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Brake and Clutch Emissions Generated During Vehicle Operation

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ABSTRACT

In order to define the extent of gas and particulate emissions from automotive brakes (and clutches), a combination separation and storage collection system was devised. Unique emissions collectors for both disc and drum brakes and for a clutch were conceived, designed, and built as the main embodiment of this instrumentation. The hardware was installed on a vehicle which was then driven through various test cycles to determine the extent and type of brake emissions generated at low- and high-operating temperatures. Typical driving conditions such as the Detroit Traffic Test as well as more abusive driving conditions such as fade tests were included.

Typical original equipment and aftermarket friction materials for both disc and drum brakes were used in the tests. Brake relines were made to simulate typical consumer-type practices. The brake emissions generated were removed from the various collectors and mass balances were performed. The particulates were processed and analyzed by a combination of optical and electron microscopy to ascertain the asbestos content and the asbestos particle size distribution in the wear debris. Comparisons of emissions from new and used friction materials, from disc and drum brakes, and from original equipment and aftermarket materials were made. Finally, an estimate was made of the total emission of asbestos by all of the vehicles in the country. On the average more than 99.7% of the asbestos is converted. The contribution to the atmosphere is 5060 lb or 3.2% of the total asbestos emission.

THE CHRYSOTILE FORM of asbestos is a major constituent in automotive friction materials: disc pads, brake linings, and clutch facings. Asbestos is used because of its thermal stability, relatively high-friction level, reinforcing properties, and low cost. During operational engagement in the vehicle, the friction material and a metal rotor form a sliding friction couple which converts the kinetic energy of rotating members into heat, absorbs the heat, and gradually dissipates it to the surroundings.

Friction material emissions are generated by wear. Abrasive and adhesive wear are considered to be the most important mechanisms below approximately 450°F; thermal wear predominates above 450°F. The organic constituents pyrolyze of oxidize and are emitted to the air as carbonaceous solid particles or gaseous reaction products. The asbestos fibers are pulverized into small particles which are either trapped in the brake (or clutch) housing, fall to the road, or are emitted to the atmosphere. Most of the asbestos is heated to temperatures high enough to cause chemical conversion and is therefore trapped or emitted as olivine or forsterite particles.

When the large number of existing cars and trucks is considered, each with eight or more pieces of friction material in the brake system plus more in the clutch mechanism, it becomes apparent that an air pollution problem may exist. Considered in another light, there are perhaps 1 billion pieces of friction material in vehicles in the United States gradually being pyrolyzed and ground to dust. The brake systems in the vehicles utilizing these friction materials can thus be considered as chemical reactors, each emitting organic and inorganic compounds including asbestos and its decomposition products to the atmosphere. The compositions of the gaseous and solid emissions are not well-known nor are the particle sizes and shapes of the solid emissions well-known.

OBJECTIVES

Because of the possible damage which asbestos emissions can produce in the human respiratory system, it is desirable to identify and quantify these emissions.

Thus the objectives of this paper are to:

1. Describe the methodology used to generate, collect, and analyze brake and clutch emissions.
2. Report the asbestos contents in emissions from a test vehicle.
3. Estimate the total asbestos emissions for all vehicles in the country.

TECHNICAL APPROACH

The detailed technical approach may be summarized as follows:

1. Select a suitable vehicle and linings representative of the marketplace.
2. Conceive, design, and build brake and clutch emissions collectors.
3. Test and check out a typical collector on an inertial dynamometer and install instrumentation on the test vehicle.
4. Select and run suitable driving test schedules representative of consumer-type driving.
5. Collect and analyze emissions to obtain the asbestos content and the particle size distribution.
6. Estimate the asbestos emission for all passenger vehicles and extend the data to trucks to obtain a result for all vehicles operating in the United States.

A passenger car was selected for testing because of the following factors:

1. Vehicle braking cannot be simulated realistically on small-scale friction test machines with the present state-of-the art.
2. Full-scale brake and clutch dynamometers provide fairly good simulation and can be used for checking out the emissions collection system; however, separate tests for brakes and clutches would be required thus increasing program costs. On the vehicle, disc and drum brakes and clutches can be tested simultaneously.

INSTRUMENTATION

METHODOLOGY AND CRITERIA - The collection of particulate and gaseous emissions from any vehicle friction couple has never, to the authors' knowledge, been reported in the literature. To define the extent of these emissions, a collection system was devised which combined the functions of separation and storage. Unique emissions collectors for both disc and drum brakes and for a clutch were conceived, designed, and built as the main embodiment of this instrumentation. The collectors separated the wear debris into three different fractions: a sump sample which included the wear debris on the lining surfaces, in the rivet holes, and on the brake drum; a surface sample which included the wear debris on the brake and collector shroud surfaces, and an airborne sample collected on membrane filters.

The major requirements for the emissions sample collection system may be summed up as follows:

1. Collect all particulate and gaseous emissions.
2. Store collected emissions unchanged.
3. Prevent intrusion of contaminants. .
4. Maintain ordinary braking and clutching conditions.
5. Be operable at high temperatures.
6. Permit easy separation and analysis of emissions.

MATERIAL SELECTIONS - For the results to be representative of average consumer-type vehicle usage, a vehicle intermediate between compact and luxury was selected. The vehicle was equipped with front disc brakes, rear drum brakes, and a dry clutch. All friction material used contained asbestos. Three vehicle tests were run.

The first vehicle test was run with the original equipment friction materials. The second vehicle test simulated a partial reline—fronts only relined—while the rears were repeated to give a replicate test and an indication of emissions trends for friction materials with continued use. The third vehicle test simulated a complete brake reline and included turned discs and drums. The friction materials selected for the program were representative of those supplied by the industry—five different manufacturers (Abex, Bendix, Raybestos-Manhattan, Thiokol, and Worldbestos) produced the original equipment and aftermarket disc pads and drum linings which were selected in part because of their high-volume usage.

VEHICLE INSTRUMENTATION - A passenger car of medium weight (4850 lb test weight) produced in high volume was selected. It was equipped with a three-speed manual transmission, ventilated cast-iron disc brakes on the front, and cast-iron drum brakes on the rear. This vehicle was selected in order that the emissions from clutches and from disc and drum brakes could be tested simultaneously on a vehicle size representing a large percentage of the present vehicle population.

The vehicle was equipped with standard brake test instrumentation. A front disc brake collector and a rear drum brake collector were installed on the right side of the vehicle. The clutch was sealed by closing the few holes in its casing. The left wheel brakes were left in their normal configuration and were used to monitor the operation of the shrouded brakes. Wear debris was taken from the left brakes as well as from those on the right. The amounts of debris formed and their compositions were used to demonstrate that the brake shroud-

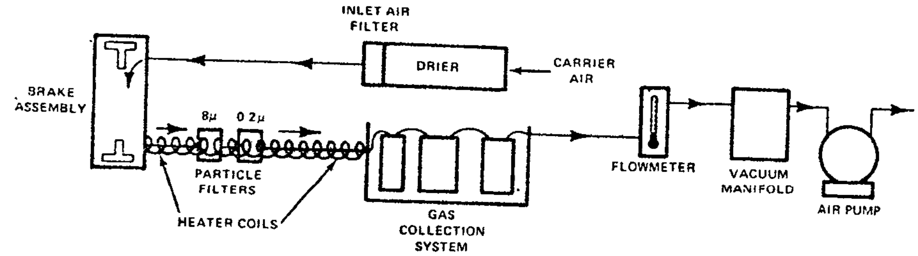

Fig. 1 - Schematic diagram for airflow of typical particulate and gas collection system

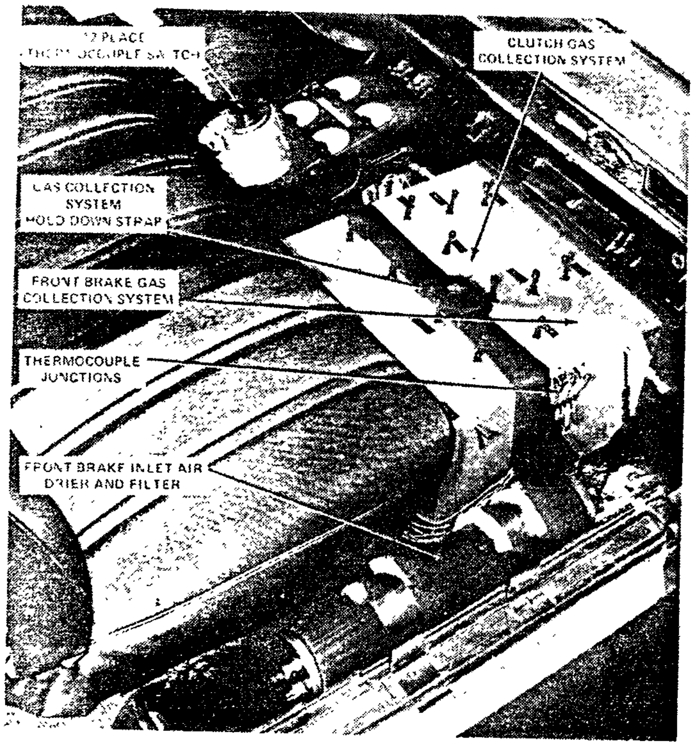

Fig. 2 - Vehicle instrumentation (front seat area)

