# FINAL REPORT

# Determination of Asbestos Content of Current Automotive Dry Friction Materials, and the Potential Contribution of Asbestos to Particulate Matter Derived from Brake Wear

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## Disclaimer

The statements and conclusions in this report were those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

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## Abstract

Motor vehicle brake dust emission rates and brake friction material inventories of asbestos, a known carcinogen, are currently largely unknown. Assessment of the potential health effect consequences from asbestos brake friction materials (BFM) requires the identification of the asbestos fiber type and classification of fiber size, as well as, the determination of the asbestos concentration in brake dust emissions. Field collection of used brake shoes from likely target vehicles indicates that very high levels of chrysotile asbestos (20-60% by mass) are still present in brake friction material (BFM) for some models, primarily in rear drum brakes. Similar to deposited dust collected from the braking system surfaces of these target vehicles, air emissions for a test vehicle operating over standard dynamometer emission cycles contained chrysotile fibers < 10 um length. Due to apparent frictional heating effects, less than 1% of the asbestos mass originally present in the BFM can be identified in both the deposited brake dust, and the airborne brake dust emission during test vehicle chassis dynamometer driving cycles. However, health effects concerns associated with the measurable level of small asbestos fibers in the air emissions may warrant early brake replacement, before warranted by wear, with the now widely available non-asbestos BFM, for a group of target vehicles, with brake shoes installed before calendar year 2000.

## Executive Summary

Although the USEPA instituted a ban on the production of most products containing asbestos in 1989, automotive dry friction materials (ADFM) including disc brake pads, and drum brake linings were subsequently exempted from the ban in 1991. Motor vehicle brake dust emission rates and brake friction material inventories of asbestos, a known carcinogen, are currently largely unknown. Assessment of the potential health effect consequences from asbestos brake friction materials (BFM) requires the identification of the asbestos fiber type and classification of fiber size, as well as, the determination of the asbestos concentration in brake dust emissions. Based on knowledge of the California registered vehicle population, and those pre-year 2000 vehicles likely to have asbestos containing BFM, a vehicle target list was used to collect used brake shoes for asbestos analysis by polarized light microscopy (PLM).

A 1985 Chevrolet van from the target list, determined to be equipped with asbestos BFM, was chosen as a representative vehicle for chassis dynamometer based brake dust emissions testing. Brake dust emissions were collected with a new split section dilution tunnel, attached to the vehicle undercarriage, which allowed the brake dust emissions to be dispersed into an air stream filtered by a high efficiency particulate air (HEPA) filter. The downstream tunnel section transported the brake dust aerosol to a sampling array consisting of a total filter, cyclone train, and optical particle counter. The total filter was used for BFM air emission mass determination. Asbestos analysis by transmission electron microscopy (TEM) was conducted on emitted dust aerosol samples collected with a cyclone sampling train designed to provide PM10 and PM2.5 fractions. TEM analysis included the measurement of length, and aspect ratio of each fiber identified as asbestos. For comparison, TEM analysis for asbestos fibers was also performed on the portion of brake dust retained inside the braking system. Sampling of the brake dust emissions from the vehicle operated on the chassis dynamometer was conducted over both California and Federal standard driving cycles, designed to model typical vehicle accelerations, decelerations, speeds, and braking patterns. During driving cycles, sensors were used to continuously record braking surface temperature, brake system hydraulic pressure, vehicle velocity, and optical particle counter channels for the size range between 0.3 and 10 um.

PLM analysis of used asbestos BFM collected from target vehicles currently in operation, determined chrysotile asbestos to be the primary constituent by mass, consistent with the manufacturer’s specifications. From the TEM analysis, deposited dust collected from the braking system surfaces of these target vehicles all contained chrysotile fibers < 10 um length. Most fibers counted were < 1um length; however, sufficient longer fibers were present for the mass distribution to extend to much longer fiber lengths. Based on the TEM fiber counting and sizing, less than 1% of the asbestos mass originally present in the BFM can be identified in the brake dust deposit. This was consistent with the low levels of asbestos mass determined in both the deposited brake dust and the airborne brake dust emission during chassis dynamometer driving cycles with the Chevrolet test vehicle. In general, the number distribution of airborne fiber length and mass were similar to those for the deposited brake dust collected from the brake system surfaces, with some variation due to driving cycle type and duration.

Field collection of used brake shoes from likely target vehicles indicates that high levels of chrysotile asbestos BFM is still present in some models, primarily in rear drum brakes. The braking system temperature observed in this study, monitored during chassis dynamometer driving cycles, was well below the level expected to denature chrysotile asbestos, and cannot explain the low levels of asbestos in the deposited and emitted brake dust. However, distinct changes in morphology and electron diffraction pattern which were observed along the length of chrysotile fibers, suggest that sufficiently high temperatures can be reached, perhaps due to the friction forces generated at asbestos fiber asperities in the BFM surface.

The level of asbestos in the deposited dust collected from the test vehicle and the PM10 air emissions from the Federal LA4 driving cycle were comparable at under 0.02% by mass, yielding an asbestos air emission rate of 42 ng/mile for the rear drum brake axle and 103 ng/mile for the entire vehicle using the scaling factor 2.45 for a vehicle with both front disc and rear drum brakes with asbestos. Although the asbestos mass fraction in the PM10 air emissions for the California driving cycle was significantly lower (0.007%), the higher air borne brake wear mass produced yielded a much higher asbestos air emission rate of 205 ng/mile-drum brake axle or 503 ng/mile-disc and drum brake axles. Of particular note was the PM2.5 fraction, which contained the highest asbestos levels as a percentage of mass for both driving cycles. These levels were significantly lower than the asbestos air emission value of 3820 ng/mile disc and drum brake axles calculated by Cha et al. (1983) for the 1972 Chevrolet Impala, which was operated over repetitive braking cycles rather than a standard emissions cycle.

Screening levels have been identified by USEPA using the AHERA (Asbestos Hazard Emergency Response Act ) permissible air limits of 0.01 fibers/cc for asbestos fibers > 5 um length, and 0.03 fibers/cc for asbestos fibers ≥ 0.5 um length. The mode for the concentration of airborne asbestos fibers emitted during both the California and Federal driving cycles, for the Chevrolet van test vehicle occurred at 0.5 um. The airborne PM10 concentration for fibers ≥ 0.5 µm length, exceeded the AHERA standard by nearly a factor of five (0.14 fibers/cc) with the UC/LA92 driving cycle. Considerably lower PM10 emissions of fibers ≥ 0.5 um length (0.022 fibers/cc) for the Federal LA4 cycle was 2/3 of the AHERA action level. For both emission cycles, the PM 2.5 fraction contained most of the asbestos fibers both when all fibers lengths were included and only fibers ≥ 0.5 µm in length.

Although over the last few years domestic manufacturers have apparently eliminated asbestos as an ingredient in BFM formulations, friction material manufacturers were considering an increase in the production of asbestos-based products. In addition, the asbestos-free BFM formulations need to be thoroughly investigated to determine the presence of substitute friction modifiers, such as crystalline silica or carbon fiber, which may present as great a health hazard as asbestos. Mitigation of the current health hazard associated with airborne asbestos exposure could utilize an early brake replacement program for target vehicles likely to employ asbestos BFM.

# 1. Introduction

## 1.1 Scope and Purpose

Since the automotive dry friction materials (ADFM) including disc brake pads, drum brake linings, and clutch facings, were exempted from the 1989 United States Environmental Protection Agency (USEPA) ban on asbestos-containing materials, the prevalence of asbestos in the ADFM has been uncertain. The continued interest in the use of asbestos in ADFM stems from the unique properties of asbestos, which allow manufacturers to formulate inexpensive brake linings with superior performance. Asbestos based ADFM offer the advantages of low noise and consistent braking efficiency independent of operating temperature. Federal safety regulations concerning braking performance have allowed continued use of asbestos in ADFM, especially in applications where a suitable substitute has not been qualified for equivalent performance.

The objective of this study was to assess the prevalence of asbestos in automotive brakes, and to obtain information that can be used to determine asbestos emission rates due to brake wear from vehicles currently on the road in California. The key elements of the objective include the identification of asbestos-containing ADFM currently utilized in braking systems, and the determination of the asbestos composition of dust produced by vehicle brake wear from these ADFM. From a public health perspective, this study would provide a preliminary assessment of the need to allocate further resources to the investigation of asbestos from ADFM.

Although several studies have been conducted on brake wear emissions, the proportion of vehicle brakes containing asbestos, as well as, the composition of asbestos in the brake lining material formulation, is currently unknown. More importantly, a thorough characterization of the asbestos fibers present in the brake dust, released from the variety of different ADFM currently available, has not been conducted. Assessment of the potential health effects consequences requires the identification of the asbestos fiber type and classification of fiber size, as well as, the determination of the asbestos concentration in brake dust emissions.

Through this survey project, representative information on the nature and use of current automotive brake lining products containing asbestos was investigated, and verified through direct laboratory analysis of ADFM. Characterization of the form, particle size, and level of asbestos present in brake dust generated from ADFM was sought to provide the background necessary to consider regulatory control to protect the public health. Brake wear asbestos emission rates as a fraction of total brake dust were also investigated to allow an estimate of the PM inventory contribution from brake wear asbestos emissions statewide.

## 1.2 General Background

Motor vehicle emission rates and inventories of asbestos, a known carcinogen, are currently unknown. Although the USEPA instituted a ban on the production of most products containing asbestos in 1989, ADFM including disc brake pads, drum brake linings, and clutch facings were subsequently exempted from the ban in 1991.

Asbestos brake linings were supplied as original equipment on some domestically produced vehicles as recently as the late 1990s. ADFM containing asbestos is reported to have been used in some high-end import vehicles and have been widely available as aftermarket brake replacement parts. The most recent industry surveys available (Brauer, 1998) suggest that as much as half of the aftermarket ADFM may contain asbestos, which yields superior performance in drum brake applications on heavier vehicles such as sport utility vehicles (SUVs). Accordingly, an assessment of the current contribution of motor vehicles to the statewide emission inventory of asbestos is required for the California Air Resources Board (CARB) to consider the necessity for regulatory control.

### 1.3 Current Knowledge

Brake wear emissions have been estimated to account for approximately 23% of the total statewide on-road emissions of motor vehicle PM10 (EMFAC2000, version 2.02). This estimate is based on the USEPA Part 5 model, which assumes a constant emission factor for brake wear as 0.0128 g/mi for all vehicles, with 98% of the particles considered to be in the PM10 size fraction. Cha et al. (1983) originally reported this brake wear emission factor based on laboratory measurements of airborne and deposited particulate matter (brake dust), generated from asbestos-containing ADFM under braking for a1972 Chevrolet Impala driven over a non-standard emissions driving cycle.

In general agreement with other studies (Jacko, et al., 1973 and Williams and Muhlbaier, 1980), these measurements indicated that airborne particle emissions represented approximately one-third of the total brake wear mass, with the remainder consisting of particles deposited in the braking system. From transmission electron microscope (TEM) analysis for asbestos fibers in the brake wear emissions, estimates of the asbestos present in the airborne and deposited particulate fractions were considered to be similar to the distribution of total brake wear generated mass in these fractions. Accordingly, from Cha et al., 11.9 ug/mi of total asbestos emissions is comprised of one-third airborne emissions (3.82 ug/mi), with the difference present in the deposited particles (8.08 ug/mi).

More recently, measurements of brake wear particulate emissions, utilizing non-asbestos ADFM with a wide variety of compositions (Garg, et al., 2000), also indicated that about one-third of the brake wear mass is emitted as airborne particles. Based on the similar elemental compositions of the airborne particle matter and deposited brake dust, Garg, et al., suggested that the mass composition of the deposited brake dust could serve as a predictor of the airborne emission.

