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EPA 550/9-82-331A

Program Summary: Truck Noise Reduction

Environmental Protection Agency

December 1981

Demonstration Truck Program

1

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This is one in a series of seven technical reports and a program summary prepared for the Environmental Protection Agency's Demonstration Truck Program. The reports in this series are listed below.

Report Number	Title	Date
1.	Program Summary: Truck Noise Reduction (BBN Report No. 4839).	December 1981
2.	Noise Reduction Technology and Costs for a Ford CLT 9000 Heavy-Duty Diesel Truck (BBN Report No. 4379).	October 1981
3.	Noise Reduction Technology and Costs for a General Motors Brigadier Heavy-Duty Diesel Truck (BBN Report No. 4507).	October 1981
4.	Noise Reduction Technology and Costs for an International Harvester F-4370 Heavy-Duty Diesel Truck (BBN Report No. 4667).	October 1981
5.	Noise Reduction Technology and Costs for a Mack R686 Heavy-Duty Diesel Truck (BBN Report No. 4795).	December 1981
6.	Field Test of a Quieted Ford CLT 9000 Heavy-Duty Diesel Truck (BBN Report No. 4700).	October 1981
7.	Field Test of a Quieted General Motors Brigadier Heavy-Duty Diesel Truck (BBN Report No. 4796).	December 1981
8.	Field Test of a Quieted International Harvester F-4370 Heavy-Duty Diesel Truck (BBN Report No. 4797).	December 1981

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16. ABSTRACT
This report presents a comprehensive overview of an EPA-sponsored program to demonstrate the technology and costs of reducing the noise of four heavy-duty diesel trucks to 72 dBA. The program comprised engineering development and service evaluation phases. Noise control treatments were developed and installed on each truck to reduce its noise to the target level. The treatments included partial engine and transmission enclosures, exhaust silencing systems, and two-stage engine mounts for 2 of the 4 trucks. Three trucks entered fleet service where they accumulated 230,000 miles. The treatments proved to be durable and effective and did not have an adverse impact on the operation of any vehicle. Maintenance labor time increased by 1.4% because of the need to remove enclosure panels while performing some maintenance procedures.

17. KEY WORDS AND DOCUMENT ANALYSIS

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DEMONSTRATION TRUCK PROGRAM SUMMARY

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PREFACE

This report presents a comprehensive overview of the Environmental Protection Agency's Demonstration Truck Program. The program, which began in early 1979 and concluded in late 1981, was sponsored by the Agency's Office of Noise Abatement and Control, and was conducted by Bolt Beranek and Newman Inc. (BBN). Its objective was to demonstrate noise reduction technology for four heavy-duty diesel trucks.

Four trucks, each with a different engine, were studied in the course of the program. The original program plan called for each vehicle to receive noise reduction treatments and then to enter fleet service for a year of field testing. Each of the four vehicles successfully completed the noise reduction part of the program. The duration of the program was shortened from the original plan, preventing all four vehicles from completing an entire year of field testing.

Seven final technical reports and this program summary were prepared by BBN for the Demonstration Truck Program. Their titles are listed on the inside cover of this report. Each technical report is intended to be internally complete; therefore some redundancy occurs between the technology and cost reports and the field test reports. For example, a reader who has read the technology and cost report for a particular truck will find that he can pass over Sec. 2 of the companion field test report for that vehicle. Information presented in overview fashion in this program summary is discussed in detail in the seven technical reports.

The authors are grateful to the many governmental and industrial organizations that have contributed to the Demonstration Truck Program. These organizations include the vehicle and engine manufacturers, the treatment suppliers and fabricators, and the participating operators. Their contributions are explicitly acknowledged in the respective technology and cost reports and field test reports. In addition, the authors acknowledge the contributions of dozens of BBN personnel through whose efforts the objectives of this program were realized.

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1. INTRODUCTION

During the course of its work on noise control, the Environmental Protection Agency (EPA) identified a number of uncertainties in the technology available for and the costs of substantially reducing the noise of heavy-duty trucks. It was not clear how technology might be employed to reduce the noise of a variety of diesel trucks, what attendant equipment and operating costs might be incurred, or how durable treatments might be during actual service operation. Accordingly, EPA sponsored a program conducted by Bolt Beranek and Newman Inc. (BBN) to demonstrate the technology and cost of reducing the noise of four heavy-duty diesel trucks. This program comprised engineering development and service evaluation phases.

The primary objective of the program was to reduce truck noise levels to 72 dBA when measured at 50 ft during the full throttle passby tests specified by EPA [1]. This level is lower than that of any trucks in current production which are designed to meet an 83 dBA goal. Corollary objectives were to design treatments that would have minimal impact on vehicle fuel consumption through increased weight and exhaust backpressure or on serviceability through restricted access to various components requiring maintenance.

The four trucks were selected for their range of vehicle and engine make and type as summarized in Table 1. In 1978, 72.5% of heavy-duty diesel trucks and over 99% of engines for heavy diesel trucks were produced by the manufacturers identified in Table 1.

Figures 1 through 4 show the vehicles in their initial or baseline condition. All were equipped with single vertical exhaust system and tandem rear axles. Beyond that, each had unique features to be addressed. The Ford had an air-suspended cab, which allowed ±2 in. of vertical movement with respect to the

TABLE 1. SUMMARY OF VEHICLE AND ENGINE MAKE AND TYPE.

Vehicle		Engine		
Make/Model	Type	Make/Model	Type	Horse-power
Ford/CLT 9000	COE*	Caterpillar/ 3406 PCTA	I-6	340
GMC/Brigadier	Short conventional	Detroit Diesel/ 6V92TT	V-6	270
Mack/R686	Regular conventional	Mack/ENDT 676	I-6	285
IH/F-4370	Long conventional	Cummins/NTC 350	I-6	350

*Cab-over-engine

chassis. This feature required careful design of the interface between cab-mounted and chassis-mounted enclosure components. The GMC had a very compact engine compartment that we believed would restrict cooling air flow once an engine/transmission enclosure was built. For this reason, we ordered the vehicle with a larger-than-standard radiator. The Mack was planned to operate in a fleet of tank trucks and was equipped with an exhaust-mounted turbo-unloader and a power take-off (PTO) driven pump. The unloader would impact exhaust system design, while the PTO required special enclosure considerations. The IH, with the most powerful engine, was felt by some to be representative of high-horsepower conventional trucks of the future.

In the remainder of this report we will summarize the major developments of the program. Section 2 describes the technology that was developed to quiet the trucks from their initial levels, ranging from 77.1 to 81.7 dBA, to their final levels of 71.6 to 73.2 dBA. In Sec. 3 we show how price increases of $1174 to $1304

FIG. 1. BASELINE TRUCK CONFIGURATION OF FORD CLT 9000.

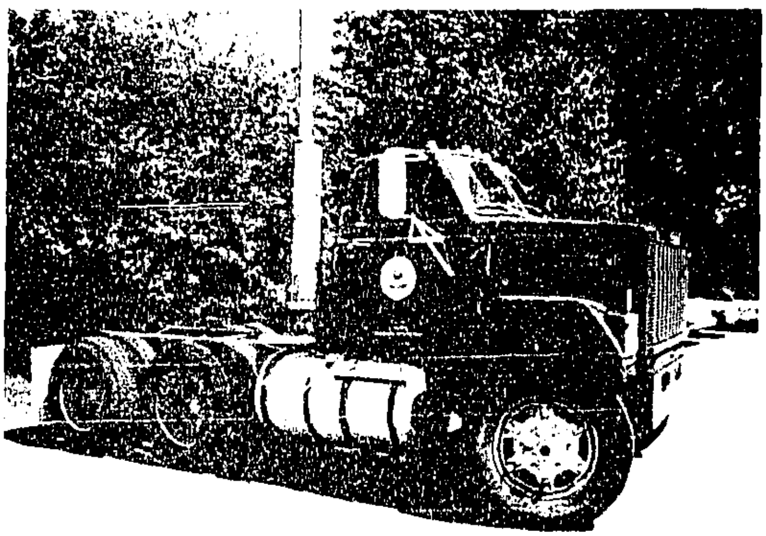

FIG. 2. BASELINE TRUCK CONFIGURATION OF GMC BRIGADIER.

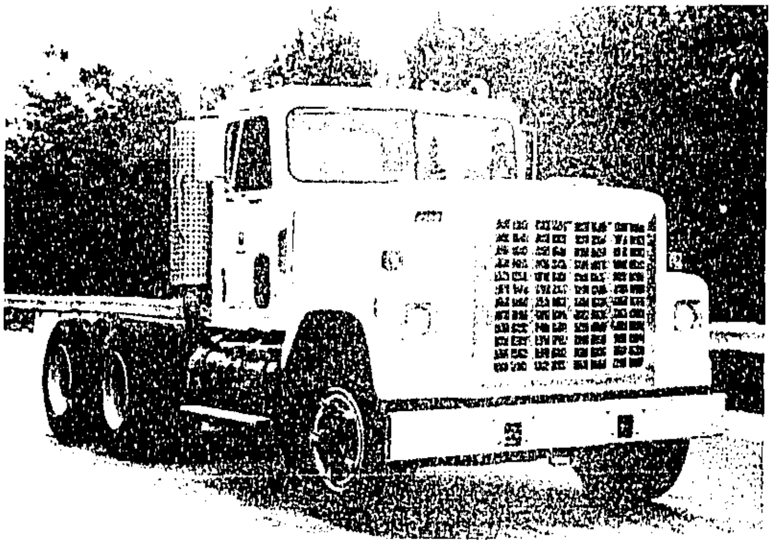

FIG. 3. BASELINE TRUCK CONFIGURATION OF INTERNATIONAL HARVESTER F-4370.

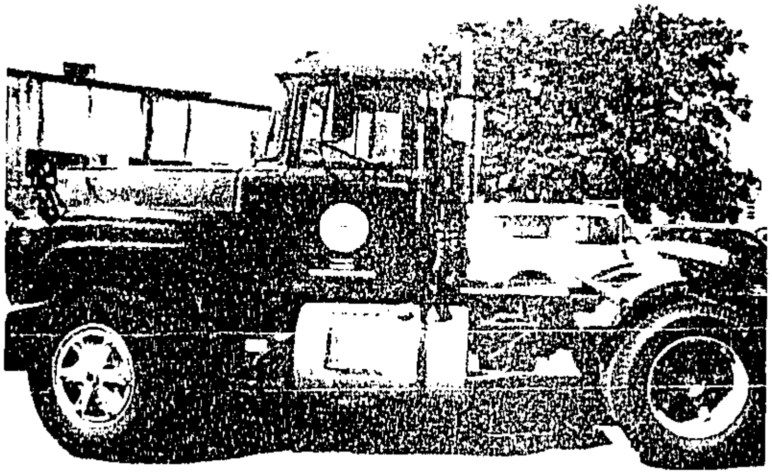

FIG. 4. BASELINE TRUCK CONFIGURATION OF MACK R686.

per truck were estimated. Section 4 deals with the major performance factors of cooling, serviceability, and fuel consumption. The major results of the operational evaluation are discussed in Sec. 5, and conclusions and recommendations for this program are presented in Sec. 6.

