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Asbestos Brake Emissions

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An enclosed brake-testing machine was built to determine the importance of asbestos emissions from automobile brakes. Higher emissions resulted from disc brakes than from drum brakes due to the smaller surface area contacting the wheel in the former case. Median emissions from one disc brake were 3.3 mg particulate/stop (55% airborne, 12% sedimentary, 34% brake-entrained), 0.6 mg C/stop as hydrocarbons, 0.7 mg C/stop as CO_2, and 0.1 mg C/stop as CO. Higher emissions were observed with increases in velocity and deceleration rate. The mass median aerodynamic diameter of the emitted particles was 3.1 μm. Although the original brake material was about 50% asbestos, the emitted particles averaged only 0.029% asbestos. Therefore, it appears that over 99.9% of the mass of original asbestos fibers was broken down into nonfibrous magnesium silicates. In addition, asbestos fibers which are on the order of millimeters in length in the brake had a median length of 0.5 μm in the emitted debris. Based on the mass emission results and a stopping rate of 1.2 stops/km, it can be estimated that 2.6 μg of asbestos/km/vehicle is emitted into the air, 0.76 μg/km settles to the roadway, and 2.2 μg/km is entrained in the wheel. Although brake emissions are responsible for a minor fraction of ambient asbestos levels, there may be a noticeable increase in asbestos levels near high-braking areas such as tollbooths.

INTRODUCTION

The major component of the lining used in brakes is chrysotile asbestos, comprising 40–60% of the final product. During a lifetime of 30,000 to 40,000 miles, the material from the lining wears away and settles to the roadway, becomes airborne, or is entrained in the wheel. If the asbestos survives the braking process, there is the possibility for the release of large quantities of asbestos to the environment. Several researchers have investigated asbestos emissions from brakes with varying results. Early studies involved collecting entrained material from brakes (Hickish and Knight, 1970; Hatch, 1970). This material was found to have an asbestos content of less than 1%, indicating that the asbestos was broken down into nonfibrous magnesium silicate. However, in another study, the brake dust was removed from a brake assembly and was analyzed by X-ray diffraction which indicated an asbestos content of 2–15%, a value considerably higher than found by any other study (Rohl *et al.*, 1976). It can also be questioned whether the material entrained in the brake is representative of the material which becomes airborne.

More sophisticated studies involved the collection of airborne particles from a brake attached to a dynamometer. A study by Rowson (1978) showed the chemical constituents of asbestos (magnesium and silicon) were preserved in the wear debris, indicating that asbestos had decomposed during the braking process.

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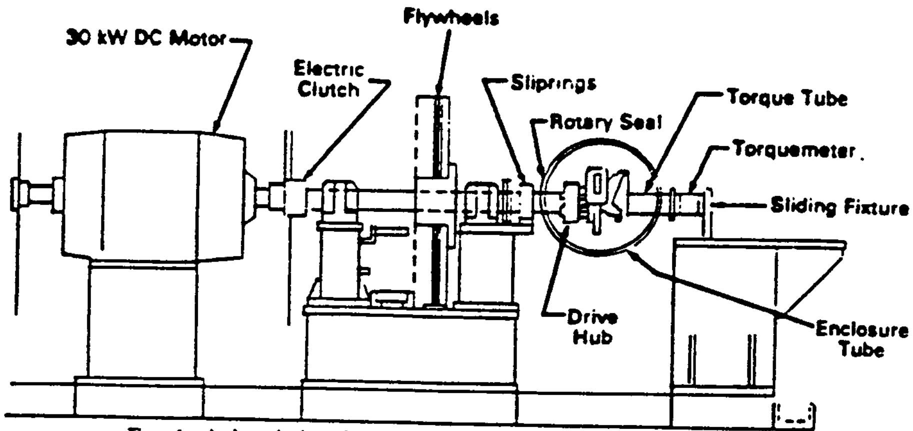

FIG. 1. A descriptive sketch of the brake-emission test dynamometer.

Lynch (1968) first used electron microscopy to identify the fibers and found levels of less than 1% asbestos in the airborne dust near a brake-dynamometer. Anderson *et al.* (1973) went one step further and used the electron microscope to quantitatively determine the asbestos in the debris and found that only 0.005% of the wear dust was asbestos fibers.