### 1.4 Research Problem

A primary intent of this study was to provide an initial assessment of the prevalence of asbestos in ADFM utilized in the braking systems of passenger cars (PC), light duty trucks (LDT), medium duty trucks (MDT), and a representative set of heavy duty trucks (HDT), currently on the road in California. Such an assessment was to utilize existing surveys of the ADFM industry to focus the research on those brake lining products which were most likely to contain significant levels of asbestos.

Accordingly, initial efforts by the Environmental Health Laboratory Branch (EHLB), and the subcontractor, Sierra Research Incorporated (SRI), were to first concentrate on the investigation of asbestos ADFM utilized in the aftermarket for most drum brakes, and some disc brakes. Other resources to be utilized in identifying prevalent asbestos-containing ADFM included: direct contact with the manufacturers, local brake shops, material safety data sheets (MSDS) obtained from ADFM manufacturers, and the Friction Materials Standards Institute (FMSI), which keeps a record of the asbestos content of all ADFM products on the market. The MSDS is an important source for identifying asbestos containing ADFM, since by federal regulations (U.S. Department of Labor, 1970) the manufacturer would be required to file an MSDS identifying the ADFM asbestos content as a health hazard.

This assessment of candidate ADFM brake products was to be used to identify a limited set of asbestos-containing ADFM brake linings for detailed laboratory analysis. Local brake shops were to be used to collect field samples from those popular vehicles known to have a high probability of utilizing asbestos-containing ADFM, such as a large SUV with rear drum brakes. Samples of the interior bulk ADFM from used brake linings and the associated brake dust were to be analyzed for asbestos by both optical and electron microscopy.

Characterization of the form, particle size, and composition of asbestos in specific brake ADFM was to be compared with the corresponding properties of the asbestos present in brake dust sampled in close proximity to the friction surface. This comparison was crucial to understanding the relationship between the characteristics of the asbestos present in the ADFM, and the asbestos released in the brake dust by high-temperature abrasion. The sampling and analysis strategies employed in the field were first to be validated using samples collected from test vehicles operated on the chassis dynamometer facility at Sierra Research. Standardized dynamometer driving cycles were to be used to produce realistic repetitive braking conditions, in order to conduct air sampling for the characterization of fugitive asbestos brake dust emissions.

Due to the limited scale of the proposed study, a comprehensive assessment of the asbestos emissions from all ADFM currently in use on California roadways was beyond the scope of the current investigation. Rather, the study design utilizes the acquisition of existing information on the prevalence of asbestos in ADFM, in order to selectively target for study those vehicles most likely to generate a significant portion of the asbestos ADFM emissions statewide. This approach was intended to provide an initial assessment of the potential magnitude of asbestos fiber emissions from vehicle brakes, now that ADFM is one of the few unregulated anthropogenic sources of airborne asbestos fibers.

## 2. Materials and Methods

The study consisted of four major research task components as follows:

1. Develop an inventory of asbestos-containing ADFM utilized in braking systems, their frequency of use by vehicle class, and their prevalence based on a sample population of currently registered vehicles. This database also included the frequency of disc versus drum brakes in the rear versus front vehicle position.
2. Establish an analysis scheme to characterize asbestos fibers in brake friction material (BFM) and brake dust, using the techniques of visible light microscopy (phase contrast and polarized), electron microscopy (transmission and scanning), as well as energy dispersive spectroscopy, and electron diffraction on individual fibers.
3. Develop the methodology to institute a brake sampling program with local auto repair shops to collect used BFM and the associated brake dust from specific vehicle makes and models with a high probability of containing significant asbestos levels.
4. Characterize the asbestos composition of the brake ADFM and brake wear-generated dust collected from vehicles including: the asbestos fiber type, fiber size distribution, and concentration as a percent of total mass.

A summary of the facilities utilized in the research project are given in **Appendix A**. The subcontractor, Sierra Research, provided elements of tasks 1 and 3. For task 1, this included an inventory of vehicles originally designed to utilize asbestos-containing BFM, and assisting EHLB to develop a list of target vehicles for BFM field sampling. For task 3, this included operating a target test vehicle with asbestos BFM through dynamometer braking cycles, to allow EHLB to collect brake dust air emissions for comparison to the brake dust deposited on brake surfaces, and to the bulk BFM.

## 2.1 Research Approach Overview

The research approach utilized asbestos analysis of the particulate matter deposited within braking systems (brake dust) in order to provide a first order estimate of the mass fraction of asbestos fibers present in the airborne emission. From an estimate of the asbestos mass fraction, the asbestos fiber emission rate could then be readily calculated from established braking system mass emission rates. Equally important was the analysis of the asbestos content of the bulk ADFM, for comparison with the asbestos emissions produced from this source material under braking. Although the asbestos content of ADFM has typically been between 20-60%, previous measurements (Seshan and Smith, 1977) found less than 1% asbestos in the particulate matter generated by brake wear. Presumably this was the result of high temperature conversion of the asbestos fibers to other forms such as forsterite. For the purposes of this study, asbestos analysis of the bulk ADFM in used brake linings can be compared with the asbestos content of the associated brake dust to develop a useful predictor of the asbestos fibers which survive the braking process to become brake wear emissions. Analysis of the used brake ADFM was also necessary to verify the asbestos content of those brake linings chosen for field collection of the associated brake wear dust.

Selection of vehicles for the field collection of used brake linings and the associated brake dust was to be based on a high probability of significant asbestos present in the

ADFM.  Preliminary contacts with the ADFM industry (Friction Materials Standards Institute) by EHLB, suggested that the prediction of asbestos content in ADFM utilized in a class of vehicles can be based on several key factors including: type of brake system (disc or drum), drive train type (front or rear drive), vehicle weight, and ADFM source (aftermarket or original equipment).  Based on this approach, the highest probability for identifying ADFM containing asbestos would occur for drum brakes, on a heavier vehicle, with rear drive, utilizing aftermarket brakes.  Although such guidelines may be oversimplifications, which must be verified for each vehicle class, they offered a good starting point for focusing vehicle choices for the collection of a limited number of field samples.  Since many replacement brakes have been sold in the aftermarket as relined original equipment manufacturers (OEM) parts, the MSDS documentation of the ADFM lining composition may be the most definitive source for asbestos content.

Collection of used brake linings and the associated brake wear dust was conducted in the field from local brake repair facilities, which had agreed to cooperate in the study. These facilities were provided a watch list of target vehicles identified to have a high probability of utilizing asbestos-containing ADFM in their braking systems.  Several techniques were explored for sampling the brake dust from surfaces close to the friction surface to minimize contamination from other sources.

### 2.2 Asbestos Analysis Approach Overview

Analysis of the asbestos present in the used brake linings and brake wear-generated dust utilized established methods most suited to characterize the fibers present as asbestos (most probably chrysotile), to determine fiber size, and to provide an estimate of the percent asbestos present in the collected sample matrix.  Historically, most of the definitive studies (such as Cha et al.) have utilized TEM to analyze brake dust for asbestos fiber content, based on the high resolution required to detect and identify single fibers which average 0.5 um in length.  When coupled with selected area electron diffraction (SAED) and energy dispersive spectroscopy (EDS) chemical analysis, TEM provides the most reliable method for the identification and quantification of asbestos fibers.  Although optical microscopy does not have the resolution to detect the large quantity of small submicron fibers often present in brake dust, polarized light microscopy (PLM) offers the ability to distinguish the larger asbestos fibers found in the bulk ADFM of the brake lining.  Conversion of the fiber counting and size measurements to asbestos mass for both fibers and fiber bundles required the application of the density of the asbestos type (specific gravity for chrysotile is 2.55) and a knowledge of the total mass per unit area of the prepared microscopy sample.  For the purposes of counting, asbestos fibers were defined as having an aspect ratio of at least 3:1. Since previous studies have found most all brake dust emissions to be in the PM10 size fraction, the inherent uncertainty in sizing all particles (not just asbestos fibers) to yield an estimate of the PM10 mass fraction based on an assumed average density appears unnecessary. However, to verify this point, sizing of all particles was conducted in a few selected samples.  A few selected air samples, collected from the brake emissions of dynamometer-mounted vehicles (during the sampling strategy development), were to be analyzed for the asbestos content of the PM10 and PM2.5 size fractions.

General guidelines for sample treatment to remove interfering substances for improved identification and sizing of asbestos fibers were taken from established methods. Quality control measures were utilized to ensure these treatments did not significantly affect the form or size of the asbestos fibers present.

### 2.3 Inventory of Asbestos ADFM

Several approaches were utilized in the development of an inventory of asbestos-containing ADFM utilized in braking systems, including their frequency of use by vehicle class, and their prevalence based on a sample population of currently registered vehicles. The following resources were utilized in an effort to establish the asbestos composition of brakes utilized in specific vehicle models:

- Friction product and materials market survey reports to define the prevalence of asbestos in ADFM according to the manufacturing source and the requirements of specific brake applications.
- Recognized industry specifications such as temperature independent braking friction performance to identify ADFM with significant asbestos content.
- ADFM manufacturers and the FMSI inquiries concerning the asbestos content of specific brake linings and for guidance on identifying classes of vehicles likely to utilize asbestos ADFM.
- MSDS, which must be supplied by the manufacturer, listing the hazardous components in ADFM utilized in different vehicle classes.

Contacts with the ADFM industry (FMSI), suggested that the prediction of asbestos content in ADFM utilized in a class of vehicles, can be based on several key factors including: type of brake system (disc or drum), drive train type (front or rear drive), vehicle weight, and ADFM source (aftermarket or original equipment). Published industry surveys (Brauer, 1998) suggested that as much as half of the aftermarket ADFM may contain asbestos, which yields superior performance in drum brake applications on heavier vehicles, such as SUVs. Based on this approach, the highest probability for identifying ADFM containing asbestos would occur for drum brakes, on a heavier vehicle, with rear drive, utilizing aftermarket brakes. Although such guidelines may be oversimplifications which must be verified for each vehicle class, they offered a good starting point for focusing vehicle choices for the collection of a limited number of field samples.

#### 2.3.1 LDV/MDV and HDV Brake System Characteristics

Accordingly, under subcontract to SRI, a model and year specific inventory of brake type (disc and drum) was integrated with current California Department of Motor Vehicles (DMV) registration populations to yield an estimate of brake type frequency for vehicles current on the road. Brakes of passenger cars (PC), light duty trucks (LDT), medium duty trucks (MDT), and a representative set of heavy-duty trucks (HDT) currently on the road in California were to be included in the inventory of asbestos-containing ADFM. Vehicles were grouped into two data sets including: light and medium duty vehicles (LDV/MDV) with gross vehicle weights (GVW) $\leq$ 8,500 lbs. and heavy duty vehicles with GVW > 8,500 lbs. These separate vehicle groups based on GVW rating were essential, since this represents a clear distinction in both brake type ADFM application markets, and vehicle classes serviced by brake repair shops. The designation of the EMFAC2000 vehicle classes included in these groups are given in **Table 2.3.1b**, as well as, those excluded vehicle classes such as motorcycles.

Sierra developed a LDV/MDV brake database that specifies the type of brake (disc, drum, or either) used on the front and rear wheels of specific makes and models of vehicles with gross vehicle weight (GVW) ratings of 8,500 pounds or less. The first step in the development of the LDV/MDV vehicle data was the combination of a comprehensive brake database developed by the Friction Material Standards Institute (FMSI) with a database of vehicle characteristics developed by Sierra Research, Inc. for use in vehicle inspection and maintenance programs. In order to complete this combination of databases, considerable review and reformatting of the FMSI database was required. This effort included a detailed manual review of the FMSI database and comparison of that database with data available from the Honeywell/Bendix print catalog of brake components and applications that was available to the automotive repair and aftermarket sales industry. The Honeywell/Bendix data was used as appropriate to augment the FMSI/Sierra database.

The finished database included detailed information regarding 1973 to 1999 model year vehicles including one of three different entries for the brake configuration on the front axle and the rear axle. The three possible entries for each brake configuration were:
D = Disc brakes
X = Drum brakes
E = Either Disc or Drum brakes

This data base was then merged with a sample of vehicle registration data provided by CARB to determine the percentage of each particular make, model, and model-year of vehicle in the California vehicle fleet. This data was then used to determine the relative abundance of disc and drum brakes in the light- and medium duty vehicle fleet. The total number of records in the DMV database for passenger and commercial vehicles, as well as, the number of those records that were successfully matched with the SRI database are summarized in the **Table 2.3.1a** below. This is also given as the percentage of records in each category of the DMV data that were matched with the SRI database. As shown, there was a very high match rate such that little if any bias should have been introduced by excluding unmatched DMV records from the estimates of relative abundance of disk and drum brakes used in the light and medium duty vehicles (LDV/MDV).

Although the matched results given here by SRI are identified as DMV “passenger” and “commercial” matched vehicles, this includes the LDV/MDV vehicle code classifications of PC, T1, T2, and T3 as given in **Table 2.3.1b**. Note that even though the vehicle categories in the **Table 2.3.1a** differ from those reported in **Appendix E**, where the detailed LDV/MDV distributions are provided, the total number of “passenger” and “commercial” matched vehicles in the **Table 2.3.1a** is relatively close in number to the total number of PC, T1, T2, and T3 vehicles given in **Appendix E**.

**Table 2.3.1a Results from Merger of DMV and SRI Databases**

| Vehicle Type | Total Vehicles | Matched Vehicles | % Vehicles Matched |
|---|---|---|---|
| Passenger | 252473 | 250626 | 99.3 |
| Commercial | 39175 | 38356 | 97.9 |

A database was also developed for heavy-duty vehicles with gross vehicle weight ratings greater than 8,500 lbs GVW (i.e. vehicle code categories of T4-T8). However, because of limitations in the FMSI database, only vehicles with disc brakes on either the front and/or rear axles were included. All other heavy-duty vehicles were assumed to be equipped with drum brakes. The resultant database included 791 entries. CARB assisted Sierra in determining which of the 791 vehicles were <14000 lbs GVW.

This database was also merged with a sample of DMV registration data to determine the percentage of each vehicle in the California vehicle fleet by make, model, and model-year. The data resulting from the merger was then used to determine the relative abundance of disc brakes in the heavy-duty vehicle fleet. It should be noted however that the DMV registration sample provided by CARB appeared to underestimate the number of heavier trucks in the fleet (particularly the T8 vehicles) which if correct would cause the estimated abundance of disc brakes to be inaccurate.

**Table 2.3.1b Grouped EMFAC2000 Classes for Brake Sample Field Collection**

| <u>Vehicle Class</u> | <u>Code</u> | Description | Vehicle Weight (lbs.) |
|---|---|---|---|
| **Light and Medium Duty Vehicles (LDV, MDV)** | | | |
| 1 | PC | Passenger cars | ALL |
| 2 | T1 | Light-duty trucks | 0 - 3,750 |
| 3 | T2 | Light-duty trucks | 3,751 - 5,750 |
| 4 | T3 | Medium-duty trucks | 5,751 - 8,500 |
| **Heavy Duty Vehicles (HDV)** | | | |
| 5 | T4 | Light-heavy duty trucks | 8,501 - 10,000 |
| 6 | T5 | Light-heavy duty trucks | 10,001 - 14,000 |
| 7 | T6 | Medium-heavy duty trucks | 14,001 – 33,000 |
| 8 | T7 | Heavy-heavy duty trucks | 33,001 – 60,000 |
| 9 | T8 | Line-haul trucks | 60,000 + |
| **Excluded Vehicle Classes** | | | |
| 10 | UB | Urban buses | ALL |
| 11 | MC | Motorcycles | ALL |
| 12 | SB | School buses | ALL |
| 13 | MH | Motor homes | ALL |

### 2.3.2 Asbestos BFM Inventory by Vehicle Application

The use of asbestos containing brake friction material (BFM) was considered to be a function of vehicle model, model year, and weight class. Accordingly, these databases combined with an inventory of asbestos containing BFM, which are available for vehicles based on model, model year and weight class, were expected to yield an estimate of on-the-road vehicles with asbestos BFM. However, efforts to develop an inventory of asbestos containing BFM, which could be used to identify candidate vehicles most likely to employ asbestos BFM, using established SRI friction materials industry contacts were largely unsuccessful.

An industry survey questionnaire was developed in an attempt to identify those BFM, which were likely to contain asbestos in drum and disc brakes. The BFM pilot survey was distributed to nine firms, including OEM and after market vendors. Unfortunately, despite efforts by Sierra to secure commitments from the firms included in the pilot survey, no survey responses were received. This may have been a direct result of litigation underway to secure compensation for workers exposed to asbestos fibers from BFM.

Since an inventory of asbestos containing BFM was crucial to framing the rest of the project, an alternative approach using on-line research was conducted by EHLB to determine that the required combination of public domain MSDS and vehicle-specific BFM application charts were available. Although more time consuming than the survey approach, knowledge of these two factors was shown to identify vehicles with a high probability of utilizing asbestos BFM. Accordingly, a two-fold approach to develop an inventory of asbestos containing BFM was employed:

(1) Develop an asbestos BFM MSDS data base and use the associated National Item Identification Number (NIIN) unique identifier to link to manufacturer part numbers through an on-line service. These part numbers were successfully identified in the associated vendors' on-line data base, but cross-referencing to the specific vehicle application was proven difficult in any efficient way.

(2) Use an on-line searchable data base from brake parts suppliers, which contain associated MSDS. This approach has proven to be the most successful, using the NAPA on-line catalogue, which includes MSDS for those brakes containing asbestos. A great deal of time was spent searching the NAPA data base for asbestos containing brakes, in order to discover patterns in brake part numbers, edge codes, and vehicle applications. In short, all the asbestos containing BFM that could be identified were brake shoes from the Safety Stop series, and the MSDS indicated the friction material was all produced by Allied-Signal and contained 20-50% chrysotile asbestos, as shown in the example of **Figure 2.3.1**. These asbestos containing Safety Stop brakes could be easily identified by unique part numbers of the form RSSSSxxx, where xxx is a three-digit number. However, the NAPA on-line catalogue does not allow a reverse search, which would be required to generate a list of vehicles utilizing asbestos brake shoes.

**Material Safety**
**Data Sheet (MSDS)**

```
RAYLOC  ALLIED BRAKE SHOE DRILLED
===========================================================================
MATERIAL SAFETY DATA SHEET
Effective Date: March 29, 1993   Code: Allied Brake Shoe Drilled   Page:
===========================================================================
===========================================================================
Section 1 - PRODUCT AND COMPANY IDENTIFICATION
===========================================================================

PRODUCT NAME: Allied Brake Shoe Drilled
Chemical Name: Cured Segment, Organic

Identity (Edge Code): NRSP11034FF, NSS2200FF, NRSP11033FF, NRSP11032FF,
NRSP11026FE, NSS2215FE, NRSP11035FF, NRST11036FG, NSS2210FG,
NRSP11037FE, NSS2205FE

MANUFACTURER'S NAME:                            EMERGENCY TELEPHONE NO.
Allied-Signal Corp.                                (313)362-7196
900 W. Maple Road
Troy, Michigan  48084                           MISCELLANEOUS INFORMATION

Formula: Mixture of
SUPPLIER'S NAME:                                Proprietary Ingredients;
Rayloc                                          See Section 2
Division of Genuine Parts Company
600 Rayloc Drive SW
Atlanta, Georgia  30336

REVISION DATE:
May 20, 1997

===========================================================================
Section 2 - HAZARDOUS INGREDIENTS
===========================================================================

CAS NO.    INGREDIENT              -----EXPOSURE LIMITS-----
                                         ACGIH  OSHA         VP
                              % BY WT.    TLV   PEL UNITS   MM  HG
===========================================================================
1332-21-4  Asbestos/Chrysotile  20-50         0.2 Fiber/cc
1317-65-3  Calcium Carbonate     5-10           5 mg/m3
7727-43-7  Barium Sulfate        5-20           5 mg/m3
1344-28-1  Aluminum Oxide        2-5            5 mg/m3
1309-48-4  Magnesium Oxide       2-5            5 mg/m3
1333-86-4  Carbon Black          2-5            3.5 mg/m3
7782-42-5  Graphite              2-5            2.5 mg/m3
1309-37-1  Iron Oxide            2-5           10 mg/m3
Non-hazardous Resins & Fillers   Balance

******************************WARNING************************************
AVOID CREATING OR BREATHING DUST.  CONTAINS ASBESTOS FIBERS AND OTHER
SUBSTANCES WHICH MAY CAUSE CANCER AND LUNG INJURY.
GENERAL REQUIREMENT: TOTAL DUST SHALL NOT EXCEED 10MG/M3
*************************************************************************
```

Figure 2.3.1 MSDS for Safety Stop RSSSS473 (Bendix RS473).

Such a reverse search database was available from Bendix on a CD-ROM and includes self-installing PC based search software. The part number cross-referencing capability of both databases, allows a reverse search to yield all those LDV/MDV from the model years 1956-2004 that are capable of utilizing a specific brake shoe part number known to contain asbestos. Extensive cross-checking established that the vehicle application list for asbestos containing Safety Stop brakes shoes, with the part number format RSSSSxxx, could be generated using the Bendix database. In the Bendix database, the corresponding part number had simply been shortened to RSxxx, where the three digit numbers were exactly the same. Bendix part numbers of the form Rxxx, AFxxx, and RAFxxx, with the same three digit number, were the asbestos free versions of the same shoes. Since the early 2000s, only the asbestos free versions have been available from the national auto parts suppliers.

The Bendix database allows the entry of a partial part number. For example, searching on RS4 will bring up all the RS4xx brake applications. A survey of vehicle models for the RSxxx series, using the Bendix reverse search, yielded a vehicle application listing, which consisted of the following number of pages with a maximum of ten vehicles per page:

RS1xx yields 51 pages
RS2xx yields 120 pages
RS3xx yields 155 pages
RS4xx yields 224 pages
RS5xx yields 226 pages
RS6xx yields 62 pages

Since the Bendix output did not provide a means for printing the search results to a file, generation of the vehicle listing required labor intensive conversion of individual on-screen page images to digital format using Adobe Acrobat. An example of the digital format conversion is included as **Figure 2.3.2.** It was important to note that the three digit portion of the brake code appears to be universal across all manufacturers, and represents the same set of make/model/year vehicle applications.

From the MSDS, all of these asbestos containing BFM were manufactured by Allied-Signal, which according to Brauer (1998), was the largest producer of BFM in the medium and light duty OEM market, as well as, the medium duty aftermarket. From Brauer, Allied-Signal accounted for 60% of sales in the medium and light duty vehicle OEM market, and the medium duty vehicle aftermarket. Accordingly, the listing generated of vehicles likely to employ asbestos brakes was expected to be comprehensive.

The leading role of Allied-Signal in the friction materials market became apparent with the acquisition of several well known friction material products manufacturers, starting after the 1970’s. As a clarification of BFM manufacturers, Allied-Signal acquired

Make Year Model Sub Model Part Number

CHEV./GMC TRUCK 1985 G10, G15 Vans-1/2Ton 11 5/32 x 2 3/4 Rear Brake JB-5 ***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1985 G20, G25 Vans-3/4Ton, G2500
Vans, Express, Savanna-3/4 Ton
G2500 JB-5, JD-5 ***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1985 K10, K15 4WD-1/2 Ton, Pickup,
Suburban
K10 JB-5, JD-5 ***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1985 K20, K25 4WD-3/4 Ton, Pickup,
Suburban
K20 JB-6, JD-6 ***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1985 P20, P25-3/4 Ton JB-6, JD-6 ***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1986 Blazer, Jimmy Rear Drum Brake ***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1986 C10, C15 2WD-1/2 Ton, Pickup,
Suburban
C10 JB-5, JD-5 ***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1986 C20, C25 2WD-3/4 Ton, Pickup,
Suburban
C20 Pickup 11" Rear Brake 7200
lb. GVWR
***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1986 G10, G15 Vans-1/2Ton 11 5/32 x 2 3/4 Rear Brake JB-5 ***B* -** 473
***S* -** RS473
CHEV./GMC TRUCK 1986 G20, G25 Vans-3/4Ton, G2500
Vans, Express, Savanna-3/4 Ton
G2500 JB-5, JD-5 ***B* -** 473
***S* -** RS473

Figure 2.3.2 Example page from Bendix reverse search for vehicles using brake shoes with part number RS473 brake.

Bendix in the early 1980's which included a large friction materials division. Allied-Signal subsequently acquired Honeywell in 2000 and was renamed Honeywell.

A make/model/year specific listing from the Bendix data base search was integrated with the brake system characteristics data base, described in the previous section to generate a LDV/MDV target list for use in the field collection of BFM likely to contain asbestos. In a test of the above approach, the EHLB 1985 Chevrolet G20 Van was successfully identified as a vehicle likely to employ asbestos containing brake shoes. Analysis of the used brake shoes currently installed on this vehicle, verified the presence of large quantities of asbestos.

A similar strategy was also investigated for heavy duty vehicles; however, unlike the Bendix light and medium duty vehicle applications, heavy duty application information sources appeared to be much more fragmented. For HDV, the Haldex Commercial Vehicle Systems, Friction Products Division, offered the most complete cross reference data base, which was available on CD-ROM for easy access. Unfortunately, the data base was organized according to brake shoe part numbers, rather than specific HDV make, and model year applications. This is not unreasonable, since unlike LDV/MDV, HDV brake shoes are replaced based on the worn brake part code numbers, with the cores returned for relining. The MSDS obtained from Haldex for all the BFM used to reline the brakes from vehicles in the heavy duty weight classes, indicated the absence of asbestos. Since Haldex is a major supplier of non-asbestos relined brakes to high volume truck service center chains, such as NAPA, and HDV brakes are expected to be replaced relatively frequently, asbestos BFM seems less likely to be found in HDV currently on the road. Accordingly, since no further refinement based on asbestos BFM inventory was possible, the HDV inventory for brake type described above was used as the vehicle target list for the field collection of BFM for asbestos analysis.

### 2.4 Brake Friction Material Field Sampling

A brake sampling program was instituted to collect approximately 50 ADFM and 50 brake dust samples from vehicles undergoing brake replacement at local auto repair facilities. These cooperating facilities were provided a hit list of target vehicles to be sampled, and were provided sampling kits to collect used ADFM brake linings and the associated brake dust. Through the target vehicle listing, sample collection was restricted to those popular vehicles in each vehicle class, which have high probability of utilizing ADFM containing significant levels of asbestos. Development of a well-defined list of asbestos ADFM target vehicles, as described above in **section 2.3**, was essential to optimize the utility of the analytical results for the limited number of field samples to be collected. The purpose of the field sampling was two-fold (1) to establish the presence of asbestos in used brake friction material from vehicles on the target list, and (2) to collect brake dust for characterization by microscopy as a potential indicator of the airborne emission from asbestos BFM wear.

#### 2.4.1 Brake Sampling Methodology

A brake sampling kit was developed and validated using the EHLB 1985 Chevrolet G20 Van, which through use of the target vehicle list, was determined to have asbestos BFM on the rear drum brakes. The most important aspect of the kit was the development of a simple means for collecting deposited brake dust retained on the brake system surfaces. For this purpose, a plastic razor blade was found to be an effective tool to scrape and deliver brake dust sample into a screw capped plastic tube for microscopy analysis. Unlike a standard razor blade, the commercially available plastic version prevented contamination of the collected dust sample with metallic particles that could interfere with the laboratory analysis.

The complete field study target vehicle brake sample collection kit is shown in **Figure 2.4.1**, and included:

a. Target Vehicle Listing (one per batch of kits).
b. Vehicle Information Sheet with sample collection instructions.
c. 50 mL plastic screw cap centrifuge tube with plastic razor blade for collecting brake drum dust (disc brakes were not to be sampled, see **section 2.3.2**).
d. Zip-lock plastic bag to isolate dust sample and information sheet.
e. Kit bag with heavy duty seal to contain the collected brake shoes, dust sample, and informational sheet.

The kit was designed for ease of use to allow used brakes and dust for vehicles on the target list to be collected by the mechanics conducting the brake replacement service. A descriptive step-by-step sample collection protocol was printed on the reverse side of the Vehicle Information Sheet. These instructions were used by the shop mechanic for identifying vehicles to be sampled, recording the required descriptive information about the vehicle, collecting the BFM and brake dust samples, and re-assembling the kit bag for return to the laboratory for analysis. The vehicle information sheet provided data fields for the entry of the required information including: vehicle description (engine,VIN number, make, model, year), repair shop site identification (address, type of facility), and sample description (ADFM or brake dust, front or rear brake, disc or drum brake, OEM or aftermarket, manufacturer code labels, replicate number, and sample date).

The only significant difference in the kits prepared for the LDV/MDV and HDV brake service shops was the modification of sample collection instructions, such that only a piece of the BFM was removed. Unlike LDV/MDV, the large worn brake cores from HDV are retained by the shop for subsequent relining and reuse. Examples of the Vehicle Information Sheet and the sample collection instructions for LDV/MDV and HDV are included in **Appendix B.** Kits pre-labeled with laboratory sample identification bar codes were supplied to brake service shops in batches of ten, inside a protective plastic storage bin with the appropriate target list for LDV/MDV or HDV.

### 2.4.2 Brake Friction Material Collection Program

Local brake service shops willing to participate in the collection of BFM and the associated brake dust from target list vehicles were identified through an initial telephone contact with all service shops located in the East San Francisco Bay Area, within a 30 minute driving distance. For the collection of LDV/MDV brake samples, 12 of 30 brake service shops contacted agreed to participate in the program and were

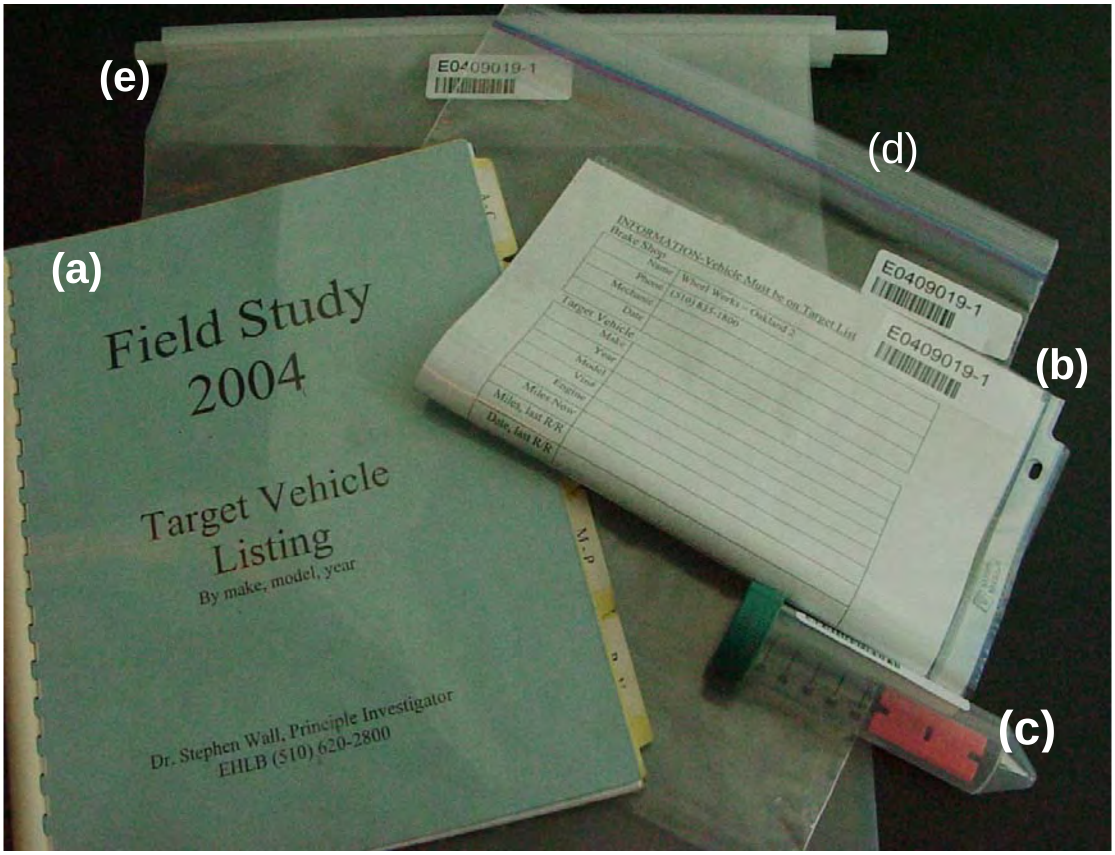



Figure 2.4.1 Field Study target vehicle brake sample collection kit, including: (a) Target Vehicle Listing, (b) Vehicle Information Sheet, (c) 50 mL plastic screw cap centrifuge tube with plastic razor blade for collecting brake drum dust, (d) Zip-lock plastic bag to isolate dust sample and information sheet, and (e) Kit bag with heavy duty seal to contain the collected brake shoes, dust sample, and informational sheet.

provided sampling kits coded with the batch numbers listed in **Table 2.4.1**. For the collection of HDV brake samples, 11 of 17 brake service shops contacted agreed to participate in the program and were provided sampling kits coded with the batch numbers listed in **Table 2.4.2**.

The brake friction material field sampling program was instituted in August 2004 and continued through May 2005, with most brake samples collected during the first six months. Participating brake service shops were telephoned bi-monthly, and any brake samples collected over the intervening two-week period were picked-up for return to the laboratory.

Collected samples were screened for the minimum required vehicle information to verify acceptability based on the appropriate Target Vehicle Listing. All BFM samples returned to the laboratory were screened for asbestos using the methodology derived from established microscopy methods, as described in the subsequent section on microscopy analysis. Accordingly, in those cases when the BFM collected was not from a vehicle on the target list, the absence of asbestos provided some degree of quality assurance that vehicles excluded from the target list did not contain asbestos.

## 2.5 Airborne Brake Dust Emission Sampling

As reported in the literature, residual brake dust can be considered as an indicator of the composition of the airborne brake-wear emission. This association is the basis for the BFM field sampling strategy, (a) to conduct asbestos screening on used BFM, collected from target vehicles, and (b) for BFM with asbestos, to fully characterize the asbestos fibers present in the associated field collected brake dust sample. In order to elucidate the relationship between the characteristics of the field collected asbestos brake dust from target vehicles, and the nature of the fugitive air emission of asbestos fibers under braking, measurements were made for a test vehicle mounted on a chassis dynamometer.

Sierra Research was under sub-contract to provide the capability to operate a chassis mounted test vehicle over standard air emission test cycles. A 1985 Chevrolet G-20 van from the target list, determined to be equipped with asbestos BFM, was chosen as a representative test vehicle for chassis dynamometer based brake dust emission measurements. Sensors were installed in the test vehicle to monitor those braking conditions considered in previous studies to be important controlling parameters for the character of the BFM emissions under braking. The dynamometer-based asbestos emission testing utilized an EHLB fabricated dilution sampling system, based on a standard PM10 sampler, to collect airborne brake wear emissions.

### 2.5.1 Air Emission Sampling System Design

Brake dust emissions were collected with a new split section dilution tunnel, attached to the test vehicle undercarriage, which allowed unobstructed vehicle operation on the dynamometer. An exploded-view schematic diagram of the split section dilution tunnel, viewed from the bottom of the vehicle, which shows the components of the sampling system, is provided in **Figure 2.5.1**. From the left side of the diagram, dilution supply air

**Table 2.4.1 Local Light and Medium Duty Vehicle Brake Collection Shops**

| Shop Name | Batch | Address |
|---|---|---|
| Participating Shops | | |
| Dan Chin Auto | E0408015 | 2558 Shattuck Avenue, Berkeley, CA 94704 |
| Big O Tire Stores - Berkeley | E0409010 | 2625 San Pablo Avenue, Berkeley, CA 94702 |
| Big O Tire Stores - Richmond | E0409011 | 12952 San Pablo, Richmond, CA |
| Big O Tire Stores - Oakland | E0409012 | 810 W. Macarthur Blvd, Oakland, CA |
| Wheel Works - Oakland 1 | E0409013 | 4240 International Blvd, Oakland, CA 94601 |
| Midas Auto Service - Berkeley | E0409014 | 1835 San Pablo Avenue, Berkeley, CA 94703 |
| Midas Auto Service - El Cerrito | E0409015 | 10903 San Pablo Avenue, El Cerrito, CA 94530 |
| Midas Auto Service - Oakland 1 | E0409016 | 3799 Broadway, Oakland, CA 94611 |
| Midas Auto Service - San Pablo | E0409017 | 14640 San Pablo Avenue, San Pablo, CA 94806 |
| Midas Auto Service - Oakland 2 | E0409018 | 3464 Foothill Boulevard, Oakland, CA 94601 |
| Wheel Works - Oakland 2 | E0409019 | 1800 Park Blvd, Oakland, CA 94606 |
| Wheel Works - Oakland 3 | E0409020 | 2359 Harrison Street, Oakland, CA 94612 |
| Non-Participating Shops | | |
| Albany Tire Service | | 742 San Pablo Avenue, Albany, CA 94706 |
| Allied Muffler | | 920 Gilman Street, Berkeley, CA 94710 |
| Auto California | | 1804 San Pablo Avenue, Berkeley, CA 94702 |
| Autometrics | | 1340 San Pablo Avenue, Berkeley, CA 94702 |
| Automotive Aces | | 3407 Adeline Street, Berkeley, CA 94703 |
| Babitt's Tune-Up & Brake Service | | 2527 San Pablo Avenue, Berkeley, CA 94702 |
| Baroo | | 544 Cleveland Avenue, Berkeley, CA 94710 |
| Bauer's Auto Repair | | 1790 University Avenue, Berkeley, CA 94703 |
| Berkeley Tire And Service | | 2099 Martin Luther King Jr Way, Berkeley, CA 94704 |
| Best Express Auto Repair | | 6006 San Pablo Ave, Oakland, CA |
| Campus Auto Care | | 1752 Shattuck Avenue, Berkeley, CA 94709 |
| Clutch Mart | | 1513 San Pablo Avenue, Berkeley, CA 94702 |
| Don's Auto | | 2144 San Pablo Ave, Berkeley, CA |
| George Oren Tire Specialist | | 1350 International Blvd., Oakland CA 94606 |
| R & R Auto Service | | 6700 Fairmount Avenue, Berkeley, CA 94702 |
| Tires and Brakes for Less | | 10201 Macarthur Blvd, Oakland, CA 94605 |
| Wise Autotech | | 2323 San Pablo Avenue, Berkeley, CA 94702 |
| YAZ Automotive | | 2720 San Pablo Avenue, Berkeley, CA 94702 |

**Table 2.4.2 Local Heavy Duty Truck Brake Collection Shops**

| | | |
|---|---|---|
| | | |
| A & C Truck Repair | E0409027a | 2226 Myrtle St, Oakland, CA 94607 |
| Alteno Truck repair | E0409027b | 2230 Willow St, Oakland, CA 94607 |
| C & E Auto and Truck | E0409027 | 1366 Dolittle Dr., San Leandro, CA |
| East Bay Truck Center | E0409028 | 333 Filbert Street, Oakland CA 94607 |
| (GMC) Oakland Truck Center | E0409029 | 8099 S Coliseum Way, Oakland, CA 94621 |
| Kelly's Truck Repair | E0409030 | 485 Hester, San Leandro, CA |
| Bett's Truck Parts | E0409031 | 950 Doolittle Drive, San Leandro, CA 94577 |
| California Fleet Maintenance | E0411010a | 2450 Whipple Rd, Hayward, CA 94544 |
| Golden Gate Truck Center | E0411010b | 8200 Baldwin, Oakland, CA |
| Bay Shore International | E0411011 | 24353 Clawiter Rd, Hayward, CA |
| Bay Area Kenworth Co. | E0411017 | 425 Market St, Oakland, CA 94607 |
| | | |
| 88 Truck & Parts Service Center | | 9201 Railroad Avenue, Oakland,CA 94608 |
| East Bay Truck & Auto Repair Inc | | 6825 San Leandro St, Oakland, CA 94621 |
| G & M Truck Repair | | 2801 San Pablo Avenue, Oakland, CA 94608 |
| J & A Truck Repair | | 2221 Union, Oakland, CA |
| J & O's Commercial Tire Ctr | | 2401 Union St, Oakland, CA 94607 |
| West Oakland Truck Repair | | 337 Chestnut St, Oakland, CA 94607 |

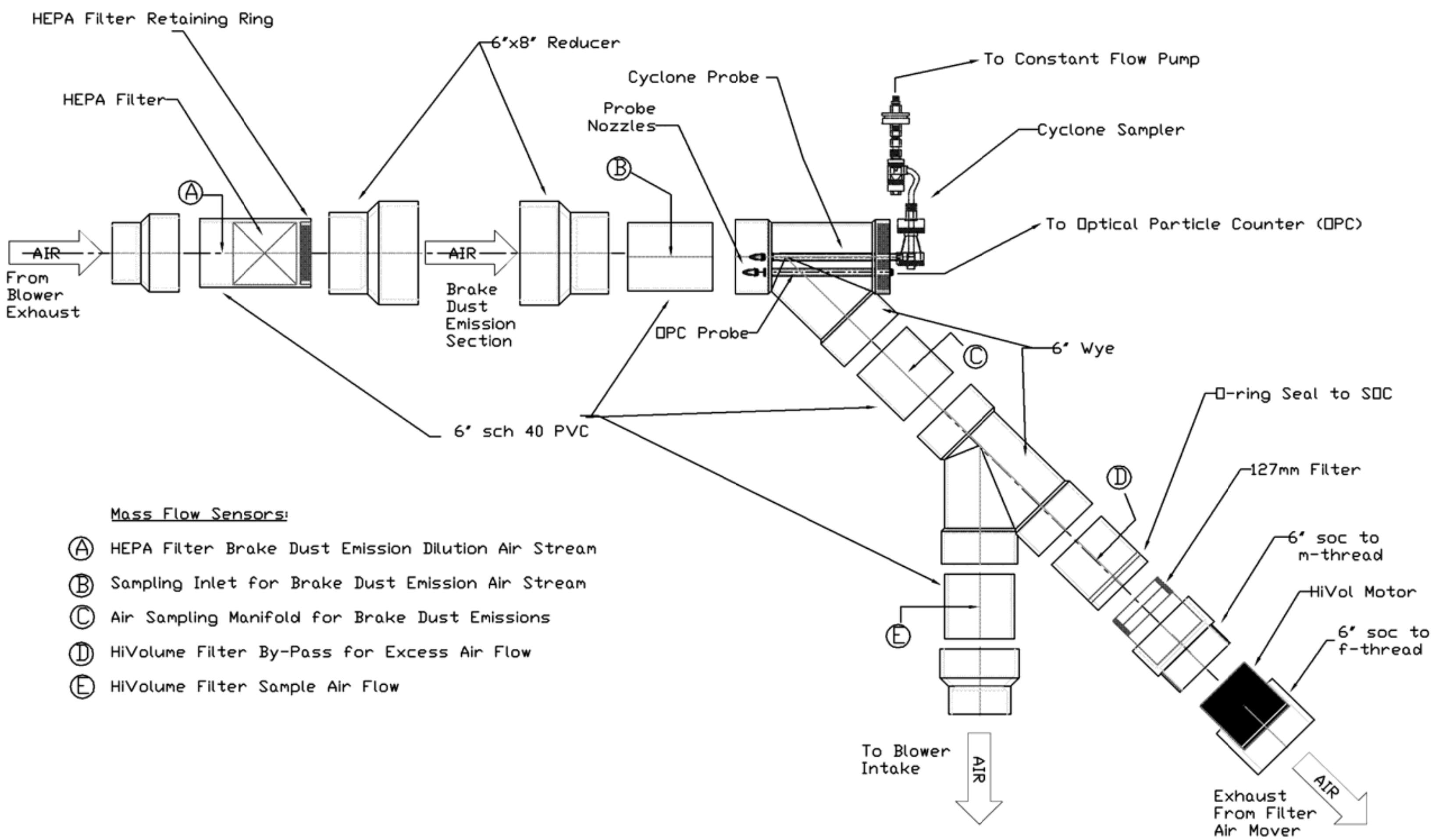



Figure 2.5.1 Exploded-vie w schematic diagram of the split dilution tunnel, viewed from the bottom of the vehicle.

was provided by a cast aluminum pressure blower (American Fan Company, model # AF-10-1044) through a flexible duct and passed through a HEPA filter in the upstream section of the 6” diameter PVC dilution tunnel. The supply air then exited into free air through an 8” diffuser just upstream of the inside face of the right rear tire of the test vehicle. The upstream section of the dilution tunnel was designed to provide a continuous supply of clean filtered air over the brake drum backing plate region where the brake dust is emitted. This dilution supply airflow was maintained at a velocity of 3.6 m/s (8 MPH) to transport the brake wear emissions to the downstream section of the split dilution tunnel for sampling.

Inlet airflow for the downstream dilution tunnel section was provided through a flexible duct connected to the intake-air side of the same pressure blower used to provide the dilution supply air. Additional airflow in the downstream section was introduced by a Hi-Volume blower motor used to collect brake emission samples for gravimetric analysis. The effect of this additional airflow was to increase the entrance air velocity (volumetric flow) into the downstream air sampling section by approximately 30% over the velocity (volumetric flow) of the upstream air supply section, in order to promote efficient capture of the brake wear emissions transported in the clean dilution air.

The purpose of this split dilution tunnel design was to allow the dilution and transport of the brake dust emissions to occur in free air space between the dilution tunnel sections, in order to avoid artifacts in particle dispersion and deposition inherent in less realistic sampling configurations. Attempts to collect brake emissions from vehicles traveling on-the-road by Jacko (1973), suffered from unrealistic particle deposition and heating effects. These unrealistic artifacts were produced by a full brake system enclosure without dilution airflow, as reported by Williams and Muhlbaier (1980). Both Williams and Muhlbaier, and Cha et al. (1983) utilized isolated braking systems without tires, which were removed from the parent vehicles and mounted inside air dilution enclosures. These enclosures prevented overheating, but were not designed to reproduce the brake air emission dilution flow dynamics of a vehicle traveling on the road.

As shown in the photograph included as **Figure 2.5.2**, the free air space, between the upstream dilution tunnel section (left side) and the downstream dilution tunnel section (right side), was subject to the dominating air flow effects of undercarriage obstructions combined with tire rotation on the dynamometer rollers. During operation, lengths of white thread attached at the perimeter of the upstream tunnel exit flow, provided verification that the air flow streamlines passed the area of brake dust emissions, and entered the downstream tunnel section containing the air samplers.

As shown in the diagram of **Figure 2.5.1**, the downstream tunnel section transported the brake dust aerosol to a sampling array consisting of a high-volume total filter, cyclone train, and optical particle counter. The 125 mm diameter total filter was mounted in a PVC holder attached to the straight downstream leg of the 6” PVC wye, with the other leg providing the connection for the dilution tunnel air

Figure 2.5.2 Photograph of the split dilution tunnel sections mounted on the vehicle undercarriage, showing the free air space between the upstream (left) and downstream (right) tunnel sections.

blower (intake side of the cast aluminum pressure blower). The open face total filter, intended for gravimetric analysis, was a 127 mm diameter, fluorocarbon (TFE) coated, glass fiber filter (Pall Corporation, Fiberfilm), with an effective sampling deposit diameter of 115 mm. The total filter flow rate was set for 1.78 m3/min (63 CFM) using a solid state A/C power controller on the high-volume blower motor, and was continuously monitored with a data logging thin profile mass flow sensor (TSI VelociCalc) mounted just upstream of the filter. A similar mass flow sensor was used to monitor the total air flow of near 4.9 m3/min (173 CFM) entering the downstream section of the dilution tunnel. Ratios between this total dilution tunnel flow and the flow rate of the individual particle samplers were subsequently used to calculate a total brake dust emission rate.

For air sampling of asbestos fiber brake emissions, a multi-stage stainless steel cyclone train designed for the USEPA EMTIC #201a stack sampling method (Thermo Anderson, model #CASE-PM2.5xp) was employed. Operated under the typical ambient conditions ($25^oC$, and 1 atm pressure) present in the dilution tunnel air flow, the cyclone train was calibrated to provide particle size cutpoints of 10 um and 2.5 um equivalent aerodynamic diameters, respectively for the first and second cyclones connected in series. Accordingly, the second cyclone catch provided the coarse particle fraction (2.5um -10um), and the fine particle fraction (<2.5 um) was collected by the afterfilter, located directly downstream at the flow exit from the second cyclone.

The advantage of using a cyclone stack sampler train was the ease with which this configuration could be adapted for use in the “stack-like” geometry of the dilution tunnel. Both the cyclone train and an optical particle counter (OPC) sampled dilution tunnel air through 13 mm (0.5 “) ID stainless steel probes, which passed through the PVC end plate installed on the first PVC wye, as shown in **Figure 2.5.1.** This configuration allowed these probes to be aligned in parallel with the flow streamlines, and a flow entrance nozzle for each probe was selected (from the well engineered set provided with the cyclone train), in order to sample the brake dust emissions iso-kinetically. Accordingly, a 7.62 mm (0.300”) diameter nozzle (#9) was used for the cyclone flow rate of 11.3 L/min, and a 9.91 mm (0.390”) diameter nozzle (#11) was used for the OPC operating at 28.3 L/min (1 CFM). Flow rate control for the OPC was provided by an integral constant flow pump, while the cyclone utilized a modular constant flow air sampler (Sierra model 110) pump. The OPC (Particle Measurement Systems, model LASAIR II) provided five size discrimination ranges between 0.3 and 10 um equivalent optical diameters.

Recovery of the size discriminated particulate matter samples followed the procedure set forth in the USEPA EMTIC #201a stack sampling method, for which the cyclone train was originally designed. As indicated on the exploded cut-away diagram in **Figure 2.5.3,** the cyclone sampling train components were disassembled into specific well-defined sections, with >10um particle deposit fraction and the coarse particle fraction (10um – 2.5 um) both recovered separately from the internal stainless steel surfaces indicated. The recovery procedure for these fractions utilized a wash-down of these surfaces with 50/50 (V/V) high purity isopropyl alcohol (IPA)/reagent grade Mill-Q water

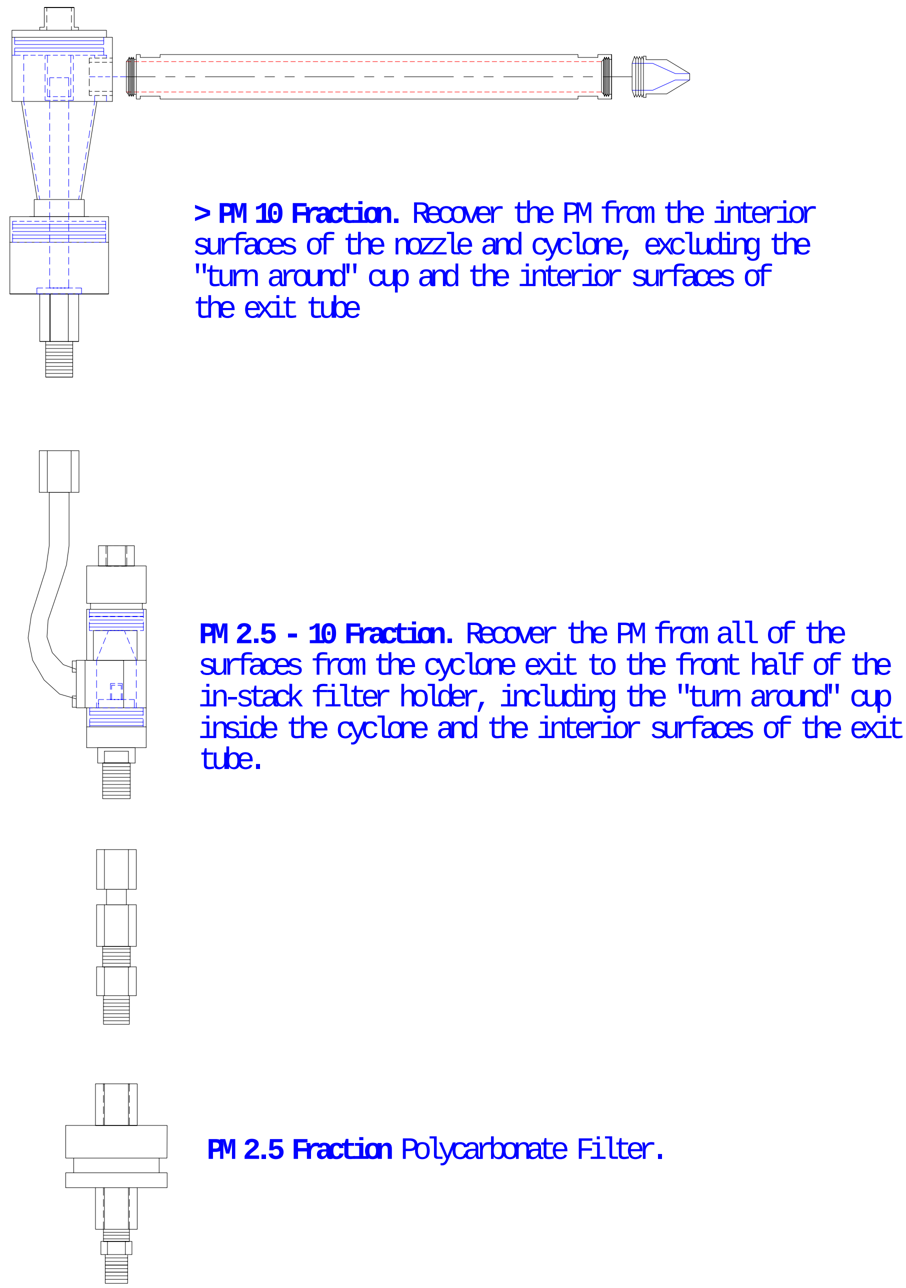



Figure 2.5.3 Exploded cut-away diagram of the cyclone air sampling train, indicating the component deposits recovered to obtain the aerodynamic size fractions for the brake dust emissions.

from a dedicated Nalgene laboratory wash bottle. Each component wash-down was conducted over a clean glass funnel and captured in a 40 mL glass vial, which was capped and labeled for subsequent TEM analysis. The fine particle fraction, collected on the 47 mm diameter 0.2 um pore size polycarbonate after filter, was exposed to a Po-210 alpha source to neutralize any static charge, before transfer to a clean tight-sealing polystyrene Petri-dish labeled for TEM analysis.

### 2.5.2 Test Vehicle Sensor Instrumentation

Identification of the 1985 Chevrolet G20 van owned by EHLB as a field study target vehicle, equipped with asbestos BFM in the rear brake shoes, made this vehicle a natural choice for dynamometer brake dust emission testing. This allowed the air emission sampling system including the under carriage mounted split section dilution tunnel, the real-time brake system sensors, and the computer based data acquisition system to be installed and tested in the EHLB laboratory garage facility. This was an important planning decision, which allowed the three day lease of the SRI dynamometer facility in Sacramento, CA to be devoted solely to emission cycle air sampling.

In addition to vehicle velocity during braking cycles, which was monitored by the dynamometer sensor software, sensors were installed to continuously monitor the hydraulic brake pressure and the brake drum friction surface temperature for the right rear (drive) wheel, where the dilution tunnel was installed for brake emission sampling. These parameters were also used to characterize the braking cycles devised by Cha et al. to conduct the brake dust mass emissions measurements currently applied in EMFAC2000 ARB emissions model. Since the test vehicle employed a proportional valve, to provide different hydraulic pressure to the front disc and rear drum brakes, the pressure transducer (Omega PX4200 series) was connected to the rear wheel brake line. Continuous measurements of the braking temperature were made using a non-contact IR sensor (Raytek, model # RAYMID10LTCB3), installed to allow the sensing zone to be focused on the brake drum friction surface through an aperture created in the brake system backing plate. Both sensors were accurate within $\pm$ 1%, and were interfaced with a signal conditioner (National Instruments model # SC-2345) with a high accuracy A/D converter (National Instruments model # 6063E). LabView software (National Instruments) was configured to process, store, and display the sensor measurements as a real-time plot on a laptop PC mounted in the cab of the vehicle. Also displayed in the laptop were the particle counts from each channel of the OPC using the manufacturer’s dedicated PeakNet software (Particle Measurement Systems).

### 2.5.3 Driving Cycle Emission Testing

A fundamental consideration in the brake dust emission testing was to configure the air sampling system to collect airborne particles emitted into a realistic free air flow field provided by the split section dilution tunnel. Although a significant improvement over previous sampling systems, the split section dilution tunnel was not designed to simulate the variation in dilution air velocity produced by changes in vehicle speed or to reproduce the complex nature of the undercarriage air turbulence produced in on road driving.

The nature of the BFM dust generated during braking and the air dispersion of emitted dust was also dependent on the type and frequency of braking cycles performed during testing. Previous researchers have used on-the-road vehicles to sample BFM dust emission, and have conducted emission measurements on isolated braking systems, removed from the parent vehicles. However, in these cases the emission measurements were made under unrealistic flow field conditions, using braking cycles that are difficult to apply to a California emissions model. Unlike these previous approaches, in this study, the BFM dust air emissions were measured for the test vehicle over standard dynamometer driving cycles, developed to represent typical real-world driving behavior for tailpipe emissions testing.

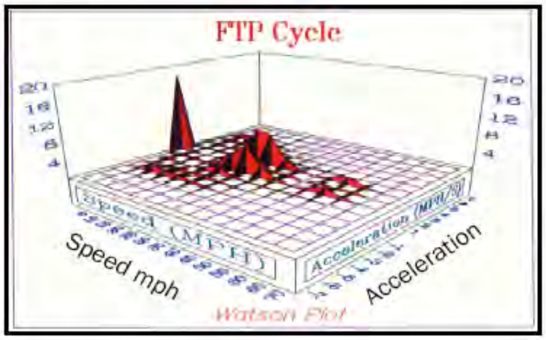
Sampling of the brake dust emissions from the vehicle operated on the chassis dynamometer was conducted over both the California Unified Cycle (LA92) and Federal Test Procedure (LA4) standard emission driving cycles, designed to model typical vehicle acceleration and braking patterns. The characteristics of each cycle are given in **Figure 2.5.4,** which was reproduced from the CARB's Emissions Inventory Series (Vol. 1, Issue 9, 2002). The LA92 cycle, developed by monitoring driving behavior using a chase vehicle, is considered to be more representative than the LA4 cycle based on a fixed urban traffic driving loop. The LA92 cycle includes higher maximum speeds, much greater accelerations (and decelerations), but fewer stops per mile than the LA4 cycle.

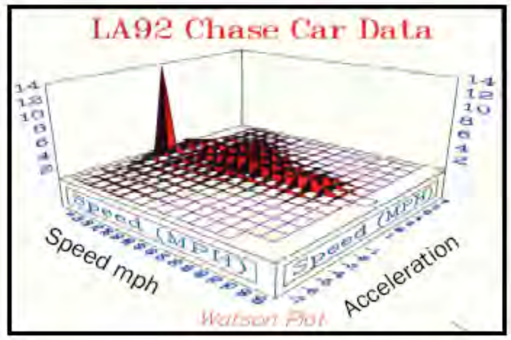
The dynamometer-simulated inertia weight for the test vehicle was adjusted by SRI to compensate for the difference in relative energy absorption by the front and rear axle brake pairs, as reflected in expected brake lifetimes. Front and rear brake lifetimes were assumed to be 35,000 miles and 70,000 miles respectively, based on the most recent brake emissions research by Garg et al. (2000). Without this adjustment, the drum brakes of the rear-wheel-drive test vehicle would absorb all the braking energy during a driving cycle and would experience brake heating unrepresentative of on-road operation.

The photograph of the experimental set-up in **Figure 2.5.5** includes the test vehicle mounted on the chassis dynamometer rollers (SRI, Sacramento), split section dilution tunnel installed on the vehicle undercarriage, flexible duct connections to the cast aluminum air mover, and the high volume total filter sampler with controller. Steel cable winches attached to the vehicle at two locations, front and rear, restricted vehicle lateral motion on the rollers and prevented significant wheel hop during hard braking. SRI staff configured and operated the chassis dynamometer for the brake emission cycle tests, with the inertial load on the rollers adjusted to compensate for braking occurring only at the rear wheels.

During each driving cycle, the test vehicle driver matched the vehicle speed with the live emission cycle trace displayed on a computer monitor, using the application of accelerator and brake. Display plots of the brake system sensors and particle counter data with time were monitored from the vehicle passenger seat. Time synchronized data records of: braking surface temperature, brake system hydraulic pressure, vehicle

## Watson Plots of the FTP and LA92 Cycles Speed Acceleration Frequency




**Comparison of the LA4, the 1992 Chase Car Data, and the Unified Cycle**

| Parameter | LA4 | Entire Data Set | UC / LA92 |
|---|---|---|---|
| Average Speed | 19.6 mph | 26.6 mph | 24.8 mph |
| Maximum Speed | 56.7 mph | 80.3 mph | 67.0 mph |
| Avg Maximum Speed | N/A | 55.8 mph | N/A |
| Percent Idle | 19.0 | 14.4 | 16.4 |
| Stops per Mile | 2.41 | 1.26 | 1.52 |
| Max Acceleration | 1.48 $m/s^2$ | 3.62$m/s^2$ | 2.75 $m/s^2$ |
| Avg Max Acceleration | N/A | 2.55$m/s^2$ | N/A |
| Cycle Length | 7.5 miles | N/A | 9.9 miles |

Figure 2.5.4 Characteristics for the emissions driving cycles used for the brake emissions testing, including the Federal (LA4) cycle, the entire 1992 chase car data set used to develop the California Unified Cycle (UC/LA92), and the UC/LA92 cycle.

Figure 2.5.5 Photograph of the experimental setup showing the dynamometer mounted test vehicle (1985 Chevrolet G20 Van), with the split section dilution tunnel and associated monitoring equipment.

velocity, optical particle counter channels for the size range between 0.3 and 10 um, as well as, dilution tunnel and total filter flow rate, were collected continuously throughout each emission driving cycle.

Airborne brake dust sampling was conducted for both standard emission cycles at the SRI dynamometer facility over three non-consecutive days during one week in mid-January 2005. During the first day, after initial vehicle setup on the dynamometer, one set of air samples (cyclone and total filter) was collected over two LA92 emission cycles, followed by a set of dynamic field blanks, collected under the same conditions, without the vehicle being put through the emissions cycle, but operated at idle. All known non-brake related sources of particles, including the engine exhaust were vented to the outside; however, the blank was necessary to account for any ambient air particles entrained in the HEPA filtered air transporting the brake emissions. No asbestos fibers or BFM particles were observed in the cyclone dynamic blank samples. During the second testing day, two sets of air samples were collected, each over three LA92 emission cycles, followed by a dynamic field blank. Finally on the third day, the emission cycle was changed for comparison, and two sets of air samples were collected, each over four LA4 emission cycles, followed by a dynamic field blank. A static blank, to measure any particulate matter introduced by the handling of the cyclone components and total filter holder, used in each sampling set, were collected at the conclusion of all emission sampling.

A sample of the brake dust generated during the brake emission driving cycles was also collected, using the same procedure developed for the BFM field sampling kit described in a previous section. Before utilizing the test vehicle to conduct the driving cycle emission measurements, the brake wear generated dust was thoroughly cleaned from all the internal brake surfaces of both rear wheels including: the brake backing plate components, brake drum, and all surfaces of the used brake shoes employed in the dynamometer emissions testing. These surfaces were not cleaned again until after the last test day when the drum brake dust was sampled for analysis. The drum dust was not sampled during the course of the emission testing to prevent introducing fugitive asbestos BFM drum dust as background contamination.

Asbestos analysis by TEM was conducted on the deposited brake drum dust samples, and emitted brake dust aerosol samples collected with the cyclone sampling train designed to provide PM10 and PM2.5 fractions. TEM analysis included the measurement of length and aspect ratio of each fiber identified as asbestos. Gravimetric analysis was conducted on the high volume sampler total filter, under well controlled conditions of temperature (21±1°C) and relative humidity (40±3%) per US EPA (US EPA/AMTIC, 1998), in order to determine test vehicle mass emission rates.

### 2.6 Asbestos Analysis in BFM and Brake Dust

Typical asbestos based ADFM contain a matrix of organic binders and inorganic fillers, which can hinder the identification and characterization of asbestos fibers. Additionally, the methods and techniques typically employed for asbestos analysis have advantages and disadvantages depending on the specific application. Accordingly, EHLB has developed an analysis scheme for asbestos in brake ADFM, the associated brake dust deposited in the brake system, and sampled as a fugitive air emission. The primary considerations in developing the methodology were as follows:

- Any pretreatment of the sample using low temperature ashing, solvent, or acid treatment to release the asbestos fibers from the matrix cannot significantly alter the chemical or physical characteristics of the asbestos fibers, as would occur with crushing or grinding.
- Light microscopy techniques, including polarized light illumination, were useful to survey the sample to establish a quantitative estimate of the asbestos composition, but were unable to resolve the finer asbestos fibers.
- Although scanning and transmission electron microscopy were capable of resolving fine asbestos fibers, their limited field of view required the development of stop-counting rules to limit the required number of fields to be counted.
- Energy dispersive spectroscopy (EDS) was used to establish that the elemental fingerprint of single fibers, observed with either the scanning or transmission electron microscope, was consistent with the asbestos fibers of the parent brake ADFM.
- Only transmission electron microscopy was capable of resolving the finest fibers and conducting SAED analysis to provide a positive identification of the form of asbestos present in the sample.

As shown in **Appendix C**, all known existing methods for asbestos TEM analysis were investigated and a table of method characteristics was created to evaluate the best approach for the study. A hybrid analytical scheme, which applies well established bulk material NIOSH method #9002 for PLM analysis of used brake ADFM to determine percent asbestos by mass (no fiber sizing), as well as, the established TEM methods ARB #427 and EPA #600/R-93/116 to analyze for the smaller sub-micron fiber size distribution found in the collected brake dust, were considered to provide the most useful approach for the current project.

Although asbestos fibers in the bulk BFM were large enough to be observed by PLM, the much smaller asbestos fibrils found in the deposited and emitted brake dust, which were produced by the abrasion of the BFM during braking, require analysis by electron microscopy methods. Since the health effect importance of size and number of asbestos fibers determined by electron microscopy is yet unclear, when compared with the percent total asbestos by mass determined by PLM, both techniques were initially included in the analysis scheme for all three matrices. The analytical scheme devised to analyze for the amount of asbestos present in the matrices of bulk BFM, surface deposited brake dust, and air samples of emitted brake dust, is given below.

A crucial component of the analysis of both deposited brake dust and brake dust air samples, was the dispersion of the collected material into particle-free water, with filtration onto a featureless polycarbonate 0.1 um filter. The water dispersion step, using a surfactant to reduce surface tension, was devised to allow clumps of brake dust, created as an artifact of air sampler collection or deposition on brake system components, to be resuspended as the individual brake dust particles emitted under braking. In this way, the results of the asbestos analysis conducted on the individual resuspended brake dust particles, will more accurately reflect the physical characteristics (size, shape) of the BFM dust particles emitted under braking. A detail protocol used to prepare the BFM, BFM deposited dust, and air samples for asbestos analysis by TEM is given in **Appendix D1**.

Included in the analysis scheme were the two sources used to collect asbestos samples: (1) dynamometer brake wear tests conducted at SRI to measure asbestos in airborne brake dust, deposited brake dust (DBD), and the associated BFM, and (2) brake shop field sampling, in which only DBD and the associated BFM were collected. It should also be noted that when present, asbestos must constitute a significant portion of the ADFM formulation (typically 20 - 60% by mass) in order to provide a useful contribution to the braking performance.

### 2.6.1 Filtration of Dust Samples

Dust samples were filtered onto 0.1 um polycarbonate filters using a water filtration method. To preserve the original particle size distribution as much as possible, no attempt was made to ash or dissolve dust matrix materials. For each sample, approximately 5 mg dust was diluted in 50 mL of deionized (DI) water, from which a 1 mL aliquot was drawn. Before taking each aliquot, the sample was briefly ultrasonicated for 6 minutes with a precision waveform proSonic™ cleaner to disperse loosely held clumps. Aliquots were filtered using a 25 mm diameter vacuum filtration apparatus that had been cleaned and ultrasonicated twice. To insure uniform deposition of each sample, 0.45 um mixed cellulose ester (MCE) filters were used as backing filters.

### 2.6.2 Filtration of Cyclone Air Samples (Coarse Fraction)

Cyclone coarse fraction washes were filtered onto 0.1 um polycarbonate filters using the same water filtration setup described above. (Cyclone fine fractions did not need to be filtered, as they were collected directly onto polycarbonate filters in the cyclone.) Again, no attempt was made to ash or dissolve dust matrix materials. For each cyclone wash, the sample tube was swirled vigorously, the entire 40 mL wash volume was filtered, and the tube was rinsed with 10 mL of DI water which was then filtered.

### 2.6.3 Grid Preparation and TEM Analysis of Dust and Air Samples

All dust samples, cyclone fine fractions, and cyclone coarse fractions were prepared on TEM grids and analyzed by TEM using a slightly modified version of CARB Method 427. The two departures from Method 427 were as follows: 1) stopping rules were based on sensitivities derived from USEPA 600/R-93/116 and Asbestos Hazard Emergency Response Act (AHERA) Methods, rather than the grid-opening-based rules given by Method 427, and 2) at the “low” magnification level, all asbestiform fibers were recorded. Method 427 only requires measurement of > 5 um long (‘NIOSH equivalent’) fibers at low magnification.

For dust samples, counting was stopped when the sensitivity of the percent asbestos in dust calculation was less than 0.00025% by mass. This is ten times lower than the required sensitivity of USEPA Method 600/R-93/ 116, as interpreted by USEPA

Region 9 in their 2004 El Dorado County study. Analytical sensitivity is defined here as the mass percent asbestos represented by one fiber:

$$Sensitivity_{TEM,\ dust}\ (\%) = (M_{single\ fiber} / M_{p,\ TEM}) \times 100,$$

where

$$M_{single\ fiber} = [(\pi/4)\ W^2 \times L] \times \rho_{chrysotile}$$

$M_{p,\ TEM}$ = mass of particles observed in TEM analysis
= $M_{sample} \times (V_{aliquot}/V_{sample}) \times (A_{TEM}/A_{filter})$

$M_{sample}$ = mass of brake dust used for sample preparation
$V_{sample}$ = volume of water used for sample preparation
$V_{aliquot}$ = volume of aliquot drawn for filtration
$A_{TEM}$ = area of grid observed during TEM analysis
$A_{filter}$ = active area of filter
W = fiber width
L = fiber length

In practice, the stop rule means that counting is stopped when $A_{TEM}$ , and thus $M_{p,\ TEM}$, becomes large enough to reach the desired sensitivity. The parameters assumed for the single fiber were $\rho_{chrysotile}$ = 2.55 g/cm$^3$, L = 2 um, and W = 0.06 um (representative dimensions observed for the single fibers in these dusts).

For air samples, counting was stopped when the analysis reached a sensitivity of 0.005 f/cc, as described by the AHERA method. Analytical sensitivity is defined here as the air concentration represented by one fiber:

$$Sensitivity_{TEM,\ air}\ (f/cc) = 1 / V_{a,\ TEM} ,$$

where

$V_{a,\ TEM}$ = volume of air sample characterized in TEM analysis
= $V_{a,\ tot} \times (A_{TEM}/A_{filter})$

$V_{a,\ tot}$ = total volume of air sample

Again, the stop rule means that counting is stopped when $A_{TEM}$ , and thus $V_{a,\ TEM}$, becomes large enough to reach the desired sensitivity.

TEM grids were prepared using a Bal-Tec MED-020 High Vacuum Evaporative Coater with carbon thread attachment and a chloroform Jaffe washer. TEM analyses were conducted using an FEI/Philips Tecnai 12 equipped with a Gatan DualView CCD camera and a ThermoNoran Vantage energy-dispersive X-ray spectroscopy (EDS) System. The TEM was operated at 100 KeV.

Fiber counting was conducted as follows: For each sample, TEM analyses were carried out at “low” and “high” magnifications of 9,700x and 58,000x, respectively. At each magnification, TEM grid openings were scanned for chrysotile fibers. Each time a chrysotile fiber was detected, an image and selected area electron diffraction (SAED) micrograph were recorded, fiber length and width was measured, and an EDS spectrum was recorded. All fibers with asbestiform morphology, > 3:1 aspect ratio, prominent magnesium and silicon EDS peaks, and appropriate SAED patterns were recorded as chrysotile. As noted in Method 427 Section 7.2.2.6 , the EDS pattern was considered sufficient in cases where no adequate SAED pattern could be obtained; this situation tended to arise for the smallest fibers only. Fiber length detection limits were set at 0.6 um and 0.01 um for low and high magnifications, respectively.

The fiber count data from each sample was imported into a Microsoft Excel spreadsheet template, which then automatically integrated the data for the two magnifications, estimated fiber volumes and masses, calculated asbestos weight percents and airborne concentrations (when applicable), and plotted asbestos fiber L distributions. Asbestos mass was determined by assuming a density of 2.55 g/cm3 and a cylindrical volume calculation based on fiber length and width, $VOL = L \times (\pi W^2/4)$. Fiber L distributions were plotted by discretizing the data into 10 size bins that were approximately evenly distributed (on a log scale) between 0.01 and 60 um.

### 2.6.4 CCSEM Estimates of Relative Particulate in Size Fractions

The distribution of airborne brake emissions between the fine and coarse particle fractions was estimated using computer-controlled SEM (CCSEM). Sections of the same polycarbonate filters, prepared for TEM fiber counting, were mounted on SEM stubs using double-sided adhesive carbon tabs. CCSEM analysis was conducted using the XL30 ESEM and Vantage system, which possesses scripting and automation capabilities.

Samples were analyzed at 3,600x and 20 KeV. Imaging was conducted using a back-scattered electron (BSE) detector. The Vantage system took images at pre-programmed stage locations, then automatically detected and sized all particles. A custom spreadsheet then converted the particle size information into particle aerodynamic diameters, masses, and size distributions. Calculations assumed a particle density, dynamic shape factor, and volume shape factor of 2.1 g/cc, 1.4, and 1.3, respectively. The automated analysis technique has been described before by Wagner and Macher (2003).

### 2.6.5 Asbestos Screening and Analysis of Brake Shoe Materials

All brake shoes from the field study were screened for asbestos content using techniques from NIOSH Method 9002. This method utilizes low-power stereozoom microscopy and PLM (see Appendix D2). In a ventilation hood, samples of each brake were prepared by breaking off pieces of the shoe material using a heavy duty end cutter tool. The pieces were then inspected under the stereozoom microscope. Using a scalpel and forceps, subsamples were removed and placed in 1.550 refractive index

Cargille oil on a slide with a cover slip. PLM was used to characterize the fibers in the brake material with respect to several key optical properties: fiber morphology, color under plane polarized light, extinction angle under crossed polars, sign of elongation, and birefringence as measured by dispersion staining, as specified in NIOSH method 9002.

If no fibers in a brake sample possessed the optical properties of chrysotile asbestos, the sample was recorded as a 'negative' sample. If any fibers did possess the optical properties of chrysotile, the sample was fully quantified using NIOSH Method 9002, both in terms of asbestos and its other components. In a few cases where the fibers' optical properties were obscured by an interfering matrix material, samples were ashed in a muffle furnace at 500°C for 24 hours to remove the matrix.

## 3. Results

### 3.1 Inventory of Asbestos ADFM

The database developed by SRI for LDV/MDV (EMFAC vehicle codes PC, T1, T2, and T3) contains over 3500 entries for different vehicle make and model years from 1973 through 1999. Each vehicle entry includes the model year, EMFAC weight class, type of brakes on each axle, and the percentage of current DMV registrations based on a random sampling of nearly 500,000 registered vehicles. A summary of the brake types for each model year based on nearly 300,000 LDV/MDV vehicles, regardless of make or model is given in **Table 3.1.1**. This population represents 3,578 different vehicle make and model years, which were screened to eliminate the potential for the double counting of MDV, which might also have been included in the HDV listing. The relative numbers of each make, model and model year in the vehicle fleet and the overall fractions of disc and drum brakes are given in detail in **Appendix E.**

Notable is the high proportion of vehicles in the LDV/MDV class (GVW $\leq$ 8,500 lbs.) with rear drum brakes, and the rare use of front drum brakes. As previously discussed, rear drum brakes are replaced infrequently, and are more likely to have older formulation BFM, high in asbestos. When integrated with the list of rear drum brake vehicles that were cross matched with asbestos BFM lined brake shoes, over 1,900 vehicle make and model years were identified as target vehicles, which could be contributing to on-the-road asbestos fiber emissions. An example of the asbestos BFM target vehicle listing for LDV/MDV is included in **Appendix F**, and a simplified target vehicle list distributed with the field sampling kit is given in **Figure 3.1.1.**

Unlike the LDV/MDV database, for the HDV (EMFAC vehicle codes T4, T5, T6. T7, and T8), an estimate of brake type frequency for vehicles currently on-the-road was accomplished by merging the small subset of HDV known to have disc brakes with the DMV database. All vehicles in the DMV database, which did not match this subset of disc brake HDV, were assumed to employ only drum brakes. A summary of brake types for the over 300 HDV of different makes and models identified for model years from 1973 through 2003 is given in **Table 3.1.2.,** and represents a total fleet of over 1,700 vehicles. Since as reported previously, there is no clear link between asbestos BFM lined brakes and specific HDV makes, model years, or weight classes, the entire data

**Table 3.1.1 Light and Medium Duty Vehicle* Brake Type for DMV Sample Distribution**

| | Front Brake Type | | | Rear Brake Type | | |
|---|---|---|---|---|---|---|
| **Model Year** | **Disk** | **Either**** | **Drum** | **Disk** | **Either**** | **Drum** |
| 1973 | 701 | 144 | 42 | 73 | . | 814 |
| 1974 | 563 | 101 | 21 | 64 | 2 | 619 |
| 1975 | 443 | 60 | 21 | 62 | 1 | 461 |
| 1976 | 989 | 1 | 5 | 131 | 33 | 831 |
| 1977 | 1450 | . | . | 115 | 39 | 1296 |
| 1978 | 1752 | . | . | 146 | 58 | 1548 |
| 1979 | 2239 | . | . | 309 | 68 | 1862 |
| 1980 | 2153 | . | . | 221 | 142 | 1790 |
| 1981 | 3695 | . | . | 335 | 68 | 3292 |
| 1982 | 4652 | . | . | 660 | 264 | 3728 |
| 1983 | 6306 | . | . | 507 | 825 | 4974 |
| 1984 | 9910 | . | . | 1013 | 1229 | 7668 |
| 1985 | 12335 | . | . | 1813 | 1057 | 9465 |
| 1986 | 14710 | . | . | 2555 | 1125 | 11030 |
| 1987 | 16361 | . | . | 2597 | 1169 | 12595 |
| 1988 | 13525 | . | . | 1833 | 1358 | 10334 |
| 1989 | 14745 | . | . | 1858 | 3370 | 9517 |
| 1990 | 14370 | . | . | 2395 | 3149 | 8826 |
| 1991 | 18380 | . | . | 2952 | 4848 | 10580 |
| 1992 | 15892 | . | . | 2756 | 5952 | 7184 |
| 1993 | 16175 | . | . | 2191 | 7310 | 6674 |
| 1994 | 14632 | . | . | 2353 | 5930 | 6349 |
| 1995 | 18410 | . | . | 3790 | 8531 | 6089 |
| 1996 | 19702 | . | . | 4369 | 9191 | 6142 |
| 1997 | 22577 | . | . | 4953 | 10380 | 7244 |
| 1998 | 20833 | . | . | 4881 | 8787 | 7165 |
| 1999 | 21087 | . | . | 5294 | 9745 | 6048 |
| **Total** | 288587 | 306 | 89 | 50226 | 84631 | 154125 |

* Includes EMFAC vehicle codes PC, T1, T2, T3

**Vehicle can be equipped with either drum or disk brakes.

| Make | Model | Year |
|---|---|---|
| TOYOT | CAMRY | 1983 |
| TOYOT | CAMRY | 1984 |
| TOYOT | