel economy provided by the drag reduction device. Annual dollar savings are presented in the nomograph of Figure 21 as a function of these variables. These savings should continue for the life of the truck and beyond, possibly at a modified rate, if the equipment is removed and reinstalled on replacement vehicles. Maintenance costs for the devices appear negligible--possible periodic painting of brackets, patching of impact damage, or cleaning off of bugs. Possible exceptions are the replacement after a few years of a flexible gap seal or its extendible mechanism, and a set of polyester straps used on one roof-mounted device.

To obtain the annual fuel cost savings a purchaser must invest in the hardware and its mounting bracketry and either pay for its installation or devote his manpower to that job. As indicated in Section 2 there are considerable differences not only in the performance of drag reducing systems but in their costs. Table 4 presents the results of the cost-benefit analyses for all systems noted in Section 2. The results are summarized by type of device and encompass the range of fuel economy improvements and installed costs. The costs of trailer-mounted devices are presented for trailer-to-tractor ratios of 1:1 and 3:1. The first tradeoff result presented is the mileage at which fuel cost savings would match total installed costs. It is seen that this can occur in as few as 15,300 miles or require as many as 87,700 miles, depending upon the trailer-to-tractor ratio. This break-even mileage cost was then converted to a break-even time and tabulated for the expected range of annual truck mileages. It is seen that the equipment will pay for itself in as few as 1 to 2 months for a busy truck, or may require as long as 21 months for low mileage and a high trailer ratio, which is an unlikely combination of parameters. Typical payoff times are in the range of from 3 to 10 months.

Figure 21. Parametric Fuel Economy Chart

Table 4. Economic Benefit Summary - Aerodynamic Drag Reduction Devices

Type/Mounting Location of Device	Fuel Economy Improvement %	System Installed Cost Dollars	Cost Break-Even Mileage	Cost Break-Even Time, Months			Three-Year Economic Benefit					
				Average Annual Truck Mileage			Total Net Savings, Dollars			Average Annual Rate of Return, %		
							Average Annual Truck Mileage			Average Annual Truck Mileage		
				50,000	100,000	150,000	50,000	100,000	150,000	50,000	100,000	150,000
1. Cab Roof-Mounted Deflectors												
a. Tractor	4 9	160 427	32,500 52,200	7.8 12.5	3.9 6.3	2.6 4.2	507 1,175	1,173 2,675	1,840 4,175	62 121	158 274	254 428
b. Single-Chassis Truck	10 10	287 327	25,800 29,400	6.2 7.1	3.1 3.5	2.1 2.4	1,340 1,380	3,006 3,046	4,673 4,713	137 160	306 354	476 547
2. Van-Mounted Flow Smoothers												
a. Trailer												
1). Trailer/Tractor Ratio = 1:1	8 12	136 390	15,300 29,200	3.7 7.0	1.8 3.5	1.2 1.3	1,197 1,610	2,531 3,610	3,864 5,610	138 293	309 620	479 947
2). Trailer/Tractor Ratio = 3:1	8 12	408 1,170	45,900 87,700	11.0 21.0	5.5 10.5	3.7 7.0	830 925	2,259 2,830	3,592 4,830	24 76	81 185	138 293
b. Single-Chassis Truck	9 15	272 390	23,400 38,500	5.6 9.2	2.8 4.6	1.9 3.1	1,115 2,110	2,615 4,609	4,115 7,109	97 180	226 394	356 608
3. Gap Crossflow Reducer Combined with Cab Roof Mounted Device												
a. Tractor	10 --	515 --	46,300 --	11.1 --	5.6 --	3.7 --	1,152 --	2,818 --	4,485 --	75 --	182 --	290 --
b. Single-Chassis Truck	10 --	287 --	25,800 --	6.2 --	3.1 --	2.1 --	1,380 --	3,046 --	4,713 --	160 --	354 --	547 --
c. Trailer												
1). Trailer/Tractor Ratio = 1:1	7 --	400 --	51,400 --	12.3 --	6.2 --	4.1 --	767 --	1,933 --	3,100 --	64 --	161 --	258 --
2). Trailer/Tractor Ratio = 1:3	7 --	660 --	84,900 --	20.4 --	10.2 --	6.8 --	507 --	1,673 --	2,840 --	26 --	85 --	143 --

NOTES:

1. <div>Lowest</div> <div>Highest</div>

2. Baseline fuel economy of 4.5 mpg and an average diesel fuel cost of \$0.50 per gallon.

3. Average rate of return on investment was calculated as the average net savings divided by the installed cost of the device, neglecting the cost of money.