Another approach was taken by Jacko and DuCharme (1973) who constructed an enclosure around an automobile brake, thus allowing the emissions to be sampled. Their extensive testing program and electron microscope analysis indicated that 0.2% of the wear debris was asbestos.

Due to the enormous range of values of asbestos in brake emissions (0.005–15%) a study was undertaken to quantify asbestos emissions from brakes. This was accomplished with a specially designed apparatus which allowed a mass balance of all emissions to be made. The particulate samples were analyzed for asbestos using a transmission electron microscope.

MATERIALS AND METHODS

Brake dynamometer. A sketch of the brake assembly is shown in Fig. 1. A 30-kW General Electric DC drive-motor was used which was capable of accelerating the brake and wheel assemblies to speeds up to 100 ± 0.1 km/hr. A variable mass flywheel was mounted on the drive train which provided a variable inertial load equivalent to a vehicle mass from 1250 to 2500 kg. The drive shaft was fitted with a hub to engage the wheel lugs which allowed the testing of complete brake assemblies of both disc and drum type.

The wheel assemblies were mounted to a torque tube which mated with a torque meter. Torque signals to 1700 N·m were read out on a digital display. The brake system used an air-actuated hydraulic system with a maximum pressure of 10,000 kPa. Brake air pressure (pedal pressure) up to 700 kPa was controlled by a regulator. Both brake air pressure and hydraulic pressure were read out on digital panel meters. The brake was activated by a solenoid valve in the air supply line.

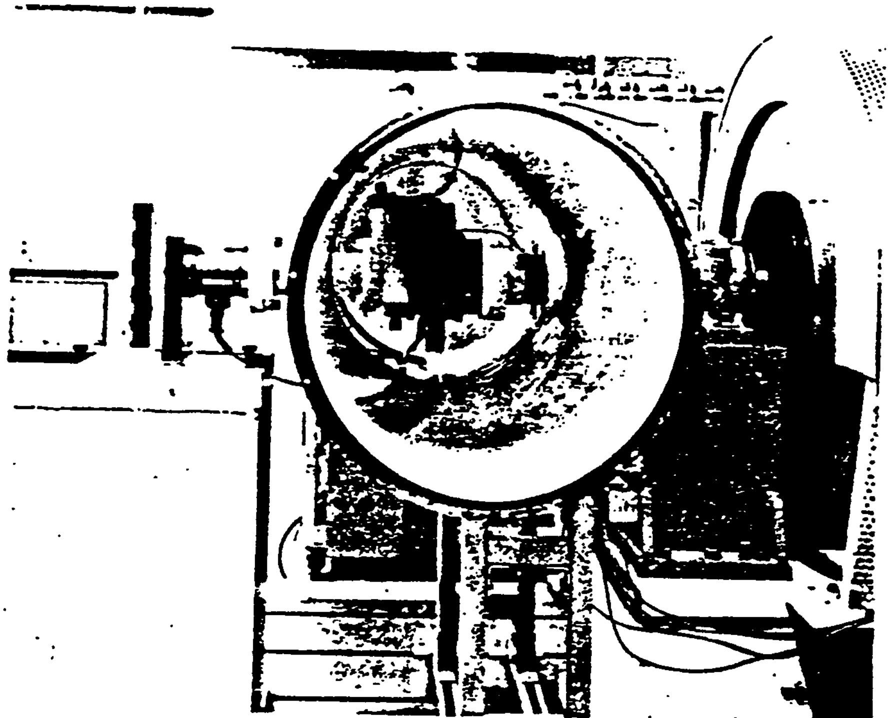

FIG. 2. Disc-brake assembly in enclosure tube.

The brake could be operated in a constant pedal-pressure mode or a constant deceleration mode.

Enclosure tube. The brake assemblies were enclosed in a sectional 0.45-m-diameter × 1.8-m-long 16-gauge steel tube coated with polyurethane paint which could be disassembled for brake cleanup. The enclosure tube and brake are shown in Fig. 2. The inlet end of the tube was fitted with a 0.6 × 0.6-m Cambridge absolute filter. Air was pulled through the tube with an American Standard air blower. A filter was also attached to the blower outlet to prevent contaminating the laboratory with brake dust.