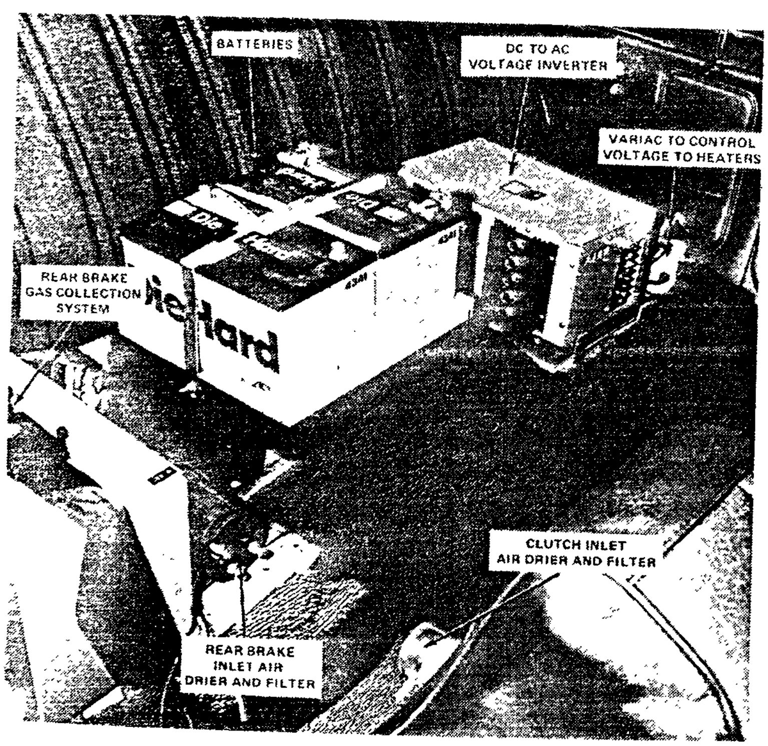

Fig. 3 - Vehicle instrumentation (rear seat area)

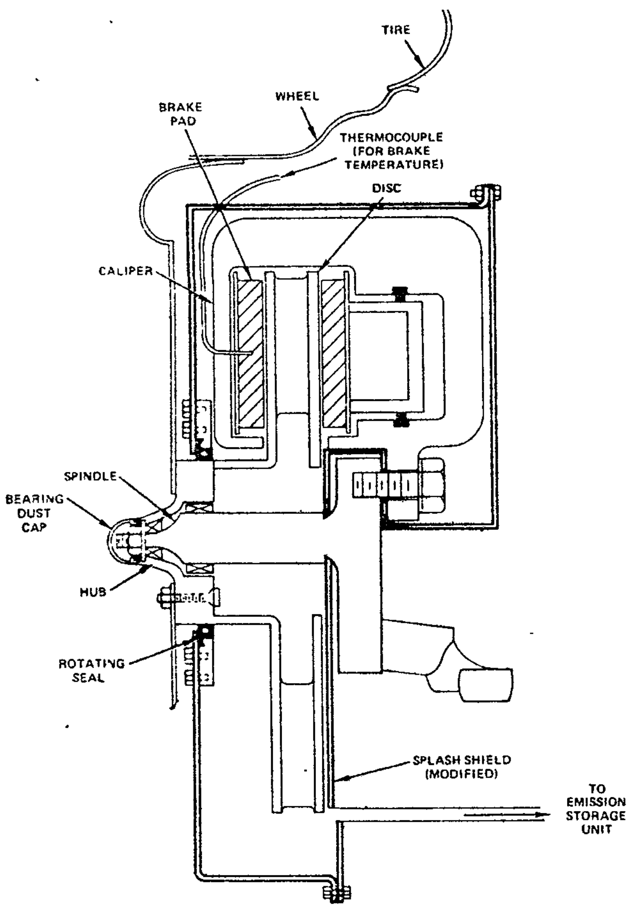

Fig. 4 - Schematic of disc brake shroud

ing did not significantly affect the operation of the brakes on the right side.

EMISSIONS COLLECTION SYSTEMS

OVERALL SYSTEM DESIGN - The basic design concept of each brake emissions collection system is shown in Fig. 1. Air from inside the vehicle was pulled through a bed which removed water and carbon dioxide from the air. The air then passed through a filter to remove all particles larger than 0.2 μm (8×10^{-6} in). The filtered air was then routed to the sealed brake assembly through clean Teflon tubing. The airstream, along with wear particles and gases, then passed out of the brake through Teflon tubing which was heated to avoid condensation. This stream passed through two filters to remove the airborne particles and preserve them for analysis. The stream then passed through three cold traps in order to condense and trap the gases evolved during braking and preserve them for analysis. The remaining airstream then passed through a flowmeter, the vacuum manifold, and finally through an air pump run by the vehicle engine where it was expelled to the atmosphere.

Fig. 2 shows, mounted in the front seat of tne test vehicle, the front brake inlet air filter and gas collection system, the clutch gas collection system, and the 12 position thermocouple switch and pyrometer used to monitor gas and filter trap temperatures. Fig. 3 shows, as mounted in the rear seat of the test vehicle, the rear brake air filter and gas collection system, the clutch air filter, and the electrical system (bat-

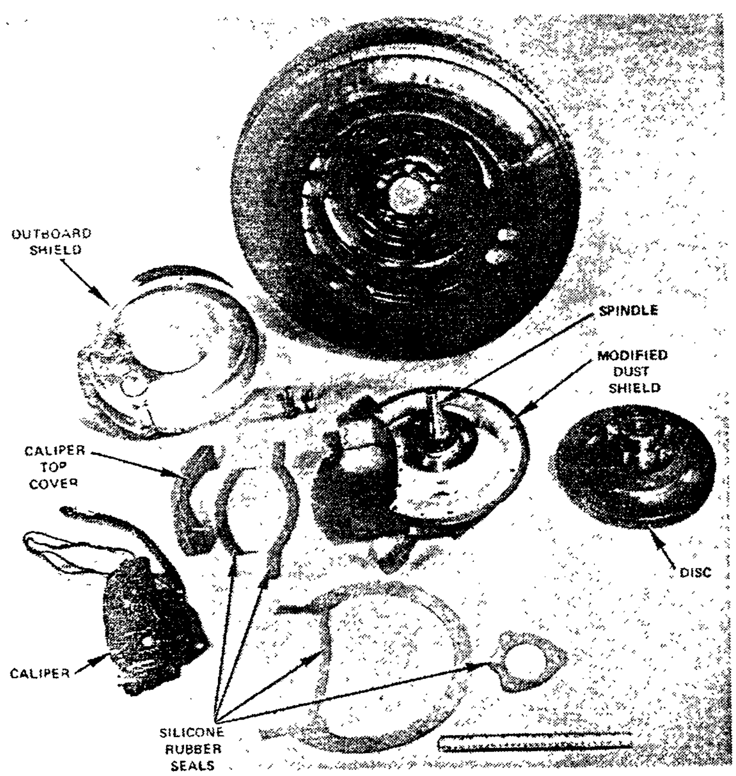

Fig. 5 - Disc brake emissions collector assembly—exploded view

teries, inverter, and Variac) which were used to supply power to the heating coils.

PARTICULATE FILTERS - The 47 mm filter holders joined in series were used for the collection of airborne particulates. Nuclepore filters were used. These filters are made from a smooth film of polycarbonate plastic with pores that do not restrict the flow of gases significantly as particle collection proceeds. The filter holders were heated by tape heaters wound around the outside and controlled by a variable transformer within the test vehicle.

GAS COLLECTION SYSTEM - Three gas collector traps held at approximately -70°C (-95°F) were used. A simple cold-finger trap, placed first, was used to remove and store the condensable vapors. These vapors included most of the organic degradation components from the brake lining. The second type of trap, of which two were used, contained activated charcoal and was used to collect the volatile hydrocarbons such as methane and other light gases.

DISC BRAKE COLLECTOR - Fig. 4 shows a cross-sectional view of the disc brake collector. The rubbing seal was located at the hat or hub section of the rotor. The seal was a spring-