4. "--" indicates that the class of device had only one candidate.

Net economic benefits to the purchaser are presented in Table 4 for an arbitrarily selected period of 3 years. As a function of annual mileage per truck, the net dollar savings are given and these are then indicated as an annual percentage return on capital investment. The dollar savings range from 500 to 7100 dollars. Return on investment is most impressive, ranging from 24 percent to 947 percent per year! Typical returns on investment are over 100 percent per year except for trailer-to-tractor ratios of 3:1. As fuel costs rise, the gains will be progressively higher.

Notice that in constructing Table 4, the lowest and highest values of each parameter for each class of device were presented. These values are the extremes which resulted from calculations performed on all devices individually and do not necessarily correspond to any one manufacturer's device.

No attempt was made to correct for lost revenues associated with the potential reduction in cargo weight due to the 15 to 115 lb weight of the installed drag reduction system. An annual cost of \$2.25 per year in lost revenues for each pound of hardware weight added to a truck has been estimated⁽²²⁾. This could therefore amount to as much as a 258-dollar loss to offset the annual fuel cost savings. Such an extreme loss is not likely to be incurred since trucks do not always operate at cargo weight capacity when leaving their terminals and rarely return with full loads.

5. ANALYSIS OF U.S. TRUCK POPULATION AND FUEL SAVINGS POTENTIAL

To evaluate the fuel savings potential of aerodynamic drag reduction devices for the U.S. trucking fleet, first the characteristics of this fleet should be analyzed. It is necessary to estimate the number and mileage of van-type trucks, as these are the only ones for which such devices are basically suitable or commercially available. Other single unit and combination truck body types typically have cross sections not significantly greater than those of the cab or tractor, or else are characterized by an inconsistent loading arrangement, such as occurs with platform trucks, which does not lend itself to aerodynamic improvement by a fixed device. It is assumed that containerized cargo is included in the van category⁽²³⁾. Some dry bulk hopper-type trailers are obvious candidates for streamlining, but add-on devices are probably not the answer.

In 1972, the U.S. Department of Commerce conducted a census of transportation--the Truck Inventory and Use Survey⁽²¹⁾. This report is the definitive summary of truck statistics and will not be superseded until late in 1978 when the results of the next scheduled census in 1977 will be reported. Pertinent data have therefore been obtained from this document and are included in Tables 5 through 9.

Most data in these tables are self-explanatory. Short-range is defined as "mostly over-the-road (beyond the local area), but usually not more than 200 miles one way to the most distant stop from the place the vehicle is stationed." Long-range is defined as "mostly over-the-road trips that usually are more than 200 miles one way to the most distant stop from the place the vehicle is stationed." Observe that some data are identified as approximate due to inconsistencies introduced into the reference data when percentages (of the truck population) were rounded off. In Table 5, for example, it was required to estimate the annual mileage per truck for vans in local, short range, and long range operations in order to account for the known number of total van truck-miles by the known numbers of vans in these range categories.

Table 5. Truck Number, Range, Type and Mileage Summary -
1972 Census

<u>Truck Type</u>	<u>Total</u>	<u>Local</u>	<u>Short Range</u>	<u>Long Range</u>	<u>Not Reported</u>
Total Trucks	19,747,000	16,057,000	1,717,000	469,000	1,504,000
• Single Unit	18,836,000	15,704,000	1,413,000	236,000	≈1,485,000
• Combinations	909,000	353,000	304,000	233,000	≈19,000
Total Trucks (excluding pickups, multistop and walk-ins)	5,284,000	4,037,000	710,000	312,000	225,000
• Average Mileage/ Truck	16,800	9,900	32,800	71,900	13,300
Total Van Trucks	1,134,000	684,000	242,000	208,000	
• Average Mileage/ Truck	30,900	≈ 9,900	≈ 32,800	≈ 97,820	
• Truck-Miles x 10 ⁻⁹	35.056	≈ 6.77	≈ 7.94	≈ 20.3	