2. TREATMENT DEVELOPMENT

The processes used to develop noise treatments were identical for each truck, though technical details varied considerably. Initially, trucks were field-tested by BBN; intake and exhaust levels were measured under laboratory conditions by the Donaldson Co., as part of a subcontract to BBN. Figure 5 shows the Ford CLT 9000 accelerating past a microphone that was connected to a remote sound level meter and tape recorder. The space used for the test is flat, hard, and clear of obstacles, in accordance with EPA [1] and SAE [2] specifications. Figure 6 illustrates the laboratory configuration for intake noise measurements; the same laboratory was used for exhaust noise measurements.

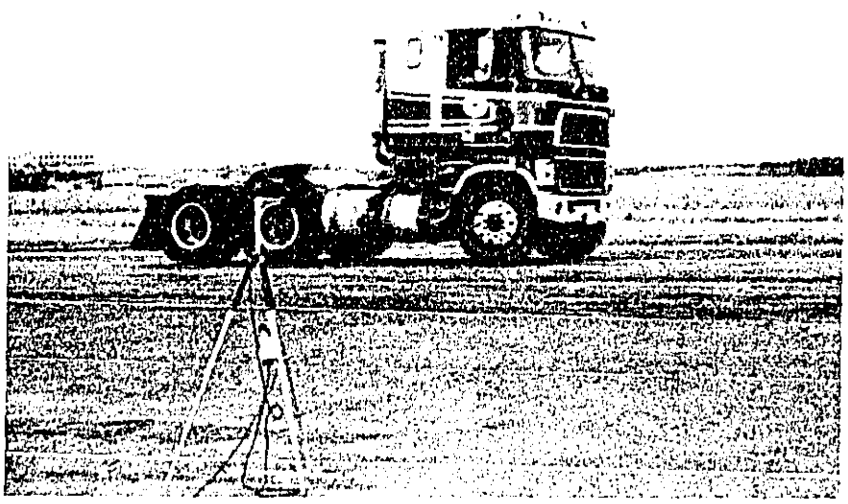

FIG. 5. FORD CLT 9000 DURING NOISE MEASUREMENT TEST.

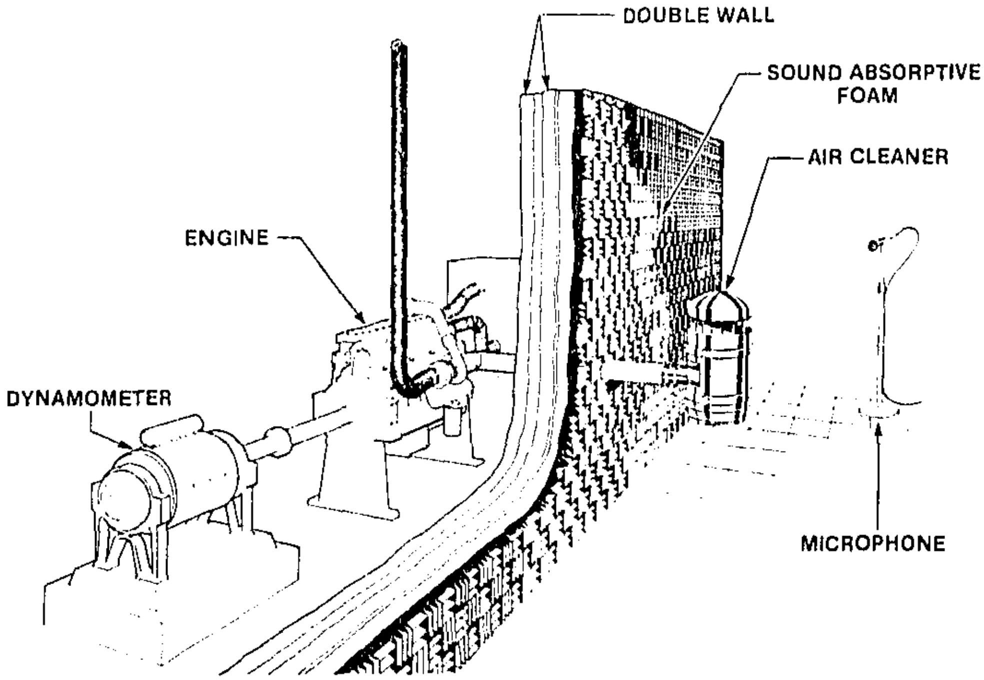

FIG. 6. EXPERIMENTAL CONFIGURATION FOR INTAKE NOISE MEASUREMENT.

The data acquired from field and laboratory tests were combined to determine overall levels and to assess the contributions from major components, namely the exhaust, engine and transmission, intake, tires, and aerodynamic flow. On the basis of these data and some judgment as to the results that could be achieved through the application of various types of treatment, goals were set and preliminary treatments designed. Exhaust systems were developed primarily in the laboratory with available components, while engine and transmission enclosures were first custom-developed on the truck with easily fabricated fiber board panels and fiberglass absorption. Figure 7 shows the portion of the mockup enclosure extending beyond the back of the cab on the Mack truck. Once the truck met its noise goals, durable aluminum

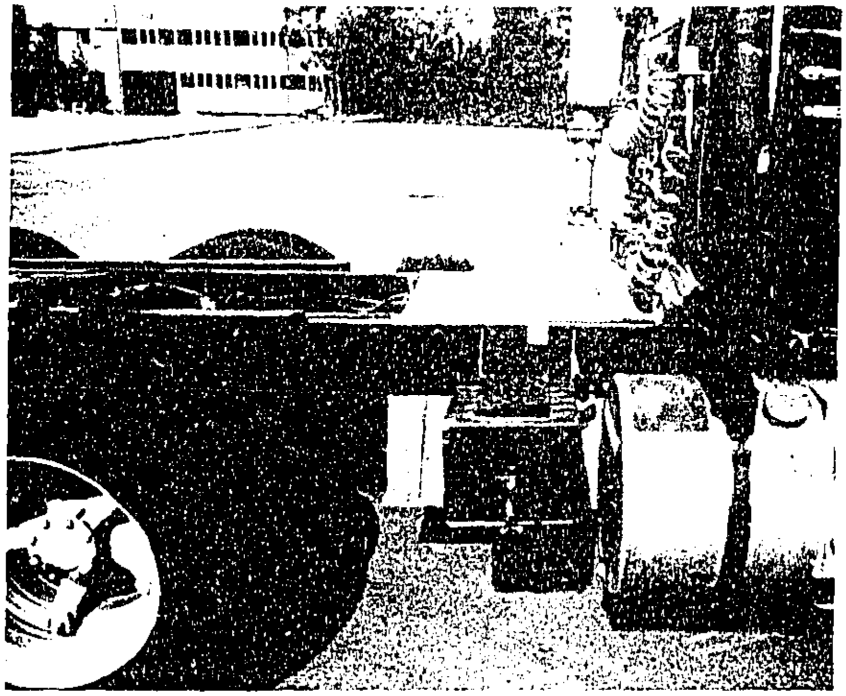

FIG. 7. MOCKUP ENCLOSURE ON MACK R686.

enclosures were built. These were then refined, and improved engine mounts were added to two of the vehicles.

2.1 Baseline Levels

The initial, or baseline, noise levels for the four trucks are presented in Table 2. Overall, the Ford was the quietest; the other three vehicles nearly the same level, from 81.1 to 81.7 dBA. Contributing to the low overall level for the Ford were low initial exhaust and engine and transmission levels. The Brigadier had the highest exhaust level but the second lowest engine and transmission level. All of the component source

TABLE 2. BASELINE LEVELS

Vehicle	Exhaust	Engine and Transmission	Intake	Other (Coastby)	Total
Ford CLT 9000	69	76.2	60	60	77.1
GMC Brigadier	79.8	77.1	51.5	62.5	81.7
Mack R686	71.7	81.1	52	63.5	81.6
IH F-4370	74	80.1	47	60	81.1

levels were comparable for the Mack and IH. The intake and coastby levels were sufficiently low for all vehicles that no noise reduction efforts were undertaken to reduce these sources further.

2.2 Noise Control Treatments

Figures 8 through 11 illustrate the treatments that were developed for each truck. The underlying designs for each are similar, consisting of an exhaust silencing system, an enclosure for the engine and transmission, and two-stage mounts for two of the vehicles.

Exhaust

The exhaust systems for the Ford, GMC, and IH trucks are fundamentally identical. For each, a 5-in.-diameter exhaust line, consisting of aluminized steel tubing and stainless steel flex hose, leads from the turbocharger to the Splitter Tee Can, seen in Fig. 9. The Tee Can provides some muffling and splits the flow into dual 4-in. exhaust lines. Each line connects to a nominal 10-in.-diameter double-shell cylindrical muffler and a 4-in. stack silencer. The Super Stack Silencer, as the manufacturer calls it, has a 3-in.-diameter perforated liner made of aluminized steel, fiberglass packing, and a pressure recovery cone at the outlet. Note that it was necessary to add a stock exhaust stack mast or support bracket to the left side of each vehicle to accommodate the dual system. For the conventional trucks, each 10-in.

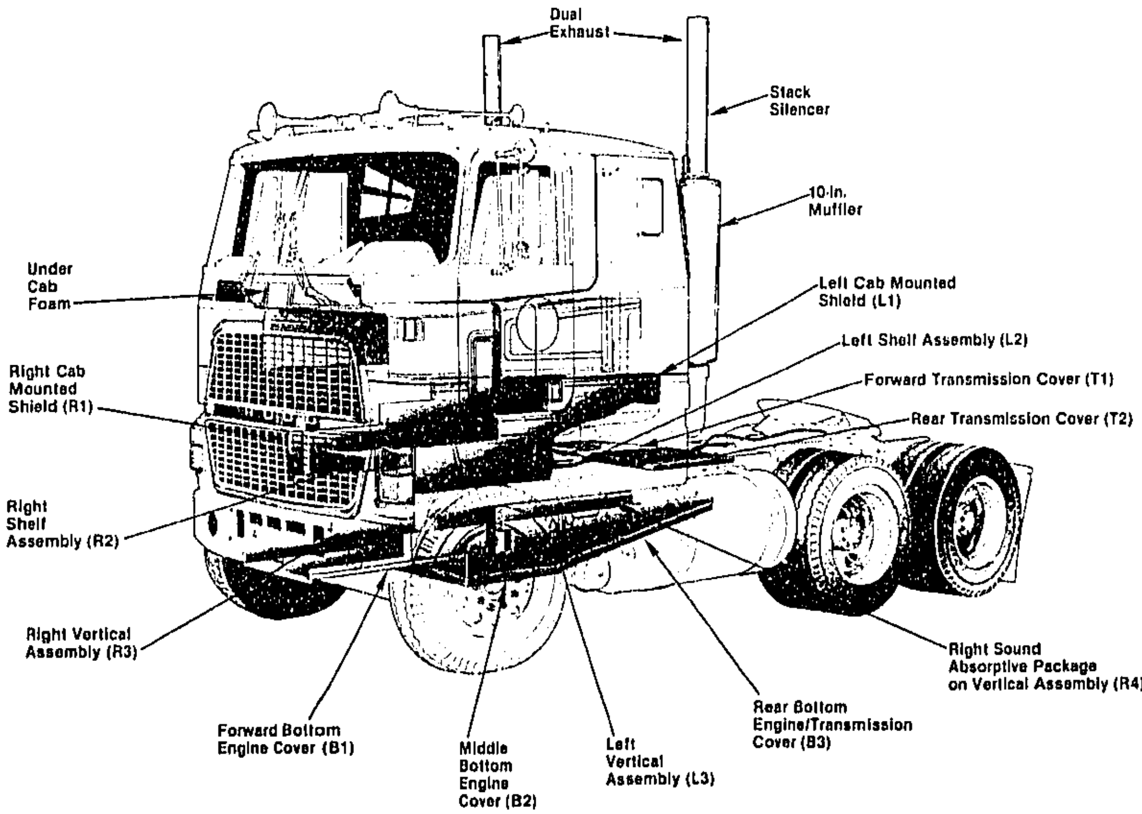

FIG. 8. THE FORD CLT 9000 WITH NOISE CONTROL TREATMENTS.