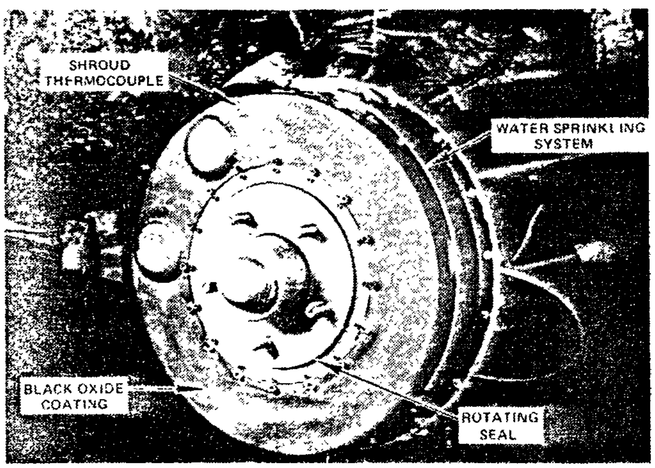

Fig. 6 - Disc brake emissions collector showing thermal control aids

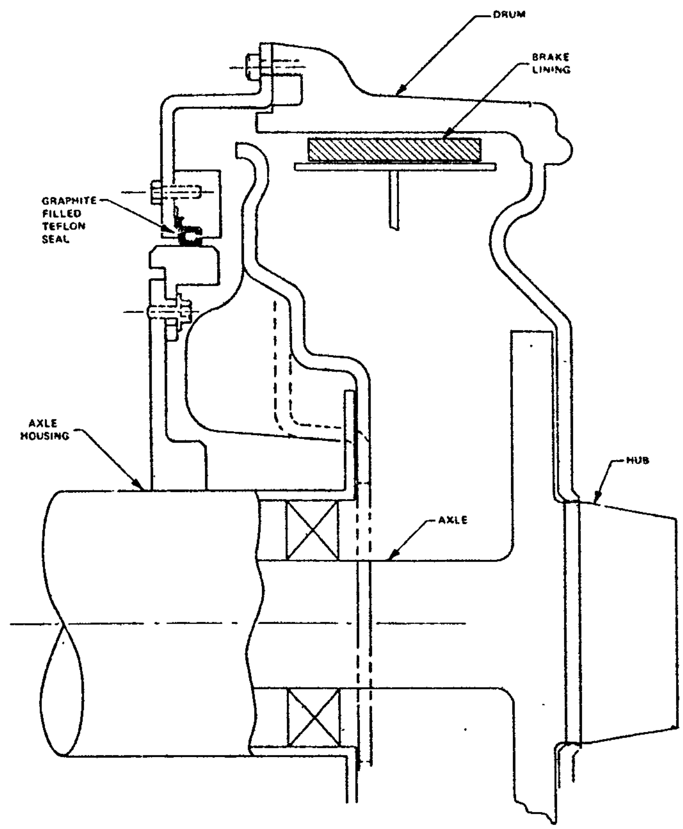

Fig. 8 - Schematic of drum brake shroud

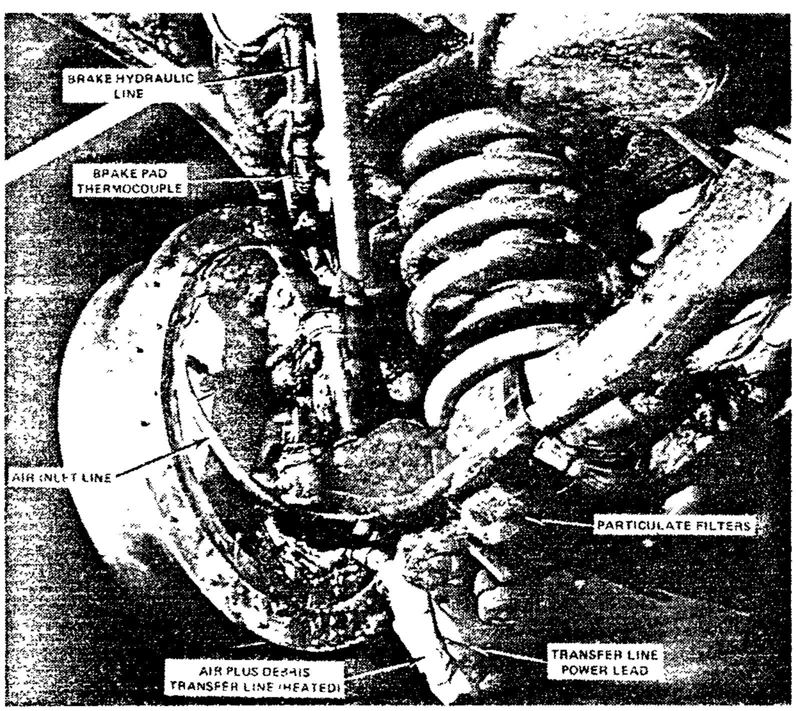

Fig. 7 - Back view of disc brake emissions collector showing instrumentation

loaded graphite-filled Teflon seal of commercial manufacture. A view of major components of the collector is shown in Fig. 5; the system, as mounted on the vehicle, is shown in Figs. 6 and 7. The main portion of the shroud was coated with black oxide; a water-cooling system was added and an open "mag" wheel was used to aid in cooling the enclosed brake.

DRUM BRAKE COLLECTOR - Fig. 8 shows a cross-sectional view of the collector along with the detail of the rubbing seal. The seal was of the same type as for the disc brake collector. The axle hub used to align the drum was modified with a piece that was concentric to the axle bearings within 0.001 in (0.0025 cm). A tapered lead was used to facilitate mounting of the drum. The close tolerances on the concentricities were necessary in order to obtain reasonable seal life. Figs. 9 and 10 show outboard and inboard views of the system as mounted on the test vehicle.

CLUTCH COLLECTOR - The clutch system consisted mainly of a filtered air inlet and an outlet to the sample storage system with all other external holes sealed.

INERTIA DYNAMOMETER TESTS

The front disc brake emission collector was tested on an inertia dynamometer to check out its operation and its most critical part, the rotating seal. Thermal response tests were made with the results indicating that for normal operation the shrouded disc brake would operate at a slightly higher temperature than the normal brake configuration. A method was devised to determine the leak rate of the collector. The rotating seal was largely responsible for the residual leak; the leak rate was reduced significantly by use of a very small amount of high-temperature grease. The rotating seal underwent durability testing and survived 7 h at 50 mph. A second series of dynamometer tests gave reproducible emissions and temperatures. Finally, a test was made in which the collector and especially the rotating seal were shown to be relatively leak-tight to external liquid and particulate contaminants.

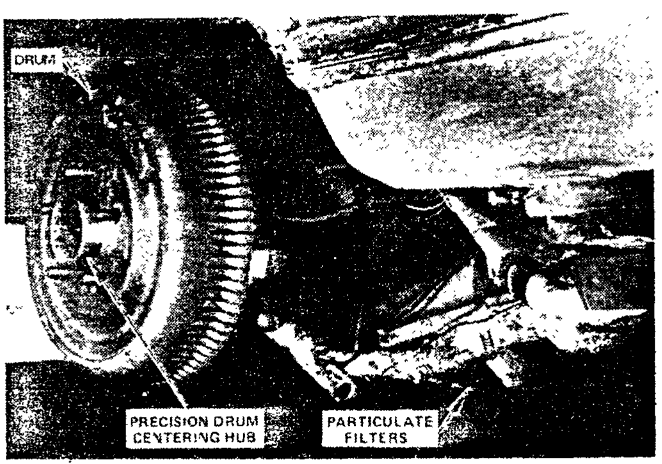

Fig. 9 - Assembled rear drum brake emission collector

VEHICLE TESTS

RATIONALE - For a given vehicle brake system, friction material wear is primarily a function of the duty cycle. For light-duty cycles, where pad and lining temperatures remain under 350°F, low wear results and is primarily due to the abrasive and adhesive wear mechanisms. Heavier duty cycles at higher temperatures give some combination of thermal, abrasive, and adhesive wear. Under severe heavy duty where the use borders on abusiveness, brake fade may occur. The inability of the brakes to hold the friction level results in part from the formation of gases (and wear debris) at the interface.

Although there are many acceptable original equipment manufacturers' friction material tests to measure a specific condition or combination of conditions, there is no one test which adequately matches normal driving conditions which would be representative of all vehicles. Consequently, it became necessary to devise a rational and meaningful vehicle test driving schedule.

SELECTED VEHICLE-DRIVING SCHEDULES - A total of seven test schedules were chosen and each was followed by a measurements procedure (take emissions samples, measure wear, inspect systems, and replace worn parts). The first three tests–Burnish, After-Burnish (A.B.) Baseline, and Detroit Traffic–represent the low-temperature tests. The final four tests–10 Stop Fade, After-Fade (A.F.) Baseline,

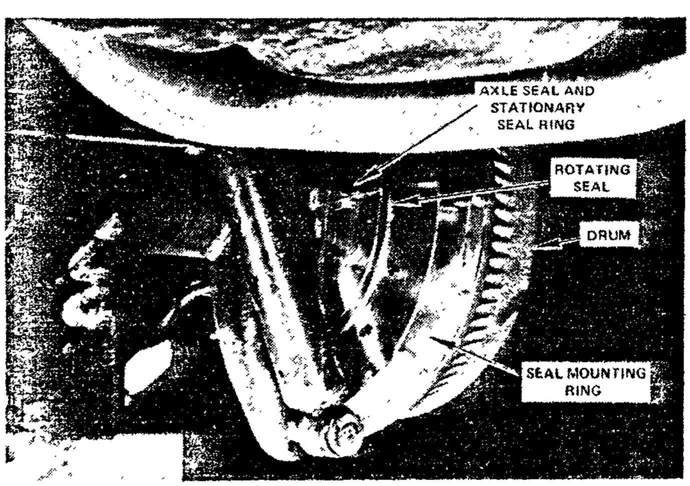

Fig. 10 - Inboard view of assembled rear drum brake emissions collector

15 Stop Fade, and Final Baseline–represent the high-temperature tests.

Burnish - During the Burnish, the original equipment and aftermarket linings mate and conform to the initial condition of the rotor whether it is in its original configuration, as-used condition after vehicle test 1, or its turned condition prior to vehicle test 3. It was anticipated that the emissions during Burnish would be different from those for worn-in linings.

A.B. Baseline - This consisted of three days of Detroit Traffic Test. It was run at this time so that the other Baselines run at later times could be compared with the A.B. Baseline for the amount and type of emissions.

Detroit Traffic Test - The Detroit Traffic Test is typical of urban driving and is used primarily to evaluate friction, life, and noise of commercial brake products. The normal operating range for passenger car brakes in the test is 180-280°F. This condition constitutes what a brake engineer calls a low-temperature wear test. Testing is intentionally accelerated to reduce test costs; consequently the test tends to be more severe than average driving.

The end of the Detroit Traffic Test was the end of the low-temperature wear testing.

10 Stop Fade and Recovery - The 10 Stop Fade and Recovery was the fourth test sequence and the start of the heavy-duty or high-temperature testing. During this test the front brakes experienced temperatures above 500°F while the rear brakes experienced temperatures above 350°F. The combination of increased temperature and increased duty was expected to change the amount and type of wear debris generated as compared with the previous low-duty tests.

The Fade and Recovery Test was then followed by the Reburnish sequence.