Table 6. Mileage Characteristics of Trucks by
Weight Class - 1972 Census

Excluding Pickup, Panel, Multistop and Walk-in Trucks

	<u>Total Trucks</u>	<u>Truck-Miles x 10⁻⁹</u>	<u>Average Miles/Truck</u>
Light ≤ 10,000 lb	1,084,000	10.2	9,400
Medium 10,001-20,000 lb	1,940,000	18.78	9,700
Light-Heavy 20,000-26,000 lb	792,000	8.34	10,500
Heavy-Heavy ≥ 26,000 lb	1,468,000	51.5	35,100
	<hr/> 5,284,000	<hr/> 88.82	

Table 7. Approximate Distribution of Van Trucks by
Weight Classification - 1972 Census

Body Type	Total Vans	Light ≤10,000 lb	Medium 10,001-20,000 lb	Light-Heavy 20,001-26,000 lb	Heavy-Heavy ≥26,001 lb
Insulated Non-Refrigerated	96,000	11,000	31,000	9,000	45,000
Insulated Refrigerated	178,000	13,000	67,000	19,000	79,000
Furniture	192,000	20,000	102,000	23,000	47,000
Open Top	53,000	11,000	16,000	3,000	28,000
All Other Vans	610,000	98,000	175,000	59,000	278,000
	<u>1,134,000</u>	<u>153,000</u>	<u>391,000</u>	<u>113,000</u>	<u>477,000</u>

Table 8. Approximate Breakdown of 1972 Census
Van Truck Population

Body Type	Total Vans	Single-Unit Truck			Combination Truck				
		2 Axle (18,289,000)	3 Axle (548,000)	Total (18,836,000)	3 Axle (125,000)	4 Axle (273,000)	5 Axle (417,000)	Other (95,000)	Total (909,000)
Insulated Non-Refrigerated	96,000	49,000	7,000	56,000	5,700	11,500	19,100	3,700	40,000
Insulated Refrigerated	178,000	97,000	17,000	114,000	2,500	10,600	44,600	6,300	64,000
Furniture	192,000	137,000	12,000	149,000	17,200	19,100	2,900	3,800	43,000
Open Top	58,000	30,000	4,000	34,000	3,100	7,400	11,700	1,800	24,000
All Other Vans	610,000	<u>326,000</u>	<u>23,000</u>	349,000	<u>43,000</u>	<u>100,000</u>	<u>92,000</u>	<u>26,000</u>	261,000
		639,000	63,000		71,500	148,600	170,300	41,600	
	<u>1,134,000</u>			<u>702,000</u>					<u>432,000</u>

Note: Numbers in parentheses are total trucks of all body types in truck-type axle category.

Table 9. Mileage Characteristics of Van Trucks -
1972 Census

Body Type	Number of Van Trucks				Annual Mileage	
	All Ranges	Local	Short Range	Long Range	Truck-Miles x 10 ⁻⁹	Average Miles/Truck
Insulated Non-Refrigerated	96,000	51,000	28,000	17,000	3.43	35,600
Insulated Refrigerated	178,000	96,000	48,000	34,000	6.894	38,700
Furniture	192,000	107,000	26,000	59,000	4.045	21,000
Open Top	58,000	37,000	14,000	7,000	1.492	25,600
All Other Vans	610,000	393,000	126,000	91,000	16.195	31,500
	1,134,000	684,000	242,000	208,000	35.056	30,900

Table 9 indicates that in 1972 there were 242,000 vans in short-range operations and 208,000 in long-range operations. These numbers were used to determine projected fuel savings. The 684,000 local service vans operate at too low average speeds and annual mileages to offer any significant fuel savings.