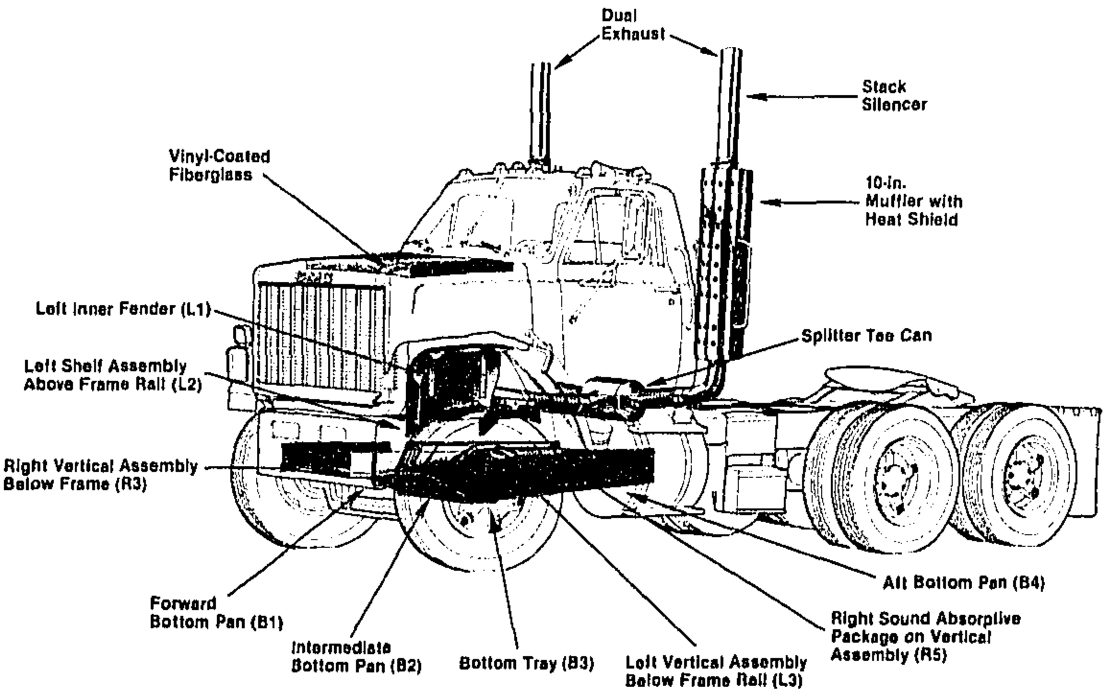

FIG. 9. THE GMC BRIGADIER WITH NOISE CONTROL TREATMENTS.

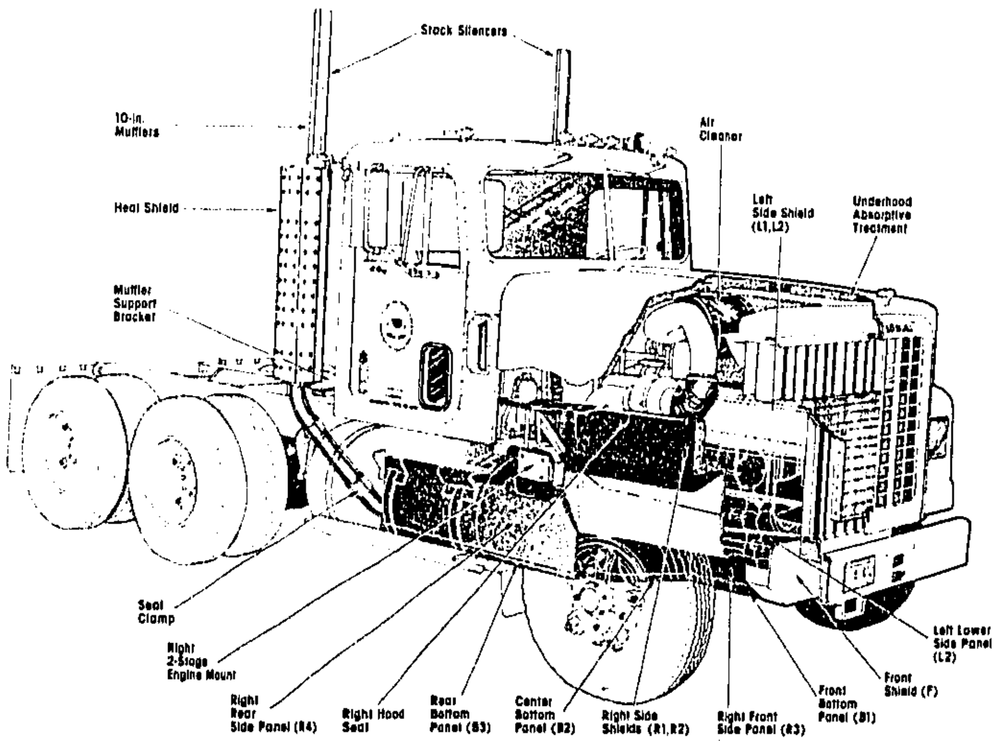

FIG. 10. THE INTERNATIONAL HARVESTER F-4370 WITH NOISE CONTROL TREATMENTS.

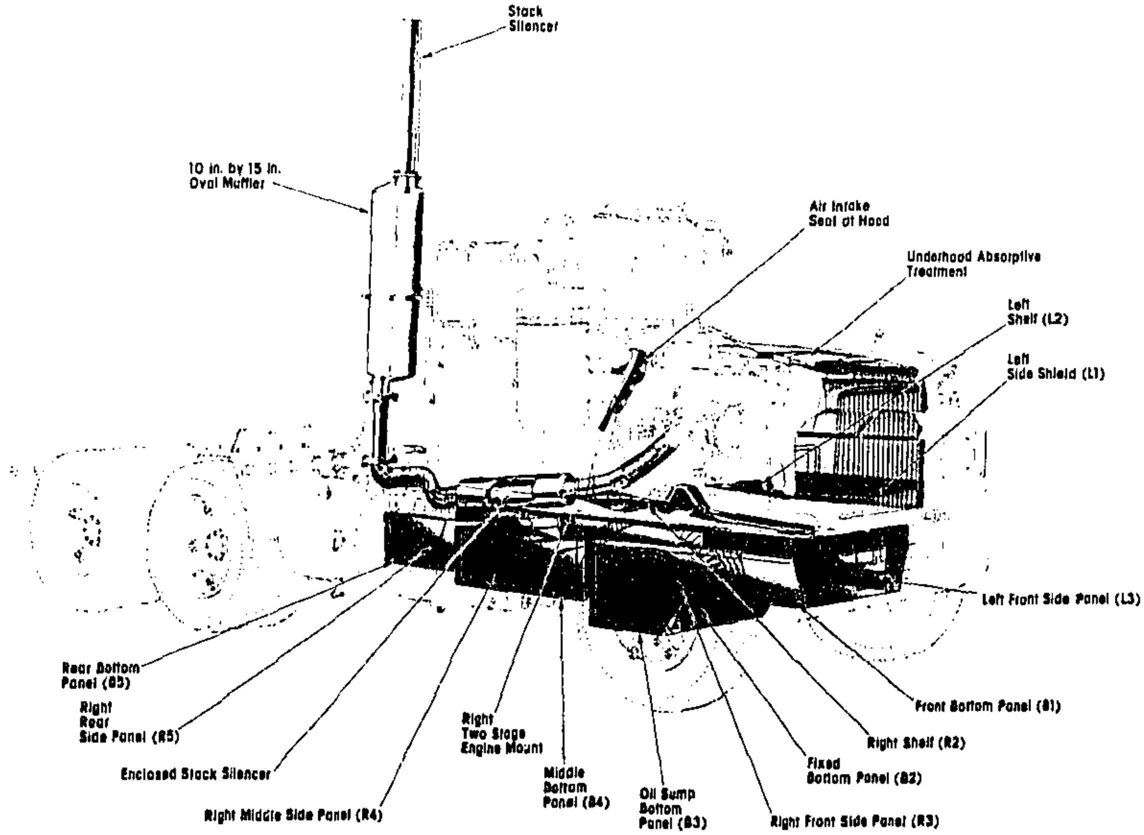

FIG. 11. THE MACK R686 WITH NOISE CONTROL TREATMENTS.

muffler is covered by a perforated heat shield to protect people entering or leaving either side of the vehicle. Shields were not required on the Ford COE, which has a sleeper cab and a safe distance between the doors and mufflers.

It was not judged practical to equip the Mack truck with a dual exhaust system. This vehicle must be capable of having a turbo-unloader installed in place of the short section of pipe seen below the oval muffler in Fig. 11. The unloader, if it were installed at this location in a dual system, would force most of the exhaust flow through the other branch and would not function properly. Accordingly, we decided to develop a single-line exhaust system for this vehicle.

The Mack exhaust system comprises three major silencing components: an enclosed stack silencer, a 10- x 15-in. oval muffler, and a 5-in. stack silencer. The enclosed stack silencer was installed primarily to attenuate the intense acoustic field in the line leading from the turbocharger. This field was causing unacceptably high levels of pipe vibration and radiation. A subordinate benefit was the reduction of exhaust outlet noise beyond that provided by the oval muffler and stack silencer. The oval muffler, developed for this vehicle, had to be larger than one of the cylindrical mufflers used on the other trucks to provide the volume needed to reduce sound occurring at the engine firing frequency. Figure 12 shows the internal structure of the muffler. A 5-in. stack silencer was used at the outlet end of the exhaust system to attenuate high-frequency noise. The 5-in. silencer, rather than a 4-in. one, was selected to maintain a lower exit flow velocity and concomitant level of flow noise than would accompany a single 4-in. silencer. Moreover, the backpressure associated with the 5-in. silencer is lower.

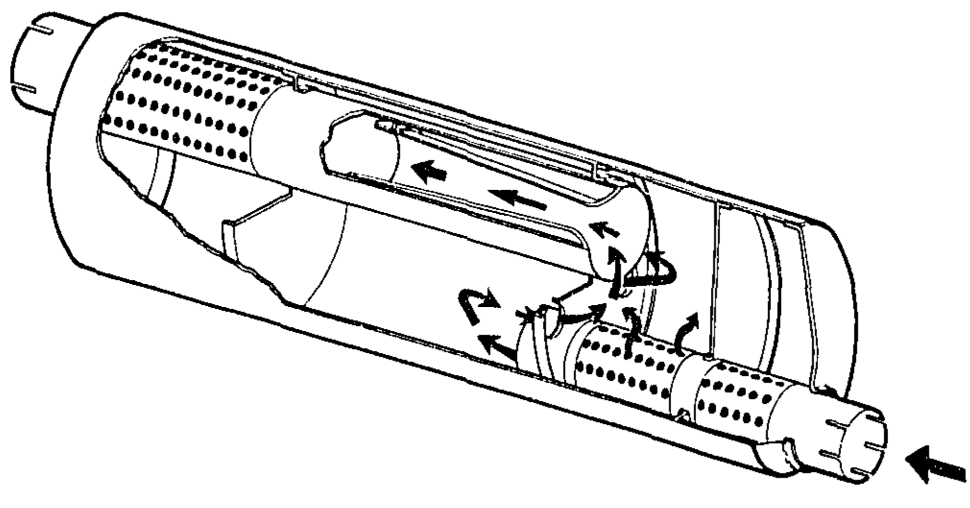

FIG. 12. CUTAWAY VIEW OF 10- BY 15-IN. OVAL MUFFLER.

Enclosures

The engine and transmission enclosure components illustrated in Figs. 8 through 11 also reveal a common design philosophy. These components, together with such existing truck components as cabs, hoods, and frame rails, form a tunnel-like enclosure for each vehicle that extends from the radiator at the front to an opening behind the cab. Sound-absorptive material lines the enclosure at convenient locations. This enclosure shields the roadside microphone from sound generated by major power train components, prevents sound buildup through multiple interior reflections, and provides a path for cooling air to flow from the radiator over the engine and transmission and out the rear of the vehicle.

For purposes of maintenance, components were designed to interfere as little as possible with access to the power train. On the Mack, IH, and Ford vehicles, underhood absorption and upper side panels tip forward with the hood or cab. The inner fenders on the GMC truck are modifications of originals installed by the manufacturer and are removed after disengaging quick-release fasteners. Below the frame rails, the vertical members of the bellypan are intended to remain in place. However, the bottom pans or panels are designed to be removed quickly by means of side latches or quarter-turn fasteners. These may be seen in Figs. 13 and 14.

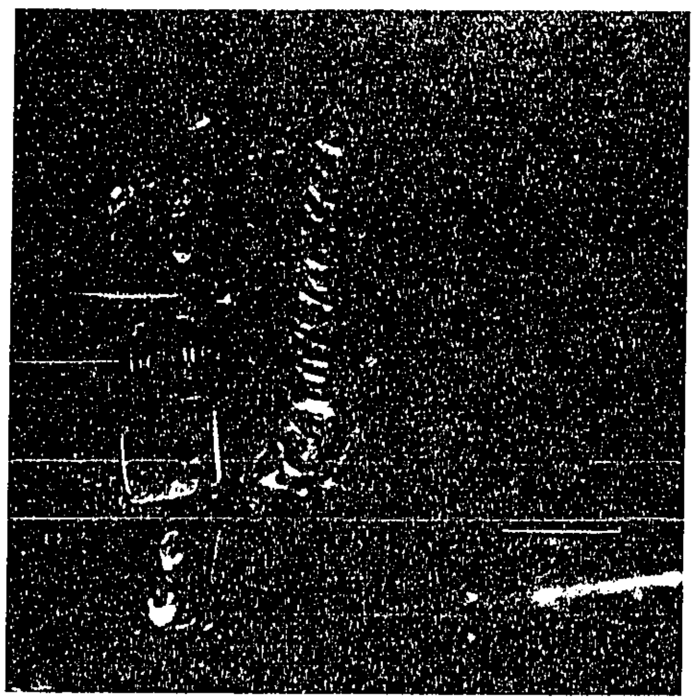

FIG. 13. SIDE-LATCHES FOR BOTTOM ENCLOSURE PANEL.

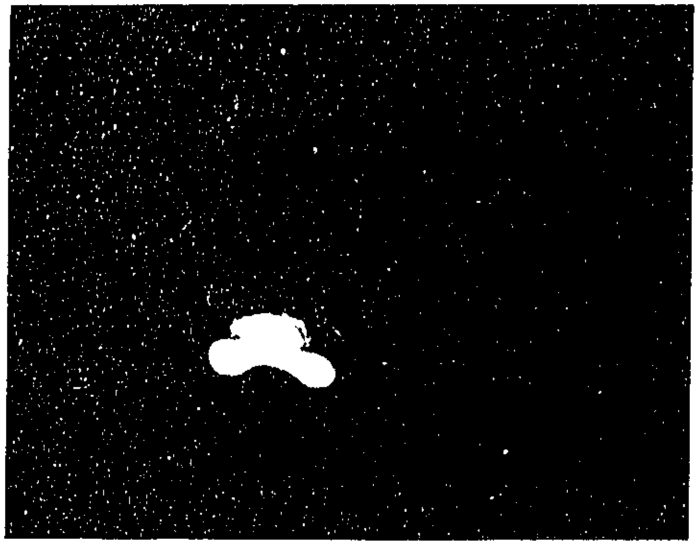

FIG. 14. QUARTER-TURN FASTENER FOR ENCLOSURE PANELS.

Several types of sound-absorptive materials were incorporated by the manufacturers in the baseline vehicles. As illustrated in Fig. 15, the underside of the Ford cab was covered with one-in.-thick panels of open cell foam faced with an aluminized polyester film. Figure 16 shows that the firewall of the IH truck incorporated one-in.-thick fiberglass coated with a binder. Similarly, the GMC Brigadier used one-in.-thick fiberglass with a sprayed-on vinyl coating under the hood.

BBN left these absorptive treatments intact and added materials of various types, depending on available space and the anticipated operating environment. The most conservative type, illustrated in Fig. 17, is designed to resist mechanical damage and contamination by oil or water, and is installed on vertical surfaces adjacent to the engine and transmission. In constructing the treatment, a 1.5-in.-thick fiberglass panel is covered with a plastic netting with the same planform and then wrapped

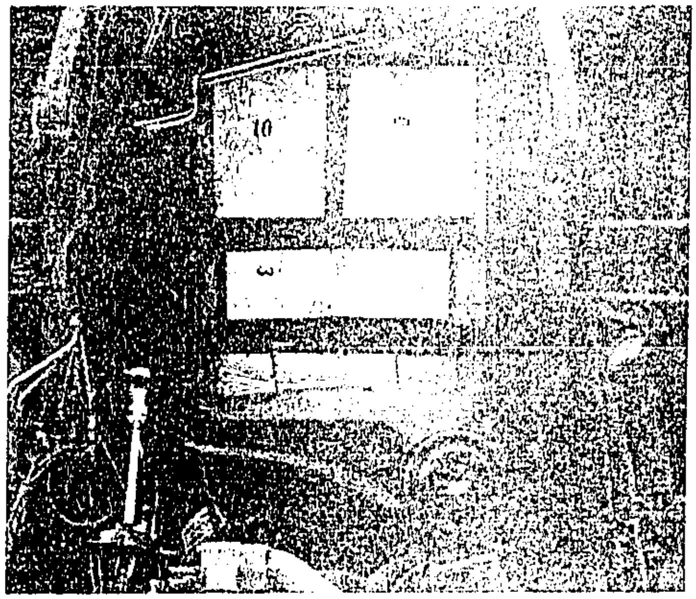

FIG. 15. UNDERCAB NOISE TREATMENT ON FORD CLT 9000.

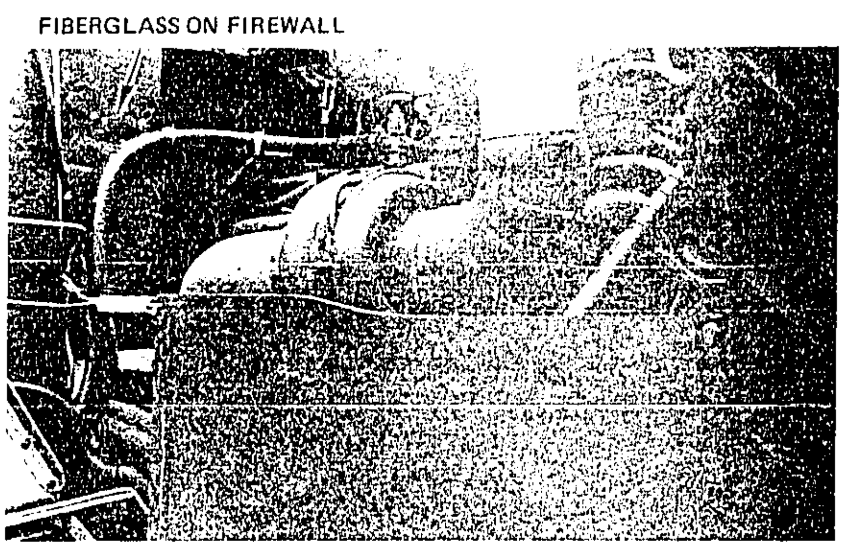

FIG. 16. FIREWALL NOISE TREATMENT ON IH F-4370.

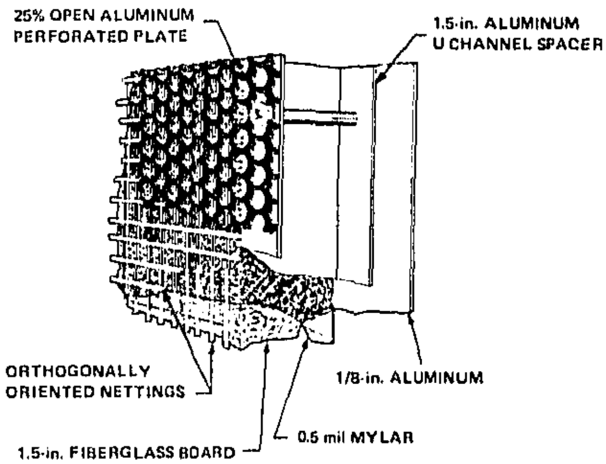

FIG. 17. DRAWING OF MYLAR-WRAPPED SOUND ABSORPTIVE TREATMENT.

with 0.5 mil Mylar. Another piece of netting is placed over the first, and then the assembly is covered with perforated aluminum on the side facing the sound source and aluminum sheet on the side away from the source. The perforated aluminum provides mechanical protection while transmitting incident sound waves, and the plastic mesh allows the very light Mylar to oscillate in response to the waves, transmitting them into the fiberglass where they are partially absorbed.