Selection of test brake materials. The disc pads and drum linings for this test program were selected to represent high-volume production components. The disc-brake set and the drum linings used for most of the tests were new, original equipment components for standard size vehicles, i.e., 4000–5000 pounds, gross vehicle weight. Two used disc-brake sets, one with 8000 km of use and one with 60,000 km of use, were also tested. All the disc-brake results will be presented as a single set since there were no significant differences in emissions among the three sets. The friction material used for testing consisted of about 60% asbestos, 22% inorganic modifiers, and 18% organic binder by weight. An inertial load of 95.5 $kg \cdot m^2$ for the front disc brake and 53.4 $kg \cdot m^2$ for the rear drum brake was chosen as appropriate for a standard-sized automobile.

Test conditions. Three sampling modes were used for each test: a dynamic mode, a quasi-static mode, and a combined mode. The dynamic mode consisted of a brake application every 2 min and a total of 100 applications. Air was drawn through the enclosure tube at a linear velocity of 1 m/sec past the brake. This air flow was sufficient to transport particles up to 60 μm diameter to the collection site. The quasi-static mode consisted of 100 brake applications without the blower operating. The only air drawn through the enclosure tube came through the collectors. This mode resulted in an improved sample-to-background ratio. The combined mode test consisted of 60 stops in a dynamic mode, 30 stops in a quasi-static mode, and 10 stops with no air flow. The final 10 stops were used to build up the concentration of emitted gases to measurable levels. By combining all three modes, each complete test consisted of 300 brake applications. After a test was completed, the brake system was disassembled. The retained dust and the sedimentary dust were collected and weighed. The weight of the brake pads before and after each test was also recorded.

The tests were made at one of the three simulated car velocities (40, 64, and 88 km/hr) and one of four deceleration rates (1.2, 1.8, 2.5, and 4.9 m/sec^2). The temperature was measured with a thermocouple embedded in the drum or rotor. During a brake application, the temperature rose rapidly to a maximum value which depended on the type of brake and the velocity of the wheel. During the disc-brake tests, the average temperatures reached were 113, 200, and 294°C for stops from 40, 64, and 88 km/hr, respectively. For comparison, the average temperature reached for a drum brake at 64 km/hr was 145°C. In general, disc brakes reach higher temperatures than drum brakes due to the smaller surface area in contact with the rotor. In both cases, the brake cooled 20 to 40°C before the next application.

Sampling equipment. Three fractions of particles were collected, representing airborne material, sedimentary material which would settle to the roadway, and material which would remain entrained in the wheel. The sampling equipment for the airborne fraction consisted of collector devices, a set of Gast pumps, manometers, and flow meters. The sample probes attached to collector devices are shown in Fig. 3. The largest probe which was used for mass measurements withdrew 313 liters/min for deposition on a 142-mm glass fiber filter. The smallest probe was connected to a 47-mm Nuclepore or Millipore filter which provided an additional particulate sample for microscopic analysis. The third probe connected to an eight-stage Andersen impactor, which was used to separate particles according to aerodynamic diameter.

The flow rate through each sample probe was adjusted to match the velocity at the probe inlet with the mainstream velocity in the enclosure tube. This isokinetic condition ensured that the sampling was indiscriminate with respect to particle size. Using this approach, the composition of the particulate obtained in the three collector devices will be identical. The total mass of airborne particulate emitted from the brake assembly can be calculated from the mass of particulate collected by a device and its fraction of the total air flow in the enclosure tube, using the principle of proportional sampling.