Table 10 utilizes the statistical data gathered on numbers of vans, their mileage and fuel economy, and indicates nationwide fuel savings potential, neglecting the aero-drag reduction equipment already in use (over 50,000 installations). Projections of total truck registration in 1975⁽²⁴⁾ and 1980⁽²⁵⁾ are used to evaluate potential fuel savings, assuming that van trucks represent a constant fraction of the total truck population. Five percent savings are very representative of reported experience to date, and ten percent savings probably represent an upper bound on a nationwide basis. The potential fuel savings for 1980 are 879 million gallons of fuel or 23.2 million barrels of petroleum (on the basis of 42 gallons per barrel and a ten percent loss in refining operations).

Many practical factors may serve to prevent the attainment of these potential fuel savings. Some of these in their basic order of importance are:

- (1) Age of truck and/or trailer may preclude payoff.
- (2) Uncertainty of fuel savings--claims versus results, long evaluation period required.
- (3) Truck configuration--interference between device and roof-mounted air conditioners, lights and horns; aerodynamic interference with van front-end-mounted air conditioners; restricted maneuverability of tractor/semitrailer combinations; van may have low drag front end.
- (4) Open-top vans may not achieve significant improvement.
- (5) Lack of capital for purchase by smaller operators.
- (6) Flexible use of tractor impaired by fixed devices.
- (7) Operational problems--dirt accumulation in air filters, side mirror obscuration in wet weather.

Table 10. Potential Annual Fuel Savings: Retrofit Aerodynamic Drag Reduction Devices

	<u>1972</u>	<u>1975</u>	<u>1980</u>
Estimated Total Truck Registration	19,745,000	24,700,000	27,500,000
<u>Long Haul Vans</u>			
Number	208,000	260,000	290,000
Average Annual Mileage per Truck, mi	98,000	98,000	98,000
Fuel Consumed by Fleet, 10 ⁹ gal	4.53	5.67	6.32
Fuel Savings for 5% Economy Improvement, 10 ⁶ gal	226	283	316
Fuel Savings for 10% Economy Improvement, 10 ⁶ gal	453	567	632
<u>Short Haul Vans</u>			
Number	242,000	303,000	337,000
Average Annual Mileage per Truck, mi	33,000	33,000	33,000
Fuel Consumed by Fleet, 10 ⁹ gal	1.77	2.22	2.47
Fuel Savings for 5% Economy Improvement, 10 ⁶ gal	88	111	124
Fuel Savings for 10% Economy Improvement, 10 ⁶ gal	177	222	247
<u>Total Annual Fuel Savings Potential for Vans</u>			
5% Fuel Economy Improvement, 10 ⁶ gal	314	394	440
10% Fuel Economy Improvement, 10 ⁶ gal	630	789	879

Notes:

Excludes Vans in Local Usage (684,000 vehicles in 1972)

Includes Single-Chassis and Combination Trucks

Average Fuel Economy for Subject Vans = 4.5 mpg

Percent Fuel Savings Roughly Equated to Percent Fuel Economy Improvement

An estimate was made of the number of trucks in short-haul and long-haul service which might be equipped with various aerodynamic drag reduction devices by 1980 if a suitable program of education and example were carried through. It was concluded that of the 627,000 van trucks expected to be engaged in long- and short-range operations in 1980, approximately 443,000 could, on a voluntary basis, be equipped with suitable devices. On this basis, the corresponding fuel savings from such aero drag reduction devices would therefore range from 315 to 630 million gallons of fuel per year (8.3 to 16.7 million barrels of petroleum). The current largest producer of this class of equipment has estimated that 100,000 line haul tractors would be equipped by 1980 without government assistance, and that this might increase to about 350,000 with government assistance⁽²⁶⁾. The required average production rate of roughly 8000 truck installations per month is about 8 times the current sales rate, but no problem is seen in satisfying this demand.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

6. RECOMMENDED IMPLEMENTATION PROGRAM

The national fuel savings potential of truck aerodynamic drag reduction devices is sufficiently large that steps should be taken to assure that the utilization of these devices is increased from its present level of 50,000 units to over 400,000 units by 1980. Although it is evident that such drag reduction devices are very cost effective, it is believed that governmental action and encouragement would be required to significantly change the utilization rate in the 1976 to 1980 time period.

Two basic problems currently exist which are felt to be inhibiting factors to more rapid commercialization rates. First, there are not only several classes of truck-device combinations (e.g., cab roof-mounted deflectors, van-mounted flow smoothers, gap crossflow reducers, etc.), but also several different manufacturers of devices within each class. This multiplicity of choices, in combination with conflicting fuel economy improvement claims, makes the selection process difficult for a truck fleet owner. Second, the fuel economy improvement claim for any given device is not statistically sound. Many claims are based on the results from a single vehicle test and therefore a high confidence cannot be placed on the results because of known vehicle-to-vehicle variation effects.

Many of the larger fleet operators are fairly well informed about the device options available to them and the generally short cost break-even times for high annual mileage operations. They often conduct their own road evaluations and then usually equip all or a portion of their long-haul fleet. They are generally aware of current developments through participation in trucking associations and through their contacts with device manufacturers and distributors. Approximately 90 percent of all units sold by the largest aerodynamic drag reduction device manufacturer in the United States have been sold to medium and large common carriers, private carriers, and lease companies⁽²⁷⁾. However, as shown in Table 11, fleets of 20 or more trucks represent only 17.7 percent of the truck population and accomplish 30.8 percent of the total truck-miles. The bulk of the truck population is in smaller

Table 11. Mileage Distribution by Truck Fleet Size -
1972 Census

<u>Truck Fleet Size</u>	<u>No. of Trucks</u>	<u>Truck-Miles x 10⁻⁹</u>	<u>Average Miles/Truck</u>
1	960,000	13.263	13,800
2-5	2,310,000	27.163	11,800
6-19	1,079,000	21.065	19,500
≥ 20	935,000	27.336	29,200
Not Reported	-----	-----	-----
	<hr/> 5,284,000	<hr/> 88.827	

fleets averaging less than half the number of miles per year per truck. These smaller fleet owners are sought after less assiduously by suppliers, are skeptical of many performance claims, are less likely to conduct valid comparative experiments with their trucks, pay higher unit prices because of the smaller quantities involved, require more than twice as long to achieve a payoff, and typically have less ready cash. In order to achieve the desired utilization level of over 400,000 units by 1980, active participation by the smaller-size trucking fleets would be required.

Therefore, it is recommended that the government institute a program to clarify the above issues and to encourage and permit owners of all sizes of truck fleets to intelligently select drag reduction devices of maximum benefit in their particular operations. This program should include experimental evaluation of a representative cross section of promising drag reduction devices in both short and extended tests with single chassis and combination van trucks of the types used in short- and long-haul trucking. It should encompass the acquisition of statistically significant fuel economy improvement data and the timely dissemination of this information to both large and small trucking fleets. Suggested elements of this program are delineated below.

6.1 DEVICE COMPARISON TESTS

In this first phase of the program, a series of short road tests would be performed in which representative devices of each general class (e. g., cab roof-mounted deflectors, van-mounted flow smoothers, gap crossflow reducers, etc.) would be tested with several straight truck and tractor / trailer van configurations consistent with their intended applications. The two-truck approach (using two vehicles traveling a common route about 1/2 mile apart) over a 100- to 200-mile test route should be adequate.

These short tests should be run several times under varying conditions, thereby developing a larger data base concerning fuel economy improvements attributable to such devices. Great care should be taken in establishing the baseline fuel economy of the trucks used in the experiments.

This is important since the truck-to-truck variations (of "identical" vehicles) can have fuel economy differences in the order of the improvements being determined. The maximum number of devices, different trucks, and runs should be the aim of the first phase of this test program. Longer tests of a single device or fewer devices are considered less useful because of run-to-run testing errors and vehicle-to-vehicle performance variations.

The output of this phase of the program, then, would be comparative fuel economy improvement data for the spectrum of devices under carefully controlled test conditions. These results would be indicative of the maximum benefits achievable with the devices tested.

6.2 IN-USE STATISTICAL CONFIDENCE TESTS

As a second phase of the program, the better devices (in each class, if appropriate) would be placed in actual service with trucking companies, in combination with a data recording system, to track changes in fuel economy over a reasonable in-service time period (e. g., six to twelve months).

In order to acquire statistically significant information, there are the problems associated with sample size and control groups. In general, to establish statistical precision for the order of fuel economy improvement expected, the test fleet may have to involve up to 100 vehicles. This suggests that large fleet owners would have to be considered to implement this phase of the program. In order to secure their services, it may be appropriate for the government to purchase or cost-share the device acquisition, to install and maintain recording equipment, pay for records kept, and evaluate the data.

As noted in Table 12, the federal and local governments own a substantial number of heavy-duty straight trucks and tractor/trailer combinations. It may be possible to involve one or more of these governmental agencies in this second phase of the program, as well as large commercial trucking lines. This action would both reduce government expense and provide an appropriate example.

Table 12. Government Owned Trucks

	<u>No. in 1972*</u>	<u>No. in 1973**</u>
Federal Government:		
Total Trucks	165,113	171,006
Single-unit Trucks ≥ 17,000 lb GVW	5,019	
Trailers and Semitrailers	2,102	
State, County, Municipal Governments:		
Total Trucks	848,305	886,221
Trailers and Semitrailers	98,062	

* 1972 Highway Statistics, U.S. Department of Transportation⁽²⁸⁾

** 1975 Motor Truck Facts, Motor Vehicle Manufacturers Association⁽¹⁸⁾

The output of this phase of the program would be high-confidence-level in-use fuel economy improvement data that could be disseminated to the industry at large.

6.3 DOCUMENTATION AND INFORMATION DISSEMINATION

In this phase of the program, the results of the first and second phase test programs, the fuel economy improvements expected for all the truck configurations, and aerodynamic drag reduction devices tested would be documented and widely disseminated. In addition to the fuel savings benefits, the economic factors such as acquisition cost, pay-back time, return on investment, etc., would also be summarized. This information-transfer process would be expected to greatly enhance the prospects for increased device utilization rates.

6.4 WIND TUNNEL AND CORRELATION PROGRAM

In addition to the foregoing, consideration should be given to a corollary wind tunnel test and correlation program. Although there are a substantial number of specific devices currently being marketed, it is not known with certainty that these devices are optimal in terms of size, shape, contour, etc., for the many and diverse tractor and trailer shapes and combinations. It would be useful to perform tests of additional configurations and to develop correlation techniques which enable the prediction from wind tunnel tests to actual road test and fleet use results.

APPENDIX

LIST OF COMPANIES/ASSOCIATIONS CONTACTED

THIS PAGE
WAS THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

MANUFACTURERS OR DESIGNERS OF
AERO-DRAG REDUCTION DEVICES

Air Flo Company, Elkhart, Indiana

Aero Van, Inc., Smyrna, Georgia*

Aerovironment, Inc., Pasadena, California

Black & Lee Mac Associates, Ripley, West Virginia

CBF Industries, Dallas, Texas

Clenet Design, Santa Barbara, California

Creative Engineering Consultants and Associates, Bellbrook, Ohio*

General Motors Corp., Pontiac, Michigan

Nose Cone Manufacturing Company, La Habra, California

Rudkin-Wiley Company, Stratford, Connecticut

Systems, Science and Software, La Jolla, California

Uniroyal Plastic Products, Mishawaka, Indiana

* Not reached by phone or responsive to letter. Information obtained from published literature.

DISTRIBUTORS

New Haven Moving Equipment Corp., Los Angeles, California

Trailmobile Division of Pullman, Inc.,

Chicago, Illinois

Pico Rivera, California

Merchantville, New Jersey

Transportation Maintenance Corp., Newcastle, Delaware

Trucking Equipment Supply Co.,

Columbus, Ohio

Los Angeles, California

White-Autocar Truck Sales and Service, Los Angeles, California

TRUCK FLEETS

Aero Mayflower Transit Company, Indianapolis, Indiana
Arkansas Best Freight System, Fort Smith, Arkansas
Ashland Chemical Co., Columbus, Ohio
Associated Transport, Inc., New York, New York
Atlanta Constitution, Atlanta, Georgia
Bartlett Trucking Company, La Mirada, California
Beatrice Foods Company, Chicago, Illinois
Bell Helicopter Company, Fort Worth, Texas*
Boise Cascade Corporation, Compton, California
Campbell Sixty-Six Express, Springfield, Missouri
Capitol Bakers, Inc., Harrisburg, Pennsylvania
Carl Subler Trucking, Inc., Versailles, Ohio
Clayton Manufacturing Company, Temple City, California
Columbus Show Case Company, Columbus, Ohio
Consolidated Freightways Corporation, San Francisco, California
D & N Transport, La Puente, California
Douglas Aircraft Company, Long Beach, California
E.I. DuPont de Nemours and Company, Wilmington, Delaware
Garrett Freightlines, Inc., Pocatello, Idaho
G & H Transportation, Inc., Montebello, California
Globe Union, Inc., Louisville, Kentucky

* Not contacted. Data obtained from company publication.

TRUCK FLEETS (Continued)

Gordon Fast Freight, Tacoma, Washington
Graves Truck Line, Inc., Sabina, Kansas
Hennis Freight Lines, Winston-Salem, North Carolina
IML Freight, Inc., Salt Lake City, Utah
Interstate Motor Freight System, Grand Rapids, Michigan
Lancaster Storage Van Company, Lancaster, Pennsylvania
Lee Way Motor Freight, Inc., Oklahoma City, Oklahoma
Lauderback-North American Van Lines, Philadelphia, Pennsylvania
Lounge, Inc., Brockton, Massachusetts
Maislin Brothers Transport, Ltd., Montreal, Canada
McLean Trucking Company, Winston-Salem, North Carolina
Mobil Oil Corporation, Atlanta, Georgia
Northwest Agricultural Cooperative Assoc., Inc., Ontario, Oregon
ONC Freight Systems Company, Bell, California
Overnight Transportation Company, Richmond, Virginia
Pacific Intermountain Express, Oakland, California
Pacific Motor Trucking Company, San Francisco, California
Packaging Systems, Inc., Chicago, Illinois
Pan American Van Lines, Inc., Long Beach, California
Phillips Petroleum, Kansas City, Missouri
Red Star Express Lines of Auburn, Inc., Auburn, New York
Roadway Express, Akron, Ohio

TRUCK FLEETS (Concluded)

Ryder Systems, Inc., Miami, Florida
Schneider Transport, Inc., Greenbay, Wisconsin
Stalcup Trucking, Inc., Coos Bay, Oregon
Standard Oil Company, Atlanta, Georgia
Standard Oil Company of California, San Francisco, California
Standard Trucking Company, Inc., Charlotte, North Carolina
Sterling Transit Company, Inc., Montebello, California
Terminal Transport, Atlanta, Georgia
Texaco, Inc., Wilmington, California
Tom's Food's Ltd., Columbus, Georgia
United Parcel Service, Greenwich, Connecticut
Vaught Brothers, Lexington, Kentucky
Von's Grocery Company, El Monte, California
Vornado, Inc., Whittier, California
Wood Terminal, Louisville, Kentucky

INDUSTRY ASSOCIATIONS

American Trucking Associations, Inc., Washington, D. C.

Motor Vehicle Manufacturers Association of U. S., Inc., Detroit, Michigan

Western Highway Institute, San Francisco, California

OTHERS

Freightliner Corp., Portland, Oregon (Truck Manufacturer)

General Motors Corp., Research Laboratory, Detroit, Michigan

Maritime Administration, Washington, D. C.

National Research Council, Ottawa, Canada

Sea-Land Service, Inc., Long Beach, California

University of Maryland, College Park, Maryland

THIS PAGE
WAS THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

REFERENCES

1. "Reducing Truck Aerodynamic Drag," Automotive Engineering, Vol. 83, No. 8, August 1975
2. Holmes, H.R., "Practical Economic Aspects of Tractor/Trailer Aerodynamics," SAE Paper No. 760103, Detroit Meeting, February 23-27, 1976
3. Hoerner, S.F., "Fluid Dynamic Drag," 2nd Edition, Published by author, 1965
4. Marks, C.H., et al, "An Evaluation of the Aerodynamic Drag Reductions Produced by Various Cab Roof Fairings and a Cap Seal on Tractor-Trailer Trucks," SAE Paper No. 760105, Detroit Meeting, February 23-27, 1976
5. Tatom, J.W., "A Tractor Mounted, Air Deployable, Aerodynamic Drag Reduction System," Proceedings of the Conference/Workshop on Reduction of the Aerodynamic Drag of Trucks, Pasadena, California, October 10-11, 1974
6. Buckley, F.T., Jr., "Comparisons of Effectiveness of Commercially Available Devices for the Reduction of Aerodynamic Drag on Tractor Trailers," SAE Paper No. 750704, Seattle Meeting, August 11-14, 1975
7. Private Communication with Kevin Cooper, National Research Council, Ottawa, Canada, May 12, 1976
8. Bauer, P.T. and R.A. Servais, "An Experimental and Analytical Investigation of Truck Aerodynamics," Proceedings of the Conference/Workshop on Reduction of the Aerodynamic Drag of Trucks, Pasadena, California, October 10-11, 1974
9. Walston, W.H., Jr., et al, "Test Procedures for the Evaluation of Aerodynamic Drag on Full Scale Vehicles in Windy Environments," SAE Paper No. 760106, Detroit Meeting, February 23-27, 1976
10. Montoya, L.C. and L.L. Steers, "Aerodynamic Drag Reduction Tests on a Full Scale Tractor-Trailer Combination with Several Add-on Devices," Proceedings of the Conference/Workshop on Reduction of the Aerodynamic Drag of Trucks, Pasadena, California, October 10-11, 1974
11. "SVT-137 System Performance Test," Bendix Automotive Development Center, May 3, 1974

REFERENCES (Continued)

12. Private Communication with Drs. C.H. Marks and F.T. Buckley, Jr., University of Maryland, March 1976
13. "Maryland System to Cut Wind Drag," Washington Star, February 28, 1976
14. Wentz, W.H., Jr., "Development of a Drag-reducing Device for Tractor-Trailer Rigs: From Wind Tunnel to Operational Vehicle," Proceedings of the Conference/Workshop on Reduction of the Aerodynamic Drag of Trucks, Pasadena, California, October 10-11, 1974
15. Lissaman, P.P.S. and J.H. Lambie, "Reduction of Aerodynamic Drag of Large Highway Trucks," Proceedings of the Conference/Workshop on Reduction of the Aerodynamic Drag of Trucks, Pasadena, California, October 10-11, 1974
16. Private Communication with Alain Clenet, Clenet Design, Santa Barbara, California, March 1976
17. "Transport Statistics in the United States, Year Ended Dec. 31, 1972," Interstate Commerce Commission
18. "1975 Motor Truck Facts," Motor Vehicle Manufacturers Association
19. "Study of Potential for Motor Vehicle Fuel Economy Improvement Truck and Bus Panel Report," Report No. 7, Prepared by US DOT and US EPA, January 10, 1975
20. Hurter, D.A. and W.D. Lee, "A Study of Technological Improvements to Optimize Truck Configurations for Fuel Economy," Arthur D. Little, Inc., Report No. DOT-TSC-OST-75-46, September 1975
21. "1972 Census of Transportation, Truck Inventory and Use Survey," Report TC72-T52, U.S. Department of Commerce, October 1973
22. Bauer, P.T. and R.A. Servais, "Criteria for Choosing and Evaluating Aerodynamic Devices for Reducing Fuel Consumption of Trucks," SAE Paper No. 750701, Seattle Meeting, August 11-14, 1975
23. Personal Communication with Stanley S. Roe, Motor Vehicle Manufacturers Association of U.S., Inc., Detroit, February 1976
24. Memorandum to Allan C. Flott, Director of Department of Economics of American Trucking Associations, Inc., from Richard A. Staley, Assistant to the Director, January 23, 1976

REFERENCES (Concluded)

25. "An Evaluation of Truck Aerodynamic Drag Reduction Devices and Tests," Innocept, Inc., June 1975
26. Letter to Author from N. C. Wiley, Jr., President, Rudkin-Wiley Corporation, March 8, 1976
27. Letter to Author from N. C. Wiley, Jr., President, Rudkin-Wiley Corporation, March 2, 1976
28. "1972 Highway Statistics," U. S. Department of Transportation