Less complex absorptive treatments were used on areas that are somewhat less likely to be damaged or contaminated. A 2-in. sheet of urethane foam faced with an aluminized polyester film was cemented to the underside of the cab of the Brigadier. Two-in.-thick fiberglass panels were fastened directly to the underside of the hood of the IH truck.

Engine Mounts

Both the Mack and IH trucks showed evidence of transmitting sufficient vibrational energy through the existing rubber engine mounts to cause the chassis to radiate significant levels of noise. Accordingly, two-stage rear engine mounts were developed and installed to attenuate this path of structureborne sound. Figure 18 shows the mount assembly for the Mack truck. (Similar assemblies were built for the IH truck.) The top bracket is bolted to the transmission and the bottom bracket to the frame rail. The blocking mass in the center is isolated from each bracket. At frequencies above the resonance of this mass on the upper and lower isolators, the mass tends to remain still and block the transmission of vibration to the frame rails.

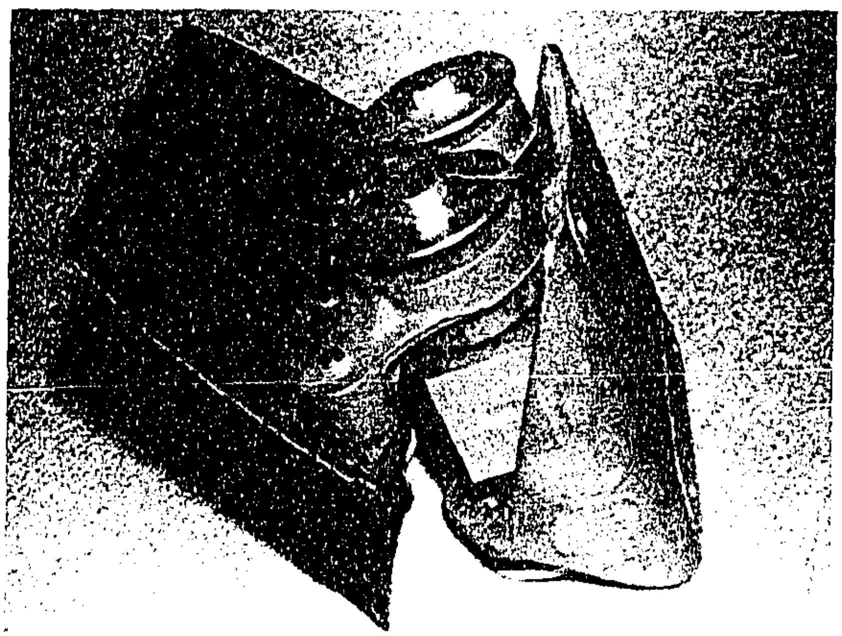

FIG. 18. TWO-STAGE ENGINE MOUNT OF IH F-4370.

2.3 Final Noise Levels

Table 3 summarizes the initial and final noise levels for the treated sources and the total vehicle. The exhaust includes outlet and shell noise for the Mack, and the engine and transmission include airborne and structureborne components for all vehicles. Intake and coastby levels were the same before and after treatment. The table clearly shows that the smallest amount of total vehicle noise reduction was achieved for the Ford CLT 9000, which began with the quietest exhaust and engine/transmission levels. The greatest exhaust noise reduction (almost 20 dBA) was achieved for the Brigadier. The Mack and IH trucks required the greatest amount of engine and transmission noise reduction. (This became evident during the development process as greater effort was expended to seal all openings in the sides of these enclosures.)

TABLE 3. INITIAL AND FINAL LEVELS OF TREATED SOURCES AND TOTAL VEHICLE - dBA.

Noise Source and Level		Vehicle: Ford CLT 9000	GMC Brigadier	Mack R686	IH F-4370
Exhaust	Initial	69.0	79.8	71.7	74.0
	Final	59.5	60.0	58.1[1]	59.5
	Noise Reduction	9.5	19.8	13.6	14.5
Engine and Transmission[2]	Initial	76.2	77.1	81.1	80.1
	Final	71.5	71.1	72.5	72.3
	Noise Reduction	4.7	6.0	8.6	7.8
Total Vehicle	Initial	77.1	81.7	81.6	81.1
	Final	72.3	71.6	73.2	72.7
	Noise Reduction	4.8	10.1	8.4	8.4

[1] Includes shell noise.

[2] Includes both airborne and structureborne noise.

3. COST ESTIMATES

This section presents estimates of the costs of the noise control treatments described in the previous section. The noise control treatments increased the price of the trucks an average of $1270 - a 3% increase over the $42,830 average purchase price of the 4 trucks. Several different techniques were used to estimate these increases; each technique is described below. The description of techniques is followed by a discussion of the estimated cost of each treatment for each truck and a comparison of these costs.

Table 4 presents the distinctions between costs and price used throughout the program. The convention is that the seller sells at a price, and a buyer buys at a cost. There are three sellers: the manufacturer of noise control products (e.g., a muffler manufacturer), the truck manufacturer, and the truck dealer. The three buyers are the truck manufacturer, the truck dealer, and the truck operator. A markup is applied in moving from one level to another. Hence,

manufacturer's price x dealer markup = dealer's price .

TABLE 4. SUMMARY OF COSTS AND PRICES.

Transaction	Cost	Price
Sale of Component Supplier's Parts to Truck Manufacture	Manufacturer Cost	Supplier Price
Sale of Truck by Manufacturer to Dealer	Dealer Cost	Manufacturer Price
Sale of Truck by Dealer to Operator/Customer	Operator Cost	Dealer Price

3.1 Cost Estimation Techniques

A specific cost estimation technique was developed for each of the three noise control treatments:

- engine/transmission enclosure
- exhaust system modifications
- 2-stage engine mounts.

All costs are estimated in 1979 dollars since that is the model year of each truck, and it facilitates comparison of the results for each truck.

Engine/Transmission Enclosure

The cost of the enclosures was based on the weight of each enclosure and a derived relationship between enclosure weight and enclosure price. The weight of each enclosure was determined from the weight of individual enclosure components and the material from which they were fabricated. The weight of the enclosures ranged from 165 to 244 lb, and aluminum was the predominant material.

A weight-cost relationship was derived from data presented in Fax and Kaye [3] and the EPA Background Document [4]. The data on weight and enclosure costs from these sources was thoroughly analyzed and updated to 1979 with the Producer Price Index for nonferrous metals. Figure 19 presents a plot of the eight data points and a least-squares regression equation derived from these data. The equation is

$$Y = 61.3 + 1.92\ X,$$

where Y = manufacturer's price
X = enclosure weight .

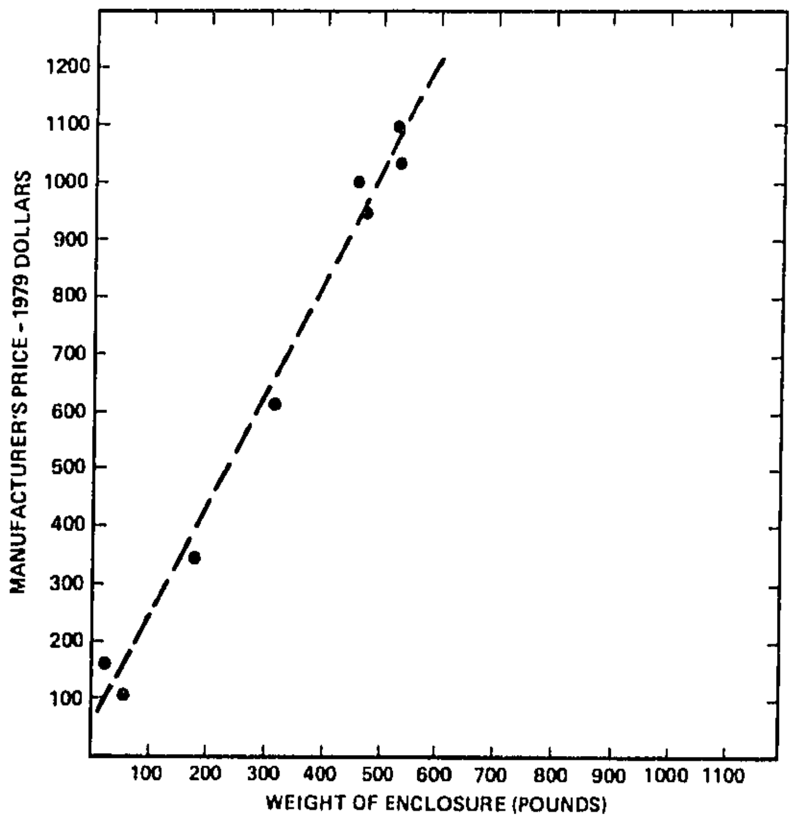

FIG. 19. RELATIONSHIP BETWEEN MANUFACTURER PRICE AND ENCLOSURE WEIGHT.

The estimated slope coefficient is statistically significant and indicates that a 1-lb increase in enclosure weight would increase cost by $1.92.

This relationship provided a basis for enclosure cost estimation, but excluded research, testing, tooling, and development costs. Analysis of available data, the estimated enclosure prices derived with the equation, and overall weight-cost relationships for heavy duty trucks indicated that manufacturer's price should be escalated by 19% to cover these costs excluded from the equation. Finally, a markup of 1.5 was applied to manufacturer's price to obtain dealer price based on Ref. 3.

In summary, the price of engine enclosures was estimated in the following process:

- Estimate enclosure price as a function of weight
- Escalate that estimate for research, testing, and tooling costs
- Apply a markup to manufacturer's price to obtain dealer price.

Exhaust System

BBN installed a dual exhaust system in place of a baseline single muffler exhaust system on three of the four trucks. These dual exhaust systems were the same in terms of the major components, but there was variation in costs because of different mounting and exhaust pipe requirements. A specially modified exhaust system was installed on the Mack truck.

All the exhaust system components, except for the mounting masts or brackets for the dual systems, were manufactured by one exhaust system supplier. This supplier provided confidential price information for "computational purposes" that was used to estimate the price at which this supplier sold exhaust system components to the individual truck manufacturer. In addition, the truck manufacturers publish the prices of the exhaust system options available for their trucks. BBN was able to obtain both dealer cost and dealer price for currently available exhaust system options. This information, i.e., supplier price of exhaust system components, and dealer cost and price of exhaust system options, was then used to estimate the markups that were applied at both the manufacturer and dealer levels. We estimate a 1.4 markup by the manufacturer and a 1.35 markup by the dealer. Therefore, $100 of components sold by a supplier of exhaust systems to a truck manufacturer will eventually become $189 for a purchaser of the truck on which those components are installed.

Once these markups had been determined, it was necessary only to identify the baseline exhaust system components removed from each truck and the new components installed by BBN. The cost of the components was available from the supplier's price list. The estimated incremental price of the modified exhaust system was then determined by the cost of the individual components removed from and installed on each truck, escalated by the markups that BBN estimated.

Two-Stage Engine Mounts

The rear engine mounts were modified on two of the trucks. In each case the original mount was modified to accept a steel blocking mass. The design of the two-stage mount was very similar to that described in Ref. 3, and we adopted the costing technique used in that analysis - i.e., a weight-cost relationship. When the analysis was updated, the data indicated a per-pound price of $1.75 at the manufacturer price level, including an allowance for research, tooling, and other such costs. Again we applied a 1.5 markup at the dealer level for a dealer price of $2.62 per lb. We then applied this per-pound price to the increased weight of the two-stage mounts to estimate their price increase.

3.2 Estimated Treatment Costs

The weights of the treatments installed on the trucks are presented in Table 5. The entries for enclosures and engine mounts are the data used to estimate the costs of these treatments using the techniques described above.

TABLE 5. SUMMARY OF TREATMENT WEIGHTS (LB).

Treatment	Ford	GMC	IH	Mack
Engine/Transmission Enclosure				
• Components added	241	165	180	244
• Components removed	-20	-8	-10	-
• Net increase	221	157	170	244
Exhaust System				
• Components added	248	262	221	189
• Components removed	-27	-95	-85	-77
• Net increase	176	167	163	112
Engine Mounts				
• Net increase	-	-	26	42
Cooling System				
• Components added	-	197	-	-
• Components removed	-	-181	-	-
• Net increase	-	16	-	-
Total Increase	397	340	359	398
Baseline Tractor Weight	18,220	16,100	14,048	15,780

The average weight increase was 367 lb, a 2.4% increase at the average 15,037 lb tare weight of these trucks. The Mack had the heaviest enclosure, reflecting its length, complex configuration, and requirements for extremely tight seals. The weight of the exhaust systems for the Ford and GMC trucks includes the weight of frame-mounted masts for the additional vertical muffler installed by BBN. While the Mack exhaust system was still a single vertical design, the 122-lb weight increase primarily indicates the size of the muffler installed by BBN.

The cost and price increases attributable to the treatments are summarized in Table 6. The average estimated price increase was $1270 or 3% of the $42,830 average purchase price. Three of the trucks are within $13 of one another, $1296 to $1309. The estimated price for the GMC reflects its relatively smaller and, hence, less expensive enclosure. The $83 estimate for cooling system modifications was supplied by GMC.

The entries in Table 6 are consistent and reasonable. On an overall basis, the per-pound costs of the treatments are slightly above the average per-pound cost of each of the trucks. This is generally what we expected. Perhaps the best validation of the BBN cost estimates is a comparison of the BBN estimate for the GMC truck with an estimate that GMC provided. GMC estimated the 1981 price increase for the treatments installed on the GMC truck to be $1500. When this 1981 estimate is adjusted to 1979 dollars, using the Producer Price Index for medium and heavy trucks, GMC's estimate becomes $1183, in comparison to BBN's $1174 estimate, a difference of 0.8%.

TABLE 6. SUMMARY OF ESTIMATED DEALER COST AND PRICE INCREASES.

Treatment	Ford	GMC	IH	Mack
Engine/Transmission Enclosure				
• Cost	587	435	460	630
• Price	880	653	691	946
Exhaust System				
• Cost	318	324	402	177
• Price	429	438	543	240
Engine Mounts				
• Cost	-	-	46	74
• Price	-	-	68	110
Cooling System				
• Cost	-	55	-	-
• Price	-	83	-	-
Total Increase				
• Cost	905	814	908	881
• Price	1,304	1,174	1,302	1,296
Truck Price - Baseline	48,000	42,099	40,464	40,757

4. PERFORMANCE FACTORS

The addition of noise treatment to the trucks can affect the vehicle's performance in several ways. Of primary concern were the impacts of the enclosure on cooling performance and of the entire treatment on fuel economy.

4.1 Cooling Performance

Each of the three trucks that entered operational evaluation was first tested in a facility designed to evaluate truck cooling performance. Each facility was equipped with a chassis dynamometer to control engine load and speed, a blower to supply air at a constant velocity and temperature, and instrumentation to measure variables of interest. Figure 20 shows the Ford CLT 9000 in a wind tunnel operated by the Modine Manufacturing Company and made available in collaboration with the Ford Motor Company. The Brigadier was tested by GMC in their own facility as illustrated in Fig. 21. The Cummins Engine Company tested the IH F-4370, as shown in Fig 22.

FIG. 20. FORD CLT 9000 IN WIND TUNNEL.

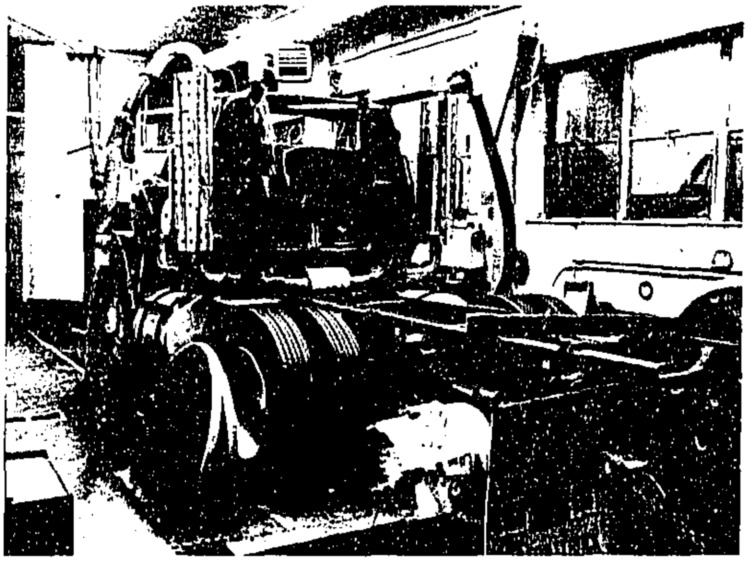

FIG. 21. GMC BRIGADIER IN WIND TUNNEL.

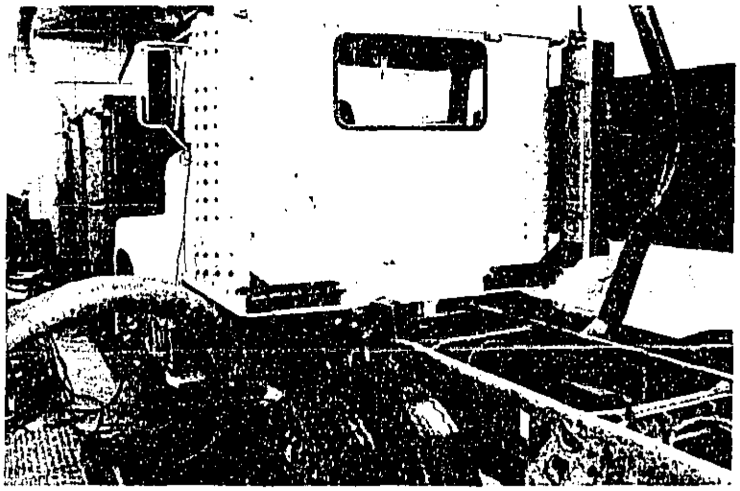

FIG. 22. INTERNATIONAL HARVESTER F-4370 IN WIND TUNNEL.

The salient test conditions and results are shown in Table 7. All of the trucks were tested at rated speed and power and at peak torque operating conditions. The Ford was tested only in its final configuration. The GMC and IH vehicles were first tested in their final configurations; then much of the noise treatment was removed and the vehicles were retested in their "baseline" configurations for purposes of comparison. For the GMC, the entire bellypan and side shelves were removed, but the inner fenders (which are standard equipment on these trucks) were left in place. For the IH, only the bottom pans were removed, since the remaining components were too well sealed in place to be removed properly within the time available for the test.

TABLE 7. COOLING TEST RESULTS.

	FORD CLT 9000		GMC BRIGADIER				IH F-4370			
	Rated Engine Speed and Power	Peak Engine Torque	Rated Engine Speed and Power		Peak Engine Torque		Rated Engine Speed and Power		Peak Engine Torque	
	Final*[1]	Final*[1]	Baseline	Final	Baseline	Final	Bottom Panels Removed	Final[2]	Bottom Panels Removed	Final[2]
Air Speed (mph)	14.0	14.4	15.0	15.0	15.0	15.0	15	15	15	15
Air Temperature (°F)	101.0	100.2	100.0	99.0	100.0	100.0	80	80	80	80
Engine Speed (rpm)	2000.0	1500.0	1950.0	1950.0	1500.0	1500.0	2090	2090	1500	1500
Vehicle Speed (mph)	56.9	42.2	58.2	58.3	44.7	44.7	39	39	36	36
Air to Boil @ 212°F (°F)										
Measured	113.1	104.7	126.0	122.0	118.0	111.0	115	112	104	98
Specified Minimum	112.0	-	112.0	112.0	-	-	122	122	112	112
Engine Oil (°F)										
Measured	224.2	224.1	229.0	233.0	234.0	239.0	222	224	229	234
Specified	235.0	235.0	(3)	(3)	(3)	(3)	250[4]	250[4]	250[4]	250[4]

NOTES:

[1]Not tested under baseline conditions.

[2]A small gap adjacent to the radiator was temporarily sealed to reduce recirculation.

[3]The vehicle manufacturer does not specify a value for this test but recommends the confinement of engine oil temperatures to the range between 200°F and 250°F during vehicle operation.

[4]Specified by the engine manufacturer as acceptable for short periods of time.

Table 7 illustrates that the vehicles were within specified limits in most circumstances. Air-to-boil temperatures for the Ford and GMC trucks met manufacturer's specifications for engine operation at both rated and peak torque conditions. In contrast, the IH vehicle did not meet specified minima for either operational condition with the vehicle in its final or "baseline" condition. The air-to-boil temperatures for the IH are comparable to those of the other vehicles, but the specifications are higher. Engine oil temperatures were comparable for all vehicles and met the (somewhat loosely defined) specifications.

4.2 Fuel Economy

Fuel economy was considered from analytical and empirical perspectives. First, an analytical prediction of incremental fuel consumption was made on the basis of experimental data on the influence of exhaust backpressure and vehicle weight on engine and truck performance. The results of these estimates were so small that it was believed unlikely that increments in fuel consumption would be detectable during field tests. Nevertheless, fuel consumption data for the quieted and similar untreated vehicles were acquired and evaluated.

The results of the analytical predictions are given in Table 8. The exhaust backpressures for the treated Ford and GMC trucks were actually less than those for the untreated vehicle. Accordingly, this effect was expected actually to reduce fuel consumption for these vehicles. The backpressure increased for the IH truck. Of course, the weights increased for all of the vehicles. The anticipated net decrease in fuel economy ranged from 0.05% for the Brigadier to 0.67% for the F-4370.

TABLE 8. ANTICIPATED CHANGE IN FUEL ECONOMY.