A.F. Baseline - This fifth test sequence was identical to the second and seventh test sequences (and similar to the third), but only the conditions of the friction materials had changed. This test was expected to determine the permanent changes in the amount and type of wear debris generated for friction materials taken through high-temperature and heavy-duty stops.

15 Stop Fade and Recovery - The sixth test sequence was the 15 Stop Fade and Recovery in which the friction materials were taken to even higher temperatures than for the 10 Stop Fade. The five additional stops performed after the brakes were already hot produced temperatures above 575°F. This is abusive braking and rarely occurs. The emissions generated were expected to be different again as compared with the low-duty tests and the 10 Stop Fade.

The Fade and Recovery Test was then followed by the Reburnish sequence.

Final Baseline - The results of this seventh and last test sequence can be compared with the results of the identical second and fifth test sequences. This test concluded the determination of the effects that high-temperature and heavy-duty tests have on brake emissions.

Table 1 - Comparison of Disc Brake versus Drum Brake Operating Conditions

Parameter	Disc	Drum
Type of system	Open	Closed
Airflow	High	Low
Emissions	Relatively few trapped	Much trapped in surfaces and in sump
Third-body abrasive wear	Relatively none	Some

SAMPLING AND ANALYTICAL PROCEDURES

GENERATION OF EMISSIONS - During the braking process, particulate emissions are generated by the rubbing action of the friction materials and the rotors. The original equipment manufacturer (OEM) brake configurations (left wheels of test vehicle) release emissions which reside in either of two areas depending on the brake type (Table 1). The disc brake releases much of the emissions to the atmosphere while a small amount remains in the brake. The drum brake releases a smaller amount to the atmosphere and retains sizeable portions on the drum-rubbing surface and on the brake parts. The brake emissions collectors perform two functions not encountered in normal brake operation: they collect all the debris generated and fractionate the debris. Table 2 summarizes the particulate emissions samples produced.

The OEM brake configurations release gaseous emissions which again reside in either of two areas. Most of the gaseous emissions are released into the atmosphere; some of the high molecular weight materials distill from the hot surfaces and condense on the cooler brake parts. The emission transfer lines used in conjunction with the collectors therefore were heated so that almost all gaseous emissions could be transferred to the gas collection traps.

PARTICULATES REMOVAL FROM COLLECTORS - A detailed step-by-step procedure was prepared for the removal of brake emissions from the collectors. The amounts of debris collected at the various locations were used later to calculate the mass balances. A detailed step-by-step pro-

Table 2 - Samples Produced by Brake Emissions Collection

Sample	Disc Brake	Drum Brake
Sump	Trapped debris*–includes that in rivet holes, on pads, and in caliper piston	Trapped debris*–includes that in rivet holes, on linings, and on drum surface**
Surfaces	Accumulated on shroud–normally road dropout	Accumulated on brake surfaces*
Airborne	Airborne samples collected on filters	Airborne samples collected on filters

*Normally not completely released during brake operation. (This may be a "controllable" material which could be disposed of properly.)
**Provides third-body wear.

cedure was also prepared for the sampling, handling, and analysis of the asbestos emissions.

ANALYTICAL PROBLEM DEFINITION - The thermal and mechanical forces which act at the friction couple interface produce a complex chemically and physically altered microstructure which cannot be accurately described at present. Table 3 gives an estimate of the chemical composition of wear debris.

Asbestos is a complex inorganic material with the approximate composition formula:

$$Mg_3\,(SiO_5)\,(OH)_4 \text{ or } 3MgO \cdot 2SiO_2 \cdot 2H_2O$$

The basic unit has a fibril form (1, 2)*. Asbestos is readily identified when alone or in simple mixtures at high concentrations by these analytical methods: x-ray diffraction, thermal methods, microscopy, and infrared analysis. However in complex mixtures or at very low concentrations the analysis for asbestos is very difficult. In brake wear debris, the problem is compounded because the reaction products of asbestos, forsterite and olivine have similar elemental ratios and similar x-ray diffraction patterns. The only sensitive method which can be used is microscopy. In extremely low concentrations, asbestos is identifiable in the electron microscope by its physical shape (tubular fibril) which is distinguishable from that of other fibers and particles.

At the beginning of the program, one optical (3) and three transmission electron microscopy (4-6) methods had been developed by others. Two of the electron microscopy methods were not suitable because they changed the fiber size distribution of the asbestos.

ANALYTICAL METHOD SELECTED - From the available analytical methods and the problems associated with brake wear debris analysis, the following considerations were necessary.

Criteria and Flow Chart - Three important criteria had to be met by the analytical method used: The very small portion of brake debris used had to be representative of the much larger sample collected; the analytical steps could not degrade the particle size distribution of the asbestos fibers obtained; the results obtained must be indicative of the actual asbestos content of the sample. These criteria were met by the analytical scheme outlined in Fig. 11.

Representative Sampling and Low-Temperature Ashing (LTA) - The analysis of brake wear debris indicated the presence of 20-30% by weight of polymeric and carbonaceous material, which in turn produced a fluffy appearance when the material was examined in the scanning electron microscope. The organic portion was therefore removed by LTA. Two representative samplings were used: the first in sample selection for LTA and the second in sample selection for distribution on a filter membrane for subsequent analysis.

Selected Microscopy Methods - In the very early tests, wear debris from a sample dynamometer was collected on the filter train of the 8.0 μ and 0.2 μ Nuclepore filters. Both filters were examined by a combination of optical and transmission electron microscopy. The following observations were made:

1. Asbestos fibers longer than 20 μ were obtained.
2. Very fine fibrils were extremely difficult to detect at less than 5000 diameters magnification.

Based on the above studies, it was deemed necessary to employ two magnifications. To detect fibers greater than 2 μ, a magnification in the range 10,000-40,000 diameters

*Numbers in parentheses designate References at end of paper.

Table 3 - Estimated Chemical Composition Characteristics of Wear Debris

Description	Percent	
Low molecular weight degradation products	2-10	
Polymeric components	12-20	20-30
Carbonaceous material	1-5	
Inorganics:		
Mineral	∿10-30	
Olivine	∿20-40	
Oxides (from lining)	0-10	70-80
Fe_2O_3 (from rotor)	5-15	
Asbestos	<1	

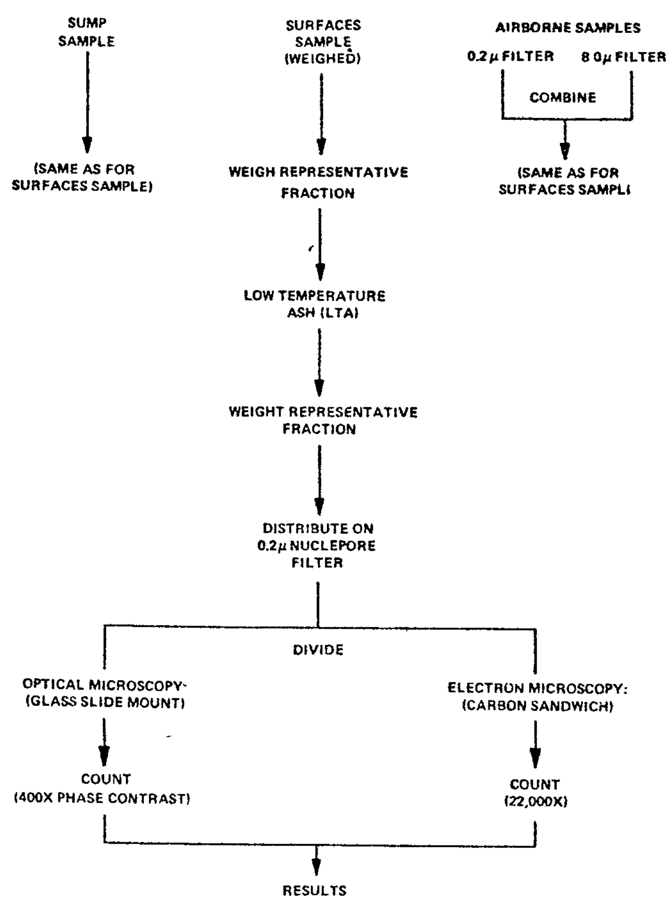

Fig. 11 - Flow chart of particulates analyses

was required. Table 4 shows the magnifications selected for use with the two microscopy techniques.

Calculations from Microscopy Results - For each fibril or fiber found it was necessary to determine its dimensions and calculate the volume of asbestos found. Because of the large number of fibers this procedure became tedious. To simplify fiber sizing, a microscopy count sheet was developed. Each fiber found by the appropriate microscopy method was classified into the proper size category containing the projected diameter and length of the fiber in question.

The volumes were summed, converted to weight, and normalized for the entire sample weighed onto the filter. A computer program was subsequently developed to minimize computational time and to eliminate errors in the processing of these calculations.

The possible sources of error associated with sample processing and analysis were minimized through the use of statistical methods. The largest effect found on the asbestos analysis was the occasional occurrence of a large fiber. The extent of error increased as the percent of asbestos in the sample decreased. The data showed that the maximum deviation for results with asbestos contents above 0.10% averaged 12-15% and had a maximum at approximately 20%. The maximum deviation increased for asbestos contents below 0.10% where errors for the small amounts of asbestos emission become less significant from the standpoint of air pollution.

VEHICLE TEST RESULTS

MILEAGE ACCUMULATIONS - The various driving schedules described earlier are listed in Table 5 with the average mileages and times for each test. The overall variation for the total mileage accumulation of all three vehicle tests was very low at ±2.4%. These mileage variations were primarily due to the varying times taken to reach the Detroit traffic circuit. Normally only one round trip was required to obtain the four circuits. Rain, seal failure, thermocouple malfunction, and other minor difficulties which required a premature return to base added to the minimum mileage possible.