Sedimentary material fell out of the brake assembly during tests, and accumu-

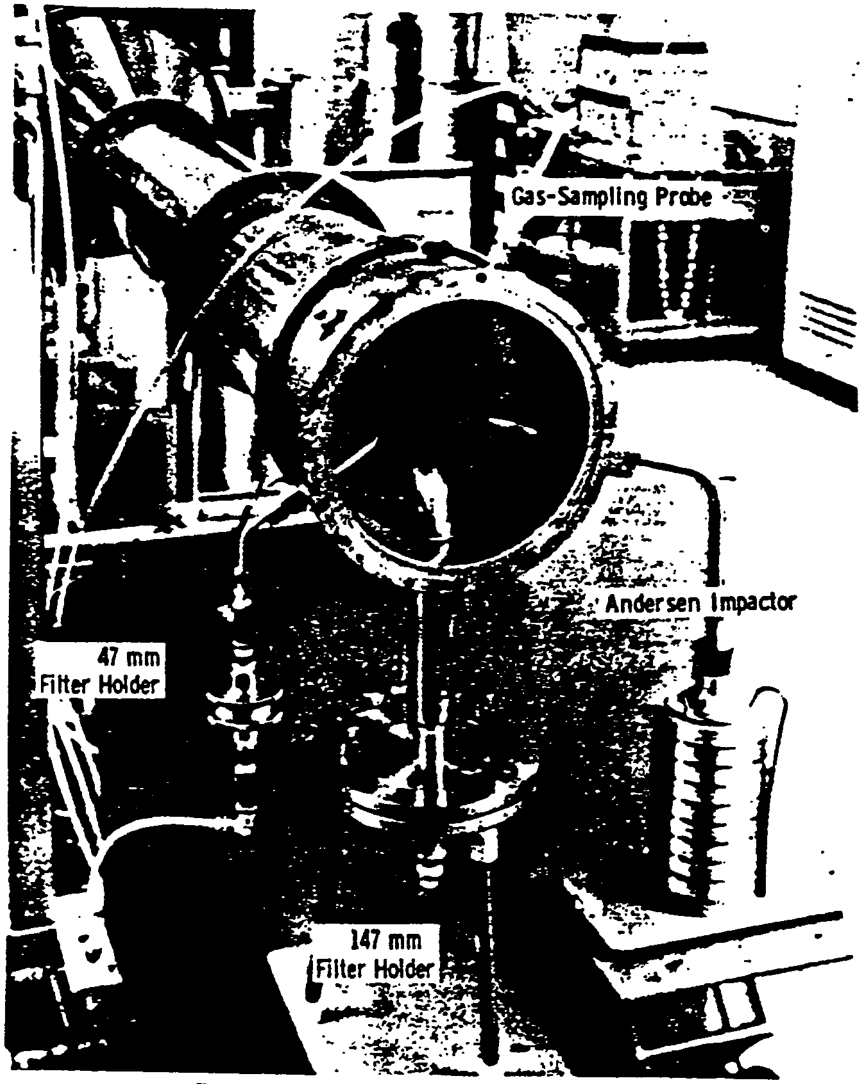

FIG. 3. Sampling probes for brake emission studies.

lated in the enclosure tube. This dust was collected in a polyethylene bottle through a short, Tygon inlet tube. The bottle was packed with glass wool and was attached to the inlet end of the hose to an industrial vacuum cleaner. This device efficiently collected the brake-wear dust which tenaciously adheres to most surfaces. The final fraction, brake-entrained material, was gently brushed into a tared vial and weighed. The vacuum device was used for final cleanup of the brake assembly, and the mass collected was added to the dust in the vial to measure the total entrained dust.

Asbestos determination. Optical microscope measurments were made using the standard OSHA procedure for counting fibers greater than 5 μm in length. Using a phase-contrast technique at magnification of 400×, 1/10,000th of the total filter area was scanned. Because asbestos fibers occur in a very wide size range, it was appropriate to consider mass concentration in addition to fiber counts. In order to make such calculations from the optical measurements, we assumed that regardless of length each fiber had a diameter of 0.25 μm and a density of 2.56 g/cm^3.

Electron microscopy was necessary for counting and sizing the smaller fibers. Transmission electron microscopy was found to be preferable to scanning electron microscopy. The method used for counting and sizing fibers consisted of the following steps:

(1) A section of the Nuclepore or Millipore filter was ashed in a low-temperature asher to remove organic material.

(2) A methanol/water mixture was added to the residue and placed in an ultrasonic nebulizer to disperse the fibers.

(3) The solution was filtered onto a 47-mm, 0.2-μm-pore Nuclepore filter.

(4) The filter was carbon-coated and placed upside down on 3 TEM grids in a petri dish containing chloroform to dissolve the filter.