	Ford CLT 9000	GMC Brigadier	IH F-4370
Increase <decrease> due to backpressure (%)	0.15	0.20	<0.44>
Increase <decrease> due to weight (%)	<0.22>	<0.25>	<0.23>
Net Increase (%)	<0.07>	<0.05>	<0.67>

Table 9 shows fuel economy data for the three test trucks and for similar trucks operating in the same fleets. The comparison CLT 9000s are equipped with the same engines but different transmissions and rear axle ratios. The comparison Brigadiers are identical. Only one IH truck was available for comparison. It had an identical engine but different transmission and rear axle ratio. The raw data in Table 9 show that the fuel economy of the quieted CLT 9000 was not quite as good as the comparison vehicles but that the fuel economies of the other treated vehicles were better than their counterparts.

TABLE 9. MEASURED CHANGES IN FUEL ECONOMY.

	Ford CLT 9000	GMC Brigadier	IH F-4370
Test Truck Fuel Economy (mpg)	3.78	5.11	4.87
Comparison Truck(s) Ave. Fuel economy (mpg)	3.83	4.94	4.19
Standard deviation	0.20	0.12	-
Increase <Decrease> Fuel economy (mpg)	<0.05>	0.17	0.68

Table 10 presents predicted and measured differences as percentages of baseline values along with standard deviations of measured data on comparison trucks. For the CLT 9000, the measured change is well within the range of values as indicated by the standard deviation. This is not quite the case for the Brigadier. However, the quieted Brigadier tended to operate across flat terrain between Little Rock, Arkansas and Houston, Texas, while the comparison vehicles ranged across the country. Therefore, it is not surprising that the treated vehicle achieved slightly better fuel economy. The treated and comparison IH trucks operated over identical routes. It is not clear why the

TABLE 10. COMPARISON OF PREDICTED WITH MEASURED CHANGES IN FUEL ECONOMY.

	Ford CLT 9000	GMC Brigadier	IH F-4370
Anticipated change (%)	<0.07>	<0.05>	<0.67>
Measured change (%)	<1.31>	3.44	18.62
Measured standard deviation (%)	5.22	2.43	-

quieted vehicle exhibits better fuel economy, but the improvement is not likely to be attributable to the treatment.

In summary, these data show that the impact on fuel economy is very small - less than 1% for all of the vehicles - and is, in fact, not measurable through the type of operational evaluation performed as part of this program.

5. OPERATIONAL EVALUATION

The trucks entered fleet service in the second phase of the program to test the durability of the treatments and to assess their impacts on the operating performance of each truck. The first truck entered the field test phase in January 1980; the last truck completed its field test in November 1981.

5.1 Treatment Durability

One of the major objectives of the operational evaluation was to assess the durability of the noise treatment in actual service. Overall, one may conclude that the treatment was durable. Major exhaust and enclosure components remained intact, as did the two-stage engine mounts installed in the IH F-4370. However, there were a number of failures and wear points, many of which were corrected midway through the operational test of a specific truck.

The exhaust system on the CLT 9000 held up without any deterioration. However, the Brigadier started to exhibit failures in the flex hose adjacent to the Splitter Tee Can. It became apparent that the dynamic loads on the long, unsupported exhaust line section from the turbocharger to the cylindrical mufflers were larger than the hose could withstand. Accordingly, a bracket was welded to the Tee Can and mounted to a frame, as illustrated in Fig. 23. This support greatly alleviated exhaust line failures. Similarly, the Tee Can on the IH F-4370 was suspended from the chassis; no exhaust line failures occurred in five months of operational service.

FIG. 23. TEE CAN SUPPORT ON GMC BRIGADIER.

Interference problems of a similar nature occurred on the Brigadier and CLT 9000. On the Brigadier, the air hose bracket on the right wheel struck and bent the right side shelf, as illustrated in Fig. 24. This problem was solved by reconfiguring the shelf to provide adequate clearance, as shown in Fig. 25. On the CLT 9000, the right front tire struck the right cab-mounted shield (R1) in Fig. 8, resulting in damage to both. The tire was replaced and the shield repaired, but the basic design was not modified. Such a modification, while perfectly feasible, would involve major changes to the shield and right shelf assembly (R2).

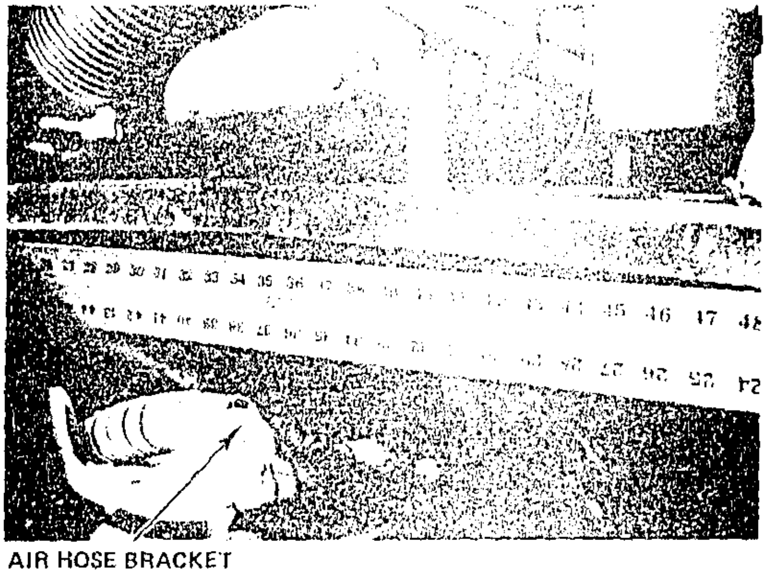

FIG. 24. BEND IN SIDE SHELF ON GMC BRIGADIER FROM CONTACT WITH AIR HOSE BRACKET.

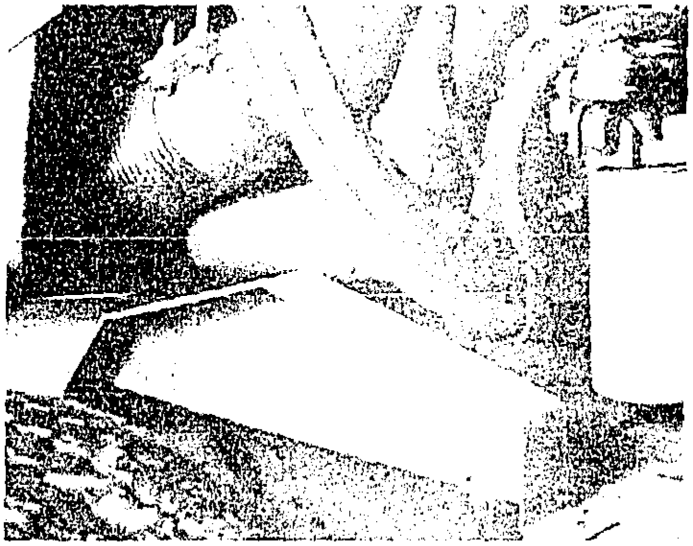

FIG. 25. RECONFIGURED SHELF ON GMC BRIGADIER.

Several areas of seal wear occurred during the operation of the CLT 9000 and Brigadier. Figure 26 shows wear of the wiping seal on the right side shield R1 of the CLT 9000. Figure 27 shows wear to a P-seal on the right side of the Brigadier. These areas of concern may be more unsightly than detrimental. As wear occurs, forces on the rubber diminish and the rate of wear decreases. During this process, the seal between adjacent parts is maintained.

Fastener durability was a chronic problem on all three trucks. Often, the bails on side latches broke and quarter-turn fasteners fell out. The operator of the IH truck solved this problem by replacing original fasteners with the type of rubber latch used to hold down the hood (Fig. 28).

Two-stage mounts received failure static load tests prior to installation on the R686 and F-4370. These tests demonstrated that the mounts' capacity exceeded specification by a wide margin. Inspection of the IH F-4370 mounts shows no visible sign of wear.

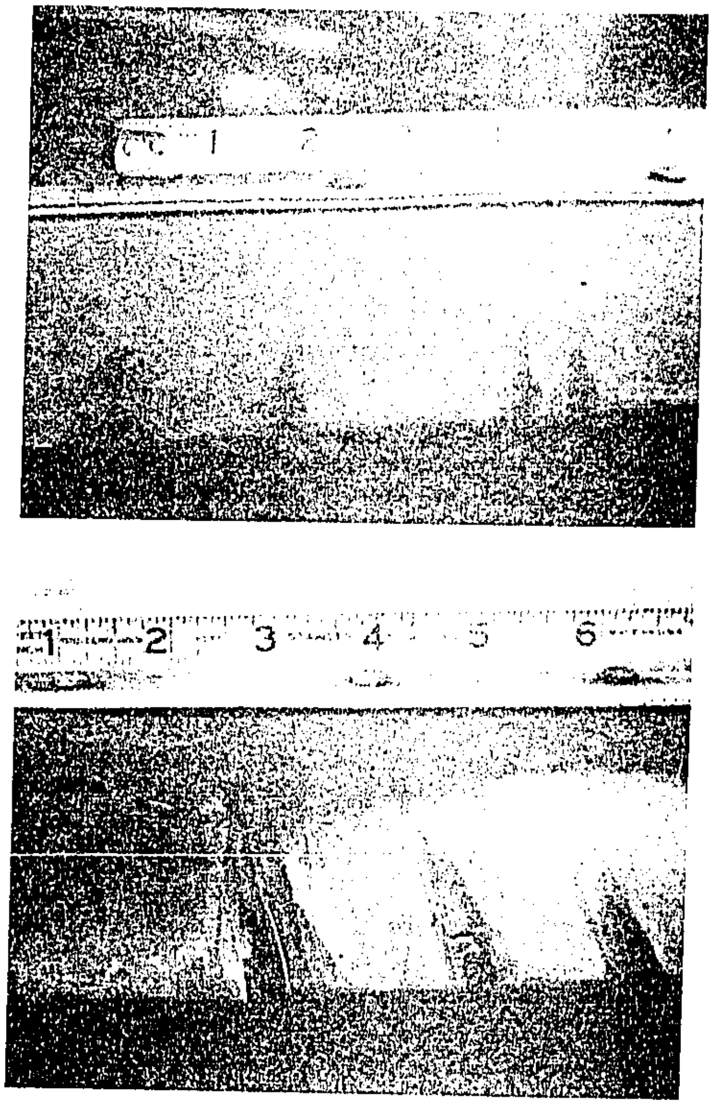

FIG. 26. WORN WIPING SEALS ON FORD CLT 9000.

FIG. 27. WORN P-SEAL ON IH F-4370.

FIG. 28. FASTENER ON IH F-4370.

5.2 Operating Performance

The three quieted trucks logged 229,844 miles of fleet service during 2 years and 5 months of field operations. The mileage of each vehicle is summarized in Table 11. The overall average was 7926 miles per month per vehicle.

TABLE 11. SUMMARY OF FIELD TEST MILEAGE.