PERFORMANCE OF EMISSION COLLECTION SYSTEMS -

Rotating Seal Life - The success of the vehicle testing depended heavily on the proper operation of the rotating seals since they were the most critical parts of the collection systems. Only one major problem occurred during the vehicle testing: during the 10 Stop Fade of vehicle test 1, the hardened steel ring on which the rotating seal slides became loose. The ring was reanchored and no further problem was encountered during the 15 Stop Fade or in any further test schedule. This result showed the durability of the collector and rotating seal design and construction. For the 8100 miles of testing, only seven front and eight rotating seals were required. This was better than anticipated at the start of the program.

Brake-Operating Temperatures - Frequent temperature monitoring was necessary for the successful completion of the vehicle tests. The temperatures were monitored at all four wheels (Table 6). The top portion of the table shows the effectiveness of the thermal control aids in keeping the temperatures of the shrouded disc brake well below the 400°F region where the exponential wear rate begins.

Since approximately 90% of the test miles were driven in the Detroit traffic circuit, it was necessary to monitor these temperatures carefully. The driver was instructed to take specific actions when greater than desired temperatures occurred. For example, during the Detroit traffic circuits the maximum allowable temperature was 330°F. When this temperature was reached the vehicle was stopped and allowed to cool to 300°F. These cool-down periods were seldom necessary. The data at the bottom of Table 6 show that on a hot July day the temperature difference between the brakes remains fairly constant as the temperatures increase with the ambient.

Table 4 - Microscopy Magnifications Selected for Asbestos Fiber Analyses

Microscopy Technique	Fibers Detected, μ: Minimum d × 1	Fibers Detected, μ: Maximum d × 1
Transmission electron at 22,000X	0.03 × 0.10	0.50 × 35
Optical (phase contrast) at 400X	0.50 × 1.50	10 × 100

Table 5 - Summary of Vehicle Mileage Accumulations

Schedule	Test	Miles	Average Miles	Days
Burnish	1	174		
	2	127	134	3.5
	3	100		
A.B. Baseline	1	328		
	2	348	348	4.5
	3	368		
Detroit Traffic	1	1439		
	2	1430	1408	13.5
	3	1355		
10 Stop Fade	1	47		
	2	53	53	4.0
	3	58		
A.F. Baseline	1	356		
	2	339	347	4.5
	3	347		
15 Stop Fade	1	47		
	2	79	59	3.5
	3	52		
Final Baseline	1	352		
	2	326	343	4.5
	3	352		
Totals	1	2756		
	2	2702	2697	38.0
	3	2632		
		8090		

Table 6 - Brake Temperatures During Burnish and Detroit Traffic Circuits

			Front Disc Brake			Rear Drum Brake		
Test	Remarks	Ambient Temperature, F	Right (Shrouded)	Left (Normal)	ΔT	Right (Shrouded)	Left (Normal)	ΔT
Burnish Vehicle test 1	Initial attempt (no thermal control aids)							
	After 20 stops	10	400	150	250	255	150	105
	After 40 stops	10	340	120	220	200	110	90
	After 60 stops	10	360	160	200	245	150	95
		Range	340-400	120-160	200-250	200-255	110-150	90-105
	Rerun (with thermal control aids)							
	After 10 stops	70	280	150	130	205	150	55
	After 40 stops	49	310	150	160	245	165	80
	After 60 stops	65	265	150	115	215	165	50
	After 100 stops	68	280	165	115	220	170	50
	After 160 stops	50	300	170	130	190	130	60
		Range	265-300	150-170	115-160	190-245	130-170	50-80
A.B. Baseline Vehicle test 2	Morning circuit (8:00 a.m.)							
	12 Mile and Woodward	79	270	150	120	150	150	0
	Michigan and Third	80	300	160	140	170	160	10
	Adams and Woodward	82	300	160	140	180	160	20
	Adams and Woodward	82	280	150	130	180	160	20
	12 Mile and Woodward	84	330	190	140	190	160	30
	Afternoon circuit (2:00 p.m.)							
	12 Mile and Woodward	90	310	210	100	160	160	0
	Michigan and Third	91	320	180	140	210	180	30
	Adams and Woodward	91	310	180	130	210	180	30
	Adams and Woodward	91	310	170	140	200	170	30
	12 Mile and Woodward	91	300	160	140	170	150	20
		Range	270-330	150-210	100-140	150-210	150-180	0-30

For the 10 and 15 Stop Fade schedules, it was expected that the shrouded brake would retain the high temperatures longer than would the nonshrouded brake. In the course of the test it was necessary to increase the time interval after the fifth-to-seventh stops to allow for additional cooling. Fig. 12 gives the temperature versus stop relationship from the 10 Stop Fade of vehicle test 1. Data taken from an inertia dynamometer and a typical vehicle test were used as baseline data to which the shrouded disc brake was programmed. All other fade tests showed similar relationships.

Mass Balances - The emissions samples were removed from the collectors and weighed. The results for vehicle test 1, which are typical of the other two tests, are given in Table 7. After each test the brake lining weight losses were also obtained. The distribution of the brake emissions was then obtained for the sump, surfaces, and airborne samples. Table 8 summarizes the distributions for the three vehicle tests.

PERCENT ASBESTOS CONTENTS - Each of the samples was analyzed for asbestos content by optical and electron microscopy as described earlier.

For vehicle test 1, the range of asbestos contents in brake emissions varies from a high of 1.65% down to a low of 0.05% (Table 9). Of the 47 analyses reported, only two were above 1.00%. The overall average was 0.38%.

For vehicle test 2, the range of asbestos contents in brake emissions varies from a high of 1.42% down to a low of 0.03%. Of the 43 analyses reported, only one was above 0.96% and

Table 7 - Weights of Brake Particulate Wear Debris Collected–Vehicle Test 1, g

		Front Brakes		Rear Brakes	
Schedule	Collector	Right (Shrouded)	Left (Normal)	Right (Shrouded)	Left (Normal)
Burnish	Sump	0.142	0.116*	0.144	0.220
	Surfaces	0.412	0.029	1.170	0 394
	Airborne	0.061	–	0.046	–
A.B. Baseline	Sump	0.083	0.128	0.185	0.208
	Surfaces	0 644	0.055	0.590	0.205
	Airborne	0.130	–	0.049	–
Detroit Traffic	Sump	0.201	0.458	0.436	1.654
	Surfaces	2.010	0.109	4.052	0.878
	Airborne	0.237	–	0.285	–
10 Stop Fade	Sump	0.580	0.244	-0.335	1.120
	Surfaces	1.212	0.076	0.371	0.275
	Airborne	0.013	–	0.017	–
A.F. Baseline	Sump	0.191	0.153	0.060	-0.516
	Surfaces	1.764	0 030	0.652	1.543
	Airborne	0.259	–	0.030	–
15 Stop Fade	Sump	0.616	0.150	-0.046	-0.330
	Surfaces	5.943	0.027	0.100	0.169
	Airborne	0.120	–	0.004	–
Final Baseline	Sump	0.154	0.138	0.097	0.017
	Surfaces	2.011	0.083	0.440	0.448
	Airborne	0.375	–	0.003	–
Totals	Sump	0.967	1.387	0.541	2.373
	Surfaces	13.996	0.409	7.375	3.912
	Airborne	1.195	–	0.434	–
	Entire test	17.158	1.796	8.350	6.285

*Estimated from cumulative sample (0.145 g) taken during this schedule only.

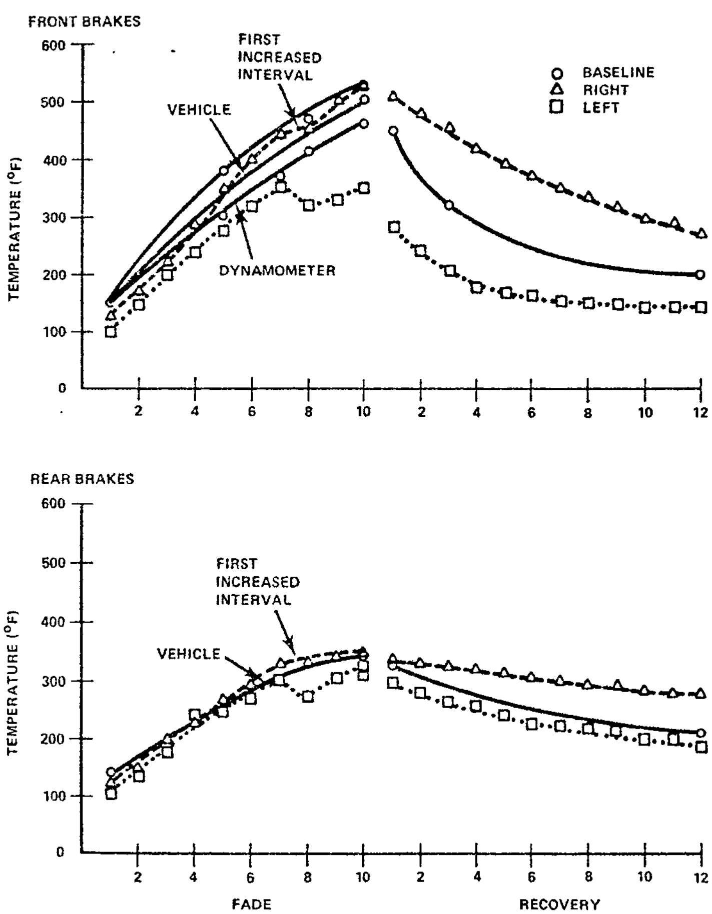

Fig. 12 - Brake temperature data during 10 Stop Fade Test

only three were in the range 0.50-0.96%; all others were less than 0.50%. The overall average was 0.25%.