(5) Two of the three grids were observed with a TEM at a magnification of 20,000×. Asbestos fibers were counted and sized in 10 grid holes of each grid. If the fiber was noticeably deformed, a selected-area electron diffraction pattern was taken to confirm its integrity.

(6) From the volume of the fibers and the density of asbestos, the mass of asbestos was calculated. The repeatability between the two grids averaged 32%.

RESULTS

The results will be divided into two sections. The first will describe the gaseous and particulate mass measurements under various conditions. The second portion will describe the results of the asbestos analysis.

Particle and Gaseous Emissions

The average results of the disc and drum tests are shown in Table 1. The particle mass is divided into airborne, sedimentary, and entrained mass. The sedimentary and entrained portions were only collected during the disc-brake tests because considerable material was lost when the drum brake was disassembled. On the average, 90% of the mass lost by the brake could be accounted for in the total emissions, which was considered to be a good recovery.

In general, the emissions were higher from disc brakes than drum brakes for a given set of conditions. Median airborne particulate emissions were 1.6 mg/brake/stop compared to 1.1 mg/brake/stop from drum brakes. Since disc brakes have a smaller friction surface area, they tended to wear faster, producing higher emissions. Median emissions from one disc brake were 3.3 mg particulate/stop, 0.6 mg C/stop as hydrocarbons, 0.7 mg C/stop as CO_2, and 0.1 mg C/stop as CO. The particles were approximately fractionated into 55% airborne, 12% sedimentary, and 34% brake-entrained material. These values were considerably different than those of Jacko and DuCharme, i.e., 7–15% airborne, 63–79% sedimentary, and 7–15% brake-entrained. The differences are probably due to the differences

TABLE 1

AVERAGE EMISSIONS FROM BRAKES (mg/BRAKE/STOP)

Number of tests	Velocity (km/hr)	Deceleration (m/sec ^{2})	Particle emissions			Gas emissions		
			Airborne	Sedimentary	Entrained	HC	CO_2	CO
Disc brakes								
2	40	1.85	0.81	0.14	0.61	0.09	0.2	0.04
2	40	2.50	0.87	0.37	0.58	0.07	0.03	0.04
2	40	4.90	0.70	0.22	0.54	0.08	0.09	0.04
1	64	1.20	1.5	0.12	1.3	0.58	—	—
4	64	1.85	1.8	0.31	1.2	0.63	1.44	0.35
1	64	2.50	2.0	0.17	1.2	0.87	—	—
1	64	4.90	2.4	0.38	1.4	0.96	—	—
4	88	1.85	12.0	3.1	3.3	2.8	6.2	2.7
Drum brakes								
3	40	1.85	0.81	N.D.[a]	N.D.	0.11	0.28	0.08
2	40	4.90	2.8			0.05	0.09	0.04
1	64	1.20	0.75			0.29	0.84	0.23
2	64	1.85	1.1			0.52	0.60	0.32
1	64	2.50	1.1			0.85	2.4	0.56
1	64	4.90	1.6			0.46	—	0.27
2	88	1.85	2.7			0.87	1.3	0.35

[a] Sedimentary and entrained particles were not determined for drum brakes, as explained in the text.

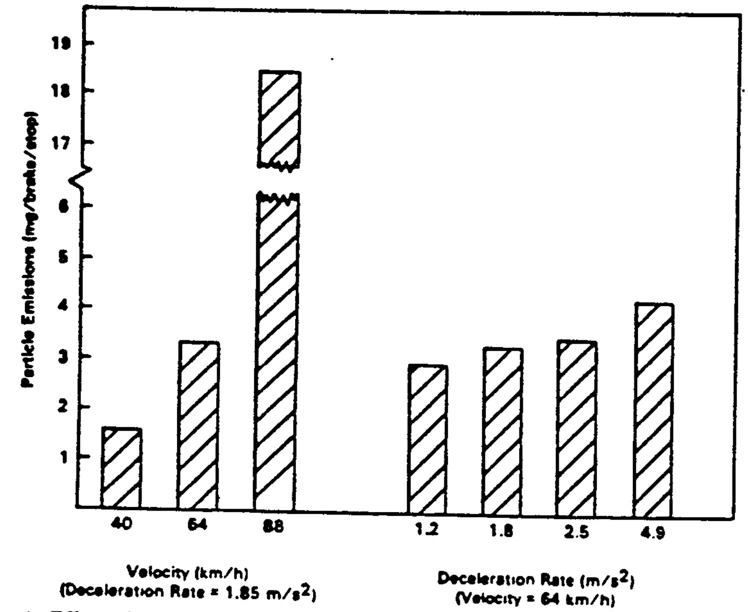

FIG. 4. Effect of velocity and deceleration rate on particle emissions from a disc brake.