Truck	Period	Miles
Ford	January 1980 - January 1981	107,201
GMC	September 1980 - September 1981	86,865
IH	June 1981 - November 1981	35,778
Total		229,844

The Ford CLT 9000 accumulated the most miles. It was operated by Tom Inman Trucking Company, Inc. of Tulsa, Oklahoma, an irregular route common carrier. The truck was often on the road for weeks at a time, and the average trip was over 3800 miles. Its operations tended to be west of the Mississippi. The GMC Brigadier was operated by ABF Freight Systems and was assigned to ABF's Little Rock - Houston route, an 875-mile round trip. The truck operated regularly on this route and was seldom assigned elsewhere. The IH F-4370 was operated by The Coca-Cola Bottling Company of Northampton, Massachusetts. The truck operated nightly between Northampton, Massachusetts and regional distribution centers in Keene, New Hampshire and Rutland, Vermont. This standard route is 331 miles and the truck operated nightly Monday to Friday.

Each operator had other vehicles to which the mileage of the quieted vehicles could be compared. These comparison are summarized in Table 12. Comparative mileage for the Ford was reported for the April 1980 - January 1981 period. Hence, the entries for

TABLE 12. COMPARISON MILEAGE.

	Quieted Truck (Mileage)	Comparison Truck (Mileage)
Ford	102,446	74,457
GMC	86,865	121,433
IH	35,778	36,986
Total	225,089	232,876

the Ford differ in Tables 11 and 12. The Ford operated well above norm for 38 other CLT 9000s in the Inman fleet. The GMC was below the average mileage of other Brigadiers in the ABF fleet because it missed four months of service during its year-long field test.* The quieted F-4370 closely matches the mileage of a comparison F-4370 that had operated on the same route. Overall, there was a 3.5% differential in the combined mileage of the quieted trucks and their comparison vehicles.

The International Harvester F-4370 hauled the largest payloads. Its average outbound payload, cases of Coca-Cola, was 42,770 lb. Its inbound payload of empty bottles was obviously less - 12,825 lb. This is shown in Table 13. Average payload for the Ford was almost 40,000 lb, whereas the GMC Brigadier carried only 35,000 lb, on average.

The GVCW (gross vehicle combination weight) column in Table 13 clearly shows that the vehicles were on average well below the 80,000-lb GVCW unit. No operator ever indicated that the weight of the noise control treatments caused payloads to be displaced. Review of payload data for individual trips indicated that even

*During this time noise testing and treatment modifications were performed.

TABLE 13. SUMMARY OF VEHICLE PAYLOAD.

Truck	Average Payload (lb)	Average GVCW (lb)
Ford	39,604	68,167
GMC	35,160	58,265
IH		Not reported
inbound	42,770	70,770*
outbound	12,825	40,825*

*Assume average trailer weight of 12,000 lb; actual trailer weight may vary between 11,000 and 13,000 lb.

with peak reported payloads, the vehicles did not exceed the 80,000-lb limit. In summary, the results of the field tests indicate that the noise control treatments did not cause payloads to be displaced.

5.3 Vehicle Maintenance

BBN closely monitored the maintenance costs of each of the quieted trucks and compared these costs, where possible, to comparison vehicles in the operators' fleets. Particular attention was given to maintenance costs that could be attributed to the noise control treatments. These treatment-related costs included

- Panel removal and access restrictions during regular maintenance
- Repairs to the treatments
- Repairs to other components caused by the treatments.

Repair costs were reported to BBN on summary sheets to which the operators attached shop tickets, labor times, and a shop ticket addendum, designed to capture information on which panels affected regular service activities.

Table 14 summarizes the maintenance costs for each vehicle. Regular maintenance at the operators' facilities was the largest single cost category, accounting for 87% of all maintenance charges. Outside repairs were largest for the Ford, since it was often away from its Tulsa base for weeks at a time.

TABLE 14. SUMMARY OF MAINTENANCE COSTS.

Cost	Ford CLT 9000	GMC Brigadier	IH F-4370	Total
Outside repairs	$ 533	$ 148	-	$ 681
Regular service	5,661	3,168	$1,153	9,982
Noise treatment-related	500	195	106	801
• panel removal	30	40	4	74
• access restrictions	13	-	45	58
• repairs to treatments	166	102	57	325
• treatment-induced repairs	291	53	-	344
Total	$6,694	$3,511	$1,259	$11,464

Noise-related costs for the three trucks totaled $801, or 7% of total costs. However, the bulk of these costs is attributable to the prototype nature of the noise control treatments. They include the cost of repairing the treatments, e.g., installing new latches and exhaust system flex pipe. As shown in Table 14, repairs had to be made to the treatments on all three trucks. In addition, the treatments caused other repairs, notably a tire replacement on the Ford (prorated) and a cab insulation package on the GMC. Again, these are costs typical of a prototype field test. These prototype-related costs account for $669 of the $801 treatment-related costs.

We were particularly interested in monitoring how the treatments affected normal maintenance. The bottom panels of each enclosure were designed for quick release and reinstallation. Time and motion studies indicated that these bottom panels could be removed and reinstalled in anywhere from 3 to 7 minutes. Yet, the real test would be what happened in the field.

The bottom panels typically were removed once per month. This held true for all three trucks. Occasionally one or two other panels were removed at that time. There was wide variation in the times that mechanics reported for removing panels. For example, one mechanic servicing the Brigadier reported that it took him 1/2 hour to remove the bottom panels on that truck, while mechanics at Coca-Cola consistently reported that it took less than 3 minutes. We carefully reviewed the reported data and the results from time and motion studies conducted by BBN to determine exactly how much time was spent removing panels. We then repeated the process to determine the extra time it took to service each truck, because the enclosure restricted access.

We estimate that panel removal costs were $74 - 0.69% of the $10,663 spent on regular service and outside repairs. This cost represents 4.24 hours for panel removal out of 308 hours of labor time charged to the three trucks, an increase of 1.4%. Access restriction costs were less - $58, and were primarily caused by a change made after the enclosure on the IH F-4370 had been installed, which made it more difficult to change the oil filter. Thus, the bulk of the access restriction costs reflects the prototype costs rather than any inherent costs of access restrictions associated with engine enclosures.

6. CONCLUSIONS AND RECOMMENDATIONS

The Demonstration Truck Program conclusively showed that technology exists to quiet the noise of a cross section of diesel-powered heavy-duty trucks to 72 dBA. Moreover, the practicability of the control technology was demonstrated in 230,000 miles of commercial fleet service.

The technology development phase of the program demonstrated that it is feasible to reduce the noise of four diverse, heavy-duty diesel trucks from current levels of 78 to 82 dBA to approximately 72 dBA. The control treatments include very effective exhaust systems, somewhat less effective engine and transmission enclosures, and - for two of the vehicles - two-stage engine mounts. These treatments add approximately 2-1/2% to the weight of the tractor, or 1/2% to the rated gross weight of the tractor and trailer combination. The price of the treatments, estimated at $1174 to $1304, represent approximately a 3% increase in the price of a truck tractor.

The operational evaluation phase of the program provided valuable information on the durability of the treatments and their impact on vehicle performance and maintenance. The treatments maintained their physical integrity and acoustic performance. There were some minor problems characteristic of a development program, but most of these were corrected during the vehicle field test. The treatments did not adversely impact the operational performance of the vehicles. Quick-release enclosure panels were typically removed once a month during routine service, and this increased maintenance labor time by approximately 1.4%.

The information obtained from the Demonstration Truck Program can be viewed from at least two perspectives:

- Technical issues in truck noise control - i.e., what was learned from the programs.
- Technical direction for truck noise reduction - i.e., where do we go from here?

The Demonstration Truck Program proved the effectiveness of current noise control technology. Vehicle exhaust system noise was reducted to essentially noncontributory levels. Noise absorption treatments, notably the BBN-designed perforated plate Mylar fiberglass "sandwich," proved to be effective and durable. The technical problems that developed involved clearance, support, or fastening mechanisms. The clearance and support problems can be easily corrected through design modifications and treatment configurations. The fastening of enclosure panels was a chronic problem. We do not believe that quarter-turn fasteners are technically acceptable for fastening bottom enclosure panels. The rubber latches installed on the IH F-3470 appear to be the best solution to this chronic problem, although more operational testing is required to confirm this preliminary conclusion.

The treatments employed in the Demonstration Truck Program were essentially retrofit treatments. As such, they represent an initial approach to noise reduction of current production vehicles. Having demonstrated the effectiveness of retrofit control technology, we believe the next logical step is a development program to incorporate low noise emission into the design of a heavy-duty truck. This program should address:

- Integration of noise control with vehicle design
- Optimization of noise control treatments with respect to fuel economy and aerodynamic drag

- Investigation of lighter, yet effective, materials, components and treatment designs.

More cost-effective noise control could be accomplished through the integration of noise control with the overall design of the vehicle. In the Demonstration Truck Program, all of the treatments were designed to fit existing vehicles, which have been built to meet standards that are approximately 10 dBA higher than the 72-dBA goal. Sometimes this fit was awkward. For example, it was easier to leave a hole in a side shelf for a Freon bottle on the International Harvester than to move it and associated tubing. Side shelves often had shapes that appeared unnecessarily complex to conform to existing hood profiles or uncertain axle clearance envelopes. Two-stage mounts had to be configured to make maximum use of dimensions. Space limitations on the Mack forced us to leave the exhaust pipe outside of the enclosure, which created shell-noise problems. Clearly, if a truck were designed to incorporate advanced noise control treatments, many of these problems could be alleviated. For example, inner fenders that would cleanly abut side shelves (or possibly frame rails) could be molded into the hood. Engine mounting brackets could be designed to accommodate a blocking mass more easily than is shown for the IH vehicle in Fig. 18.

The lower portion of any engine enclosure could be designed to have a smooth contour that could reduce aerodynamic drag and enhance fuel economy. Such treatments have been installed on automobiles with reported fuel economy improvements of several percent. If this level of improvement were achievable on a truck, it would more than offset the fuel penalties associated with backpressure and weight.

Treatment weight could probably be reduced by incorporating materials of lighter weight and different types. An analysis presented in the technology and cost report for the Ford CLT 9000 (BBN Report No. 4379) has shown that our aluminum panels were heavier than necessary for acoustical purposes and were chosen conservatively for strength and durability. The field test phase, though limited in duration, revealed no panel degradation. Clearly, lighter weight aluminum, sheet steel, fiberglass, or other materials should be incorporated in future designs. In addition, single exhaust lines achieving the same degree of noise reduction as the dual systems on the Ford, GMC, and IH trucks would be desirable and are probably feasible. The single line on the Mack reduced outlet noise to 58 dBA, weighs only 67% as much as the dual system on the Brigadier, and imposes an incremental cost that is 45% less. The technology used in this system could probably be used to make a longer 10-in.-diameter muffler that would be visually more appealing than the oval unit, yet perform as well.

In summary, much has been learned from the Demonstration Truck Program, but there is still much to learn. Further efforts in noise control development will have to be balanced against limited funds, public priorities, and technological developments. If future activities are to be undertaken, we believe the results of this program provide a solid foundation and clear directions for future programs.

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