For vehicle test 3, the range of asbestos content in brake emissions varies from a high of 0.51% down to a low of 0.003%. Of the analyses reported, three were in the range 0.20-0.51%; all others were less than 0.20%. The overall average was 0.07%.

For all three vehicle tests, the overall average of asbestos content in the brake emissions was 0.23%.

Independent Asbestos Analyses - To provide a systematic independent check on the asbestos analyses, the Environmental Protection Agency (EPA) arranged for Battelle Columbus Laboratories to analyze 24 samples generated during the Program. The Johns-Manville Research and Engineering Center also provided three analyses (7). In 19 of the 24 analyses, the Program results were slightly higher than the corresponding Battelle results (Table 10). The Program

Table 8 - Distribution of Emissions*, %

		Front Brakes		Rear Brakes	
Vehicle Test	Collector	Right (Shrouded)	Left (Normal)	Right (Shrouded)	Left (Normal)
1	Sump	6-31	61-83	8-22	36-65
	Surfaces	63-89	17-39	72-88	35-65
	Airborne	2-15	–	3- 6	–
2	Sump	2-20	63-83	12-22	39-63
	Surfaces	71-93	17-37	60-86	37-61
	Airborne	2-22	–	1- 2	–
3	Sump	2-38	–	9-36	–
	Surfaces	46-86	–	61-87	–
	Airborne	7-19	–	1-11	–

*The ranges give the lowest and highest percentage found for the seven driving schedules as a whole.

Table 9 - Summary of Asbestos Analytical Results–Vehicle Test 1, Weight Percent

		Front Brakes		Rear Brakes	
Schedule	Collector	Right (Shrouded)	Left** (Normal)	Right (Shrouded)	Left (Normal)
Burnish	Sump	0.813		–	**
	Surfaces	0.398		0.865	
	Airborne	0.144		0.349	
		(0.452)*		(0.607)	
A.B. Baseline	Sump	1.650		0.179	**
	Surfaces	0.472		0.415	
	Airborne	0.290		0.493	
		(0.804)		(0.362)	
Detroit Traffic	Sump	0.247		0.129	0.991
	Surfaces	0.137		0.373	0.265
	Airborne	0.052		0.092	–
		(0.145)		(0.198)	–
10 Stop Fade	Sump	0.463		0.280	0.275
	Surfaces	0.162		0.071	0.416
	Airborne	0.154		0.132	–
		(0.260)		(0.161)	–
A.F. Baseline	Sump	0.656		0.419	**
	Surfaces	0.507		0.242	
	Airborne	0.134		0.079	
		(0.432)		(0.247)	
15 Stop Fade	Sump	0.602		0.071	0.439
	Surfaces	1.548		0.257	0.472
	Airborne	0.175		0.222	–
		(0.775)		(0.183)	–
Final Baseline	Sump	0.435		0.585	**
	Surfaces	0.290		0.324	
	Airborne	0.167		0.145	
		(0.297)		(0.351)	
	Average	0.452	Average	0.301	

*Average value for wheel where collection took place.
**Not analyzed–indicates that analysis was not required.

Table 10 - Comparison of Analytical Results for Asbestos

			Front Disc Brakes			Rear Drum Brakes			Clutch	
Vehicle Test	Schedule	Collector	Program	JM	Battelle	Program	JM	Battelle	Program	Battelle
1	Detroit Traffic	Sump	0.247	–	0.21	0.129	–	0.025	–	–
		Surfaces	0.137	0.005	0.011	0.373	0.002	0.006	–	–
		Airborne	0.052	–	0.001	0.092	0.006	0.001	0.291	0.007
	10 Stop Fade	Sump	0.463	–	1.22	0.280	–	0.22	–	–
		Surfaces	–	–	–	–	–	–	–	–
		Airborne	0.254	–	0.31	0.132	–	0.007	–	–
2	Burnish	Sump	0.402	–	0.28	0.484	–	0.10	–	–
		Surfaces	–	–	–	1.416	–	0.38	–	–
		Airborne	0.186	–	0.10	–	–	–	–	–
	Detroit Traffic	Sump	0.304	–	0.62	0.249	–	0.057	–	–
		Surfaces	–	–	–	0.113	–	0.061	–	–
		Airborne	0.234	–	0.006	0.115	–	0.015	–	–
3	Detroit Traffic	Sump	0.018	–	0.135	0.046	–	0.010	–	–
		Surfaces	–	–	–	–	–	–	–	–
		Airborne	0.025	–	0.016	0.037	–	0.044	–	–
		Averages	0.204	–	0.265	0.289	–	0.077	–	–

Program average: 0.247
Battelle average: 0.171
Ratio: Battelle/Program = 0.69

average was 0.24% while the Battelle average was 0.17% or 69% of the Program average. The Program data were expected to be higher for the following reasons: All larger fibers (bundles of fibrils) found were assumed to be cylinders of projected diameter and length, and a fiber with an elliptical cross section was actually smaller in volume than reported; all fibers were assumed to be 100% asbestos.

Table 11 - Weight of Asbestos Generated During Braking–Vehicle Test 1, μg/mile

		Front Brakes		Rear Brakes	
Schedule	Collector	Right (Shrouded)	Left* (Normal)	Right (Shrouded)	Left (Normal)
Burnish	Sump	6.77		*	*
	Surfaces	9.42		58.11	
	Airborne	0.51		0.92	
	Total	16.70		59.09	
A.B. Baseline	Sump	0.04		1.01	*
	Surfaces	1.04		7.47	
	Airborne	1.15		0.74	
	Total	2.23		9.22	
Detroit Traffic	Sump	0.35		0.39	13.52
	Surfaces	1.91		10.50	1.61
	Airborne	0.09		0.18	–
	Total	2.35		11.07	14.13
10 Stop Fade	Sump	57.13		–	67.85
	Surfaces	41.77		22.11	24.35
	Airborne	1.70		0.47	–
	Total	100.60		22.58	92.20
A.F. Baseline	Sump	3.52		0.71	*
	Surfaces	25.12		4.43	
	Airborne	0.97		0.07	
	Total	29.61		5.21	
15 Stop Fade	Sump	78.89		–	*
	Surfaces	1957.40		5.47	
	Airborne	4.47		0.19	
	Total	2040.76		5.66	
Final Baseline	Sump	1.90		1.61	*
	Surfaces	24.85		4.05	
	Airborne	1.78		0.01	
	Total	28.53		5.67	

*Not analyzed.

(Partially degraded asbestos or olivine fibers were weak and mechanically reduced to nonfibrous material by the other analytical techniques; hence only the remaining asbestos fibrils were counted.)

ASBESTOS EMISSIONS TRENDS - To compare the emissions properly, it was found necessary to calculate the asbestos emission factors for each sample in micrograms/mile (Table 11). The values of these factors were obtained by multiplying the weights of brake debris generated by the appropriate asbestos percents then dividing by the miles per test schedule. Thus, either a high-asbestos content or a large sample gave a high factor. The following observations were made:

Table 12 - United States Braked Motor Vehicle Population

Private passenger cars			
(R.L. Polk estimate July 1, 1972: 83, 137, 324)			
D.O.T. estimate July 1, 1972			96,397,000
Trucks:			
(R.L. Polk estimate July 1, 1971: 18, 462, 287)			
D.O.T. estimate July 1, 1972 (includes 897,456 truck tractors)			
Light	Under 6000 lb gvw*	12,109,000	
	6000-10,000	4,952,000	
Medium	10,000-14,000	125,000	
	14,000-16,000	125,000	
	16,000-19,500	645,000	
	19,500-26,000	1,290,000	
Heavy	26,000-33,000	395,000	
	Over 33,000	1,165,000	
Buses:			
D.O.T. estimate July 1, 1972			403,000
Miscellaneous motor vehicles: motor cycles, etc.			
D.O.T. estimate July 1, 1972			3,787,000
Total motor vehicles in use**			
D.O.T. estimate July 1, 1972			121,400,000

*Gross vehicle weight; estimates from 1970-1971 sales data extended by this study.

**This total includes approximately 1.5 million public vehicles (450,000 cars, 920,000 trucks, and 185,000 buses) but does not include 190,000 Department of Defense vehicles in worldwide use.

Table 13 - Compilation of Annual Motor Vehicle Brake Friction Material Usage*

Vehicle	Description	Amount Used, No. and Unit	Weight per Unit, lb	Total Weight, lb
Passenger car	Front disc pads only	9,660,000 axle sets	1.0	9,660,000
	Front drum linings only	24,300,000 axle sets	1.8	43,700,000
	Rear drum linings only	32,400,000 axle sets	1.3	42,100,000
Light truck	Drum linings	4,730,000 vehicle sets	5.0	23,700,000
Medium truck or bus	Drum linings	670,000 vehicle sets	15.0	10,100,000
Heavy truck	Drum linings	781,000 vehicle sets	41.0	32,100,000
Miscellaneous (trailers, etc.)	Drum linings	–	–	10,000,000
				171,360,000

*Calculated from Friction Materials Standards Institute, D.O.T., and Stanford Research Institute Data.

1. Asbestos emissions were higher for new friction surfaces and decreased with use.

2. The drum brake produced more asbestos emissions than the disc brake initially with the difference decreasing as the friction materials continued in use.

3. Heavy (abusive) duty did not necessarily give a higher percent of asbestos; the large amount of debris produced, however, gave a significant rise in asbestos emissions.