in sampling. Our test schedule may have overestimated brake-entrained material since the brake was cleaned out after each test. After prolonged usage, the available surfaces would be filled causing additional dust to settle to the roadway or become airborne, On the other hand, it is possible that the sedimentary portion found by Jacko and DuCharme was overestimated. The shroud surrounding their

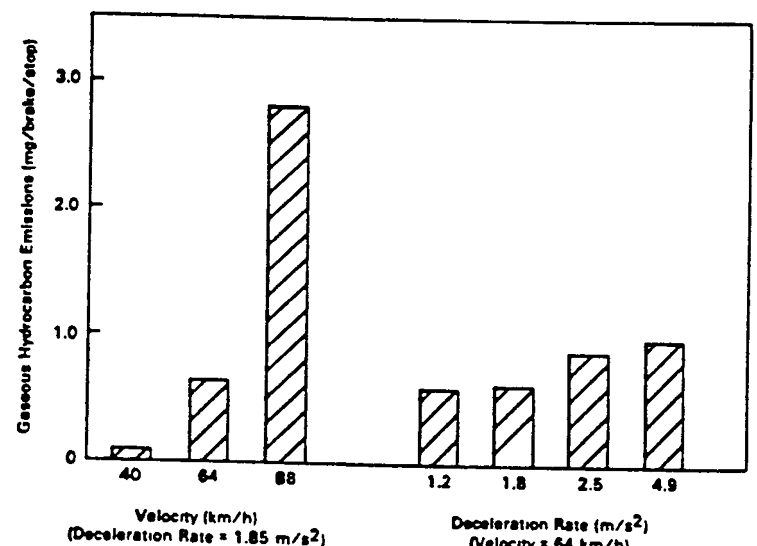

FIG. 5. Effect of velocity and deceleration rate on gaseous hydrocarbon emissions from a disc brake.

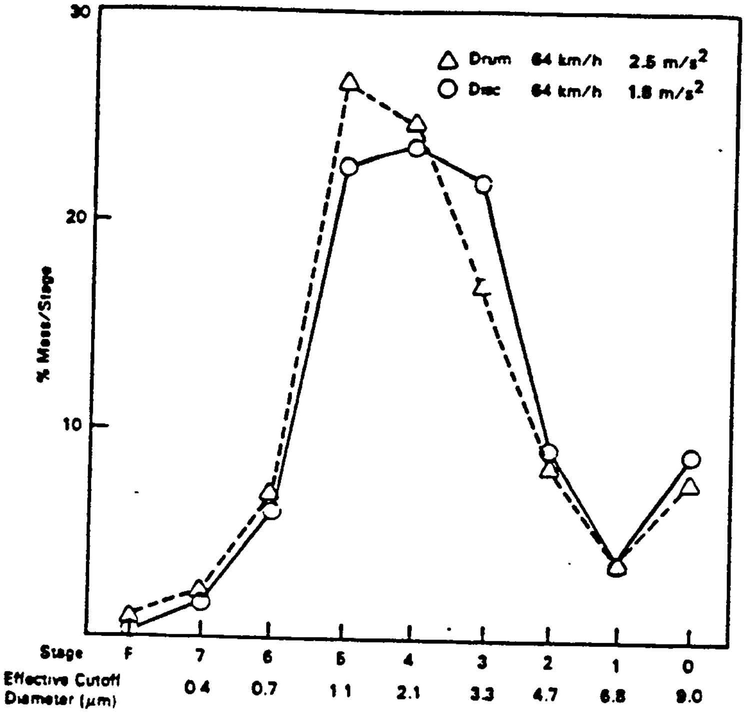

FIG. 6. Size fractionation of airborne brake particulate emissions.

brake system created artifically high surface areas for impacting material which otherwise might become airborne.

Velocity and deceleration effects. The effect of increasing velocity and deceleration rate on particle emissions from a disc brake is shown in Fig. 4. As velocity is increased with the deceleration rate held constant, the particle emissions increase rapidly. Gaseous emissions increase even more rapidly, as shown in Fig. 5, for hydrocarbons. For instance, at a deceleration rate of 1.85 m/sec^2, a doubling of the velocity causes a 12-fold increase in particulate mass, a 31-fold increase in hydrocarbons, a 31-fold increase in CO_2, and a 68-fold increase in CO. The increased gas-to-particle ratio at higher velocities suggests that a thermal-wear mechanism becomes more important while abrasive wear dominates at low velocities. Increased deceleration rate also caused increased emissions, but the effect was much smaller than for velocity. A quadrupling of the deceleration rate at 64 km/hr only increased particle emissions by 1.4 times and hydrocarbon emissions by 1.7 times.

Size distribution. Several cascade-impactor tests were made to determine the size distribution of the airborne particulate. Particle size distributions for typical drum- and disc-brake tests are shown in Fig. 6. The distributions are basically identical, peaking between 1 and 2 µm. The mass-median aerodynamic diameter averages 3.1 µm for the 10 impactor tests with the submicrometer mass making up only 10% of the total mass.

TABLE 2
AVERAGE ASBESTOS EMISSIONS FROM BRAKES

Velocity (km/hr)	Deceleration rate (m/sec²)	Number of tests	Percentage asbestos	
			Range	Mean
Disc brakes				
40	1.8	1		0.004
40	4.9	2	0.0033–0.014	0.0087
64	1.2	1		0.016
64	1.8	4	0.00095–0.18	0.049
64	2.5	4	0.0028–0.11	0.038
64	4.9	4	0.0021–0.056	0.027
65	0.3	4	0.0032–0.052	0.025
88	1.8	3	0.0027–0.0085	0.051
Drum brakes				
40	1.8	2	0.0046–0.025	0.015
40	2.5	1		0.0075
40	4.9	4	0.040–0.098	0.065
64	1.2	2	0.0055–0.0081	0.0068
64	1.8	4	0.0053–0.034	0.013
64	2.5	2	0.0028–0.0093	0.0060
64	4.9	4	0.0020–0.087	0.026
88	1.8	5	0.0040–0.19	0.051

Asbestos

Twenty-three filters from disc-brake tests and 24 filters from drum-brake tests were analyzed for asbestos fibers using both optical microscopy and transmission electron microscopy. The ratio of small fibers which can be seen with an electron microscope (less than 5 μm in length) to large fibers as determined with an optical microscope (more than 5 μm in length) was about 460 from disc brakes and 230 from drum brakes. Obviously, most fibers will be missed if the only analytical technique used is optical microscopy. Although the large fibers are few in number, they contribute almost twice as much mass as all of the small fibers. The small fibers dominate the number distribution while the large fibers dominate the mass distribution. The average asbestos concentrations found for each set of velocity and deceleration conditions are shown in Table 2. The large range found within a set results from the enormous effect of large asbestos fibers. Typically, only 0, 1, or 2 large fibers were seen in the counting area, but they greatly affected the mass when extrapolated to the entire filter.

The disc-brake test results ranged from 0.00095 to 0.18% asbestos, with an average of 0.027%. The drum-brake test results ranged from 0.0020 to 0.19%, with an average of 0.031%. There is no significant difference between the asbestos fraction from drum or disc brakes. In addition, there are no significant trends in asbestos content with deceleration rate or velocity. However, since the total particle emissions increase at higher deceleration rates and velocities, the asbestos emissions also increase.

Assuming an initial asbestos content of 50% in the brakes and a final asbestos content of 0.029%, over 99.9% of the asbestos has been broken down to nonfibrous material during the braking process. This is in agreement with the work of Jacko and DuCharme (1973) and Anderson *et al.* (1973). The particles entrained in the wheel and the sedimentary particles had a slightly higher asbestos content (0.04%) than the airborne particulate. The median length of the airborne asbestos fibers was 0.5 μm. This can be compared to the average fiber length in brakes, which is on the order of millimeters in length.

The average mass emission of particles from one disc brake is 3.3 mg/brake/stop of which 55% is airborne, 12% sedimentary, and 34% entrained. Based on four brakes/vehicle and an asbestos content of 0.030% in the airborne material and 0.040% in the sedimentary and entrained material, the total asbestos emission per vehicle per stop is 2.2 μg airborne, 0.63 μg sedimentary, and 1.8 μg entrained asbestos. Based on an average of several different driving cycles, there are about 1.2 stops/km (2.0 stops/mile) (Jacko and DuCharme, 1973). Therefore, the total asbestos emission is 5.5 μg asbestos/km, of which 2.6 μg/km is airborne, 0.76 μg/km settles to the roadway, and 2.2 μg/km becomes entrained in the wheel.

DISCUSSION

It is possible to use these asbestos emissions to calculate the influence of braking on ambient asbestos levels. This will be done for three situations: (1) total nationwide asbestos emissions, (2) typical urban asbestos levels, and (3) the situation near a tollbooth where a large amount of braking occurs.

Nationwide Asbestos Emissions

There were 114,000,000 registered automobiles in the United States in 1977, averaging 16,000 km each for a total of 1.8×10^{12} km traveled (MVMA, 1978). If airborne asbestos emissions from autos are 2.6 μg/km, annual nationwide emissions are 4.7 metric tons. This can be compared to annual estimates of man-made disposals and emissions of asbestos to the air of 2093 metric tons (Levine, 1978). Therefore, brake usage is responsible for approximately 0.2% of total asbestos emissions.

Urban Asbestos Emissions

The input of asbestos from braking to urban ambient concentrations can be determined by comparing with lead emissions from cars and urban lead concentrations. This comparison assumes that the major source of lead in the atmosphere is leaded gasoline and that particulate lead and asbestos fibers will behave the same in the environment. Between 1970 and 1974 when all cars used leaded gasoline, the average lead content of gasoline was 0.571 g/liter and the average fuel economy was 5.13 km/liter (U.S. EPA, 1977). Huntzicker (1975) estimates that 75% of the lead in the fuel is emitted as airborne particulate matter for a lead mass emission rate of 0.083 g/km. The average lead concentration in the 1960s in three urban areas was 2.4 μg/m³ in Los Angeles, 1.4 μg/m³ in Cincinnati, and 1.6 μg/m³ in Philadelphia (Landau, 1969). We will use an average urban lead concentration of 2 μg/m³. Based on our airborne asbestos emission rate of 2.6 μg/km and by comparing to lead, an expected urban concentration due to braking of 0.063 ng/m³ can be predicted. This is a small fraction, 0.06 to 0.6%, of the measured urban asbestos concentrations of 10–100 ng/m³ (Nicholson *et al.*, 1971).

Tollbooth Asbestos Values

In areas of high braking such as near tollbooths, ambient asbestos concentrations may be affected as was shown in Connecticut (Bruckman and Rubino, 1974). Ambient asbestos concentrations of 25 ng/m³ were measured near a tollbooth through which 55,000 cars passed per day. Based on our emissions experiments and dispersion estimates from the General Motors Sulfate Dispersion Experiment (Cadle *et al.*, 1977), it is possible to estimate the fraction of asbestos resulting from braking.

During the sulfate dispersion experiment, 5500 cars per hour passed the sampling point with average sulfate emissions of 23 mg/car/km for an emission rate of 127 g/km/hr. This emission rate resulted in a maximum increase in ambient concentration of 15 μg/m³. At the tollbooth, 55,000 cars passed through in a 24-hr period, or 2300 cars per hour. To relate our results to the tollbooth situation, we will assume an average deceleration rate of 2.4 m/sec² from 88 km/hr, which corresponds to a deceleration time of 10 sec and a stopping distance of about 120 m. Braking from 88 km/hr leads to airborne particle emissions of 29 mg/car/stop and asbestos emissions of 8.4 μg/car/stop. As a result, the asbestos emission rate in the braking zone is predicted to be 160 mg/km/hr. Comparing this to the roadway experiment, the maximum expected asbestos concentration would be 19 ng/m³. Therefore, a significant fraction of the 25 ng/m³ concentration at the Connecticut tollbooth could arise from braking.

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