4. Asbestos emissions from the brakes were found to decrease from fade or heavy-duty stops (highest) to burnish to moderate braking (lowest).

5. For the disc pads only, there was an increase in asbestos emissions with increased asbestos content in the friction material. (There was no such trend for the drum brake materials.)

6. Both the front disc pads and the drum linings of vehicle test 3 have wear comparable to that found in the other two vehicle tests, yet the asbestos emissions were significantly lower. (Both pads and secondary linings contained brass chips which may have been in part responsible for the more complete conversion of the asbestos in the brake emissions.)

7. For both disc and drum brakes the surfaces sample was the largest of the three (~92%), the sump sample was next (~7%), and the airborne sample was the smallest (~1%).

ESTIMATE FOR ASBESTOS EMISSIONS

The purpose of the following discussion is to develop an estimate of total brake and clutch emissions from the United States population of motor vehicles in use on the roads and highways. Inputs include all of the test results described earlier together with a supplementary data base on United States motor vehicle population and usage and on friction material usage and consumption obtained from other sources.

Because of the uncertainties in all of the data available, emissions can only be considered as a broad range, rather than as a single value, with the expectation that the true average emissions for both individual vehicles and the motor vehicle population in general will be within the range of values calculated below.

DATA BASE - To calculate the asbestos emissions for all vehicles it was necessary to assemble the following data base.

Number of Vehicles in Use - Table 12 lists the total United States motor vehicle population as estimated by both Department of Transportation (DOT), National Highway Traffic Safety and Federal Highway Administration (8), and by the R. L. Polk Co. (9). The Polk census is said to be more precise because it eliminates multiple registrations of the same vehicle. Polk considers that DOT estimates may be as much as 13% too high. Both Polk and DOT omit military vehicles but include all other motor vehicles that are state-licensed including police cars, school buses, and the like. Independently, the General Services Administration reports that 190,000 Department of Defense vehicles are in use worldwide. In addition, there are 6.6 million braked trailers and 38.4 million motor vehicles with dry clutches.

Motor Vehicle Usage - The approximate total number of miles traveled by all United States motor vehicles was 1.249 trillion miles for 1972 according to a recent DOT estimate (8). The average annual mileage for passenger cars is 9978 miles while for trucks it is 9807 miles.

An attempt was made to estimate the proportion of United States driving that takes place in predominantly hilly or mountainous areas where long steep grades are common. Basic data on miles driven in each state were obtained from DOT. The percentage of driving that takes place in mountainous areas, where abusive brake use may be necessary, is estimated to be 11.5% of all driving. The estimate is subjective to a large degree and may be high, but no better data have been located.

Asbestos in Friction Materials - The data in Table 13 indicate that the total amount of asbestos contained in all of the automotive brake friction materials sold each year is calculated to be about 103 million lb which corresponds to ~118 million lb used prior to grinding. Two of the most knowledgeable sources (10, 11) report that 90-120 million lb per year are used. A report from IIT Research Institute suggests that 67 million lb are used annually in brake linings (12). A Bureau of Mines Report (13) based on 1968 data credits only 50 million lb of asbestos to automotive use, a number the authors find to be much too small. Ignoring the two latter values, the three estimates of asbestos contained in brake friction materials range from 90-120 million lb. Using the calculated vehicle of 118 million lb and assuming a 15% grinding and drilling loss, the maximum amount of asbestos incorporated in brake friction materials is taken to be 103 million lb per year.

A compilation of data on clutch friction materials was also made (14). Based on these data, the total amount of asbestos contained in all automotive clutch friction materials sold each year is calculated to be about 4.5 million lb.

AMOUNT OF FRICTION MATERIAL ACTUALLY WORN - For several reasons the amount of brake lining (and asbestos) worn away during a year is significantly less than the total amount installed on vehicles. Brake linings are seldom completely worn away. (Due to the geometry of brake

Table 14 - Compilation of Calculations for Amount of Brake Friction Material Worn Away Annually

Calculation	Total Brake Friction Material, million lb
Installed weight each year	171.4
Discarded on relining, ~25%	42.7
Discarded on vehicles retired	11.7
(7 million cars × 2.38 lb × 40% = 6.7 +	
0.75 million light trucks × 5 lb × 40% = 1.5 +	
0.10 million medium trucks × 15 lb × 40% = 0.6 +	
0.15 million heavy trucks × 41 lb × 40% = 2.4 +	
miscellaneous = 0.5)	
Amount worn away annually	117.0

systems, perhaps 10% of the lining is still left on a brake when lining wear-through occurs.) Linings are usually replaced in sets rather than piecemeal. As a consequence of this and other actions about 25% of all brake linings are discarded at relining time. Furthermore, millions of vehicles are retired from service each year, many with brake linings that are far from worn out. Perhaps the average retired vehicle has about 1/3 of its usable lining remaining, or 1/3 X 90% + 10% = 40% of the installed weight of the lining. Combining these figures, the amount of brake friction material worn away each year is calculated in Table 14.

Employing the same reasoning for clutches, the amount of clutch material worn away is calculated to be 6.56 million lb.

Summarizing, the combined total of brake and clutch friction material worn away annually is 117.0 + 6.6 = 123.6 million lb. Assuming that the average asbestos content is

Table 15 - Distribution-Weighting Factors for Test Vehicle

Simulation	Test Schedule Required	Airborne (Atmosphere)	Road Dropout	Vehicle Retention
Disc brake:				
New friction couple	Burnish	0.04	0.85	0.11
After 2632 miles	Composite	0.07	0.91	0.03
After 8100 miles	Composite	0.06	0.93	0.01
After 20,000 miles	Composite	0.06	0.93	0.01
Drum brake:				
New friction couple	Burnish	0.01	0.54	0.35
After 2632 miles	Composite	0.02	0.72	0.26
After 20,000 miles	Composite	0.02	0.79	0.19

Table 16 - Severity-Weighting Factors for Test Vehicle

Simulation	Test Schedule Required	Weighting Factor
New friction couple	Burnish	0.013
Surfaces preparation	A.B. Baseline	0.013
Moderate braking	Detroit Traffic	0.934*
Severe braking	10 Stop Fade	0.020
Renewal of friction surfaces	A.F. Baseline	0.020

*Determined by difference.

Table 17 - Total Asbestos Emissions Calculated from the Test Vehicle, Average for the Three Vehicle Tests

Schedule	Friction Couple	Asbestos Emissions, μg/mile: Vehicle Test 1	2	3	Average	Per Axle	Severity-Weighting Factors	Weighted Emissions, μg/mile
	Disc brake	16.70	36.35	7.21	20.09	40.18		0.52
Burnish	Drum brake	59.09	24.43	11.67	31.39	62.78	0.013	0.82
	Clutch	–	–	–	1.11	–		0.01
	Disc brake	2.23	4.71	1.96	2.97	5.94		0.07
A.B. Baseline	Drum brake	9.22	2.38	1.98	4.52	9.04	0.013	0.12
	Clutch	–	–	–	1.11	–		0.01
	Disc brake	2.35	12.75	0.48	5.19	10.38		9.70
Detroit Traffic	Drum brake	11.07	5.50	0.63	5.73	11.46	0.934	10.70
	Clutch	–	–	–	1.11	–		1.03
	Disc brake	100.60	79.13	8.82	62.80	125.60		2.51
10 Stop Fade	Drum brake	22.58	146.14	5.03	58.15	116.30	0.020	2.33
	Clutch	–	–	–	1.11	–		0.02
	Disc brake	29.61	6.69	3.51	13.27	26.54		0.53
A.F. Baseline	Drum brake	5.21	3.28	0.32	2.94	5.88	0.020	0.12
	Clutch	–	–	–	1.11	–		0.02
							Total	28.51

Table 18 - Distribution-Weighted Asbestos Emissions from the Test Vehicle

Schedule	Friction Couple	Asbestos Emissions, μg/mile: Vehicle Test 1	2	3	Average	Per Axle	Distribution-Weighting Factors: Dropout	Airborne	Severity-Weighting Factors	Weighted Emissions, μg/mile: Dropout	Airborne
Burnish	Disc brake	16.70	36.35	7.21	20.09	40.18	0.85	0.04		0.44	0.02
	Drum brake	59.09	24.43	11.67	31.39	62.78	0.54	0.01	0.013	0.44	0.01
	Clutch	–	–	–	1.11	–	0.10	0.01		0.00	0.00
A.B. Baseline	Disc brake	2.23	4.71	1.96	2.97	5.94	0.85	0.04		0.06	0.00
	Drum brake	9.22	2.38	1.98	4.52	9.04	0.54	0.01	0.013	0.07	0.00
	Clutch	–	–	–	1.11	–	0.10	0.01		0.00	0.00
Detroit Traffic	Disc brake	2.35	12.75	0.48	5.19	10.38	0.93	0.06		9.02	0.58
	Drum brake	11.07	5.50	0.63	5.73	11.46	0.79	0.02	0.934	8.45	0.21
	Clutch	–	–	–	1.11	–	0.10	0.01		0.10	0.01
10 Stop Fade	Disc brake	100.60	79.13	8.82	62.80	125.60	0.93	0.06		2.33	0.15
	Drum brake	22.58	146.14	5.03	58.15	116.30	0.79	0.02	0.020	1.84	0.04
	Clutch	–	–	–	1.11	–	0.10	0.01		0.00	0.00
A.F. Baseline	Disc brake	29.61	6.69	3.51	13.27	26.54	0.93	0.06		0.49	0.03
	Drum brake	5.21	3.28	0.32	2.94	5.88	0.79	0.02	0.020	0.10	0.00
	Clutch	–	–	–	1.11	–	0.10	0.01		0.00	0.00
									Total	23.34	1.05

60% by weight, the amount of asbestos worn away as friction material wear debris is ~74 million lb.

WEIGHTING FACTORS - Two series of weighting factors were developed to handle the test vehicle data.

Distribution-Weighting Factors - The distribution-weighting factors were calculated from the material recoveries in the shrouded and unshrouded brakes as indicated earlier. Estimates were made for both disc and drum brakes from the test vehicle for the amounts of the different samples distributed from the brakes. These estimates were made for the Burnish schedule, for the end of a complete vehicle test, and for the end of all three vehicle tests. For the drum brake, estimates were made for up to 40,000 miles. The factors are given in Table 15.

Severity-Weighting Factors - The severity-weighting factors were calculated from the percentages of different braking modes: for new versus burnished friction materials, for severe (or abusive) versus moderate braking, and for the renewal of friction surfaces (postfade). The factors are given in Table 16

ASBESTOS EMISSION FOR TEST VEHICLES - The program results were used to develop the following estimates.

Per Mile Asbestos Emission - The total asbestos emission for the test vehicle can be estimated from the test results given earlier and the severity-weighting factors. The calculation is summarized in Table 17. The asbestos emissions for the disc brakes, drum brakes, and clutch from each vehicle test were averaged and used with the Burnish, A.B. Baseline, Detroit Traffic, 10 Stop Fade, and A F. Baseline schedules. The corresponding severity factors were used to calculate the weighted emissions. The sum of the weighted emissions is the total asbestos emission expected from an average vehicle.

Distribution - The total asbestos emissions per vehicle, as calculated above, are not merely deposited onto the ground or entirely emitted into the atmosphere. In general, the asbestos emission can and will probably end up in any of three different places:

1. Retained in the brake and/or disposed of during service.
2. Deposited on the ground.
3. Emitted to the atmosphere.

The calculation in Table 18 shows that the largest part of the asbestos emission produced is emitted from the brakes and clutch as dropout material. The fate of the total asbestos emission calculated earlier for the test vehicle is shown in Table 19.

Table 19 - Fate of Total Asbestos Emissions from Test Vehicle

Fate	Percent
Road-dropout	81.9
Airborne	3 7
Retained in brake	14.4

Table 20 - Estimated Severity-Weighting Factors for Trucks

Simulation	Test Schedule	Weighting Factor
Light truck		
New materials	Burnish	0.013
Moderate braking	A B. Baseline	0 013
Moderate braking	Detroit Traffic	0.874
Abusive braking	10 Stop Fade	0 050
Surface renewal	A.F. Baseline	0 050
Medium truck and bus		
New material	Burnish	0.013
Moderate braking	A.B Baseline	0 013
Moderate braking	Detroit Traffic	0.774
Abusive braking	10 Stop Fade	0.100
Surface renewal	A F. Baseline	0 100
Heavy truck		
New materials	Burnish	0.013
Moderate braking	A B Baseline	0 013
Moderate braking	Detroit Traffic	0.674
Abusive braking	10 Stop Fade	0.150
Surface renewal	A.F. Baseline	0.150

Table 21 - Estimated Emissions Factors for Trucks

Friction Material	Light Truck	Medium Truck (Bus)	Heavy Truck
Front drum brake	2 0	3.0	5.0
Rear drum brake	3.0	10.0	30.0
Clutch	2.0	4.0	6.0

Table 22 - Estimated Asbestos Emission per mile for Trucks

Vehicle	Asbestos Emission, μg/mile
Light truck	87.51
Medium truck (or bus)	290.72
Heavy truck	951.12

Table 23 - Total Asbestos Emission for Trucks

Vehicle	Asbestos Emissions, lb
Light trucks	32,300
Medium trucks (or buses)	16,300
Heavy trucks	32,900
Total	81,500

Table 24 - Fate of Total Asbestos Emission for Trucks

Fate	Asbestos Emission, %
Road-dropout	87.9
Airborne	2.9
Retained in brake	9.2

ASBESTOS EMISSION ESTIMATE FOR ALL VEHICLES - The test vehicle results can be extended to all passenger vehicles in the following manner.

Passenger Cars - The estimated total asbestos emission per year can be calculated from the following information:

1. Total asbestos emission per vehicle is 28.51 μg/mile.
2. Number of miles per vehicle is 9978.
3. Number of passenger vehicles is 96,400,000.

From the above, the estimated asbestos emission in pounds per year:

$$\frac{28.51\ \mu g}{\text{mile-vehicle}} \times 10^6 \frac{g}{\mu g} \times 9.978 \times 10^3 \frac{\text{miles}}{\text{year}} \times \frac{1}{454\ g}$$

$$\times\ 96.4 \times 10^6 \text{ vehicles} = 60{,}400 \text{ lb per year}$$

The distribution of the total asbestos emission calculated for the test vehicle can be determined by applying the percent distributions given earlier. The fate of the 60,400 lb calculated above for the test vehicle is shown in Table 19.

Trucks and Buses - Truck brakes usually tend to operate at higher temperatures than passenger cars. Thus a greater proportion of high-temperature use in severity weighting can be obtained by using a larger fraction of the 10 Stop Fade asbestos emission. For trucks and buses, the test results are arbitrarily weighted, as given in Table 20.

In addition to the severity factors, it is necessary to estimate the total average asbestos emission for a light truck, a medium truck (or bus), and a heavy truck. The value for the test car was 28.51 μg/mile. Assuming that trucks have results proportional to the ratios of the friction material weights, the asbestos emission for trucks are larger than for the test car by the factors shown in Table 21. A slightly larger factor is selected for the clutch as it is used more often in trucks than in passenger cars.

The estimates for the total asbestos emission per light truck, medium truck (or bus), and heavy truck were calculated using the severity and emissions factors given in Tables 20 and 21. These results are shown in Table 22. The total asbestos emission per year for light trucks can be calculated from the following information:

1. Total asbestos emission per vehicle is 87.51 μg/mile.
2. Number of miles per vehicle is 9807.
3. Number of light trucks is 17,100,000.

Estimated asbestos emission in pounds per year:

$$87.51 \frac{\mu g}{\text{mile}} \times 10^6 \frac{g}{\mu g} \times 9.807 \times 10^3 \frac{\text{miles}}{\text{year}} \times \frac{1\ \text{lb}}{454\ g}$$

$$\times\ 17.1 \times 10^6 \text{ vehicles} = 32{,}300 \text{ lb per year}$$

The estimated value for the total asbestos emission from trucks and buses is shown in Table 23.

The distribution-weighting factors for trucks were calculated based on the following considerations. The truck drum brake is designed to be more open than the car drum brake and in many instances no splash shields are used. Based on the estimates, that only about 25% as much debris remains in a truck drum brake as compared with a passenger car drum brake, distribution-weighting factors for trucks were estimated. The distribution of the total asbestos emission estimate is shown in Table 24.

SUMMARY AND CONCLUSIONS

The purpose of this program was to obtain asbestos emission data from brakes and clutches for a vehicle during actual operation. Unique emissions collectors for a disc brake, drum brake, and clutch were conceived, designed, built, and installed on a vehicle. The vehicle was driven through various test cycles to determine the extent and type of brake emissions generated at both low and high temperatures.

Typical original equipment and aftermarket friction materials for both disc and drum brakes were used in the tests. Brake relines were made to simulate consumer-type practices. The particulates were processed and analyzed by a combination of optical and electron microscopy.

Table 25 - Summary of All Brake and Clutch Emissions, pounds per years

Vehicle	No. of Vehicles	Total Asbestos Emissions	Distribution: Dropout	Airborne	Brake Retention
Passenger cars	96,400,000	60,400	49,470	2,230	8,700
Light trucks	17,100,000	32,300	28,420	940	2,940
Medium trucks and buses	2,600,000	16,300	14,330	470	1,500
Heavy trucks	1,200,000	32,900	28,920	950	3,030
Miscellaneous*	6,615,000	16,300*	14,330	470	1,500
	Totals	158,200	135,470	5,060	17,670
	Percent of total		85.6	3.2	11.2

140,530 #/yr. U.S. Total

*Estimated equal to medium trucks as weights of friction material used for both categories are almost equal (Table 12). Includes motorcycles, trailers, etc.

The range of asbestos content in the brake emissions for vehicle tests 1 and 2 went from a high of 1.65% to a low of 0.03% for the 90 analyses; only three were above 1.00%. The overall average for vehicle test 1 was 0.40% and for vehicle test 2 was 0.25%. For vehicle test 3, the range of asbestos content was from a high of 0.22% to a low of 0.003% with an overall average of 0.07%. These data are comparable to those obtained in an unpublished dynamometer study (15). In none of the samples tested in this program was a 15% asbestos content found, as reported by Lynch of the U.S. Public Health Service (16).

To compare the generation of asbestos emission properly, it was found necessary to calculate the emission factors for each sample in μg/mile. These values were obtained by multiplying the weight of generated brake debris by the appropriate asbestos percent followed by dividing by the miles per test schedule. Thus, either a high-asbestos content or a large sample gave a high factor.

The estimates of total emissions and their distribution for the test vehicle were obtained by employing distribution- and severity-weighting factors. These data were then extended to all passenger vehicles and trucks and buses in the United States. The summary of the total asbestos emission estimates and their distribution are given in Table 25. On the average, more than 99.7% of the asbestos is converted. The contribution to the atmosphere is 5060 lb, or 3.2% of the total asbestos emission. These estimates are considered to be maximum values.

The total asbestos emission estimates, and especially the airborne emissions estimate, are considerably lower than the 540,000 lb estimated by IIT Research Institute (12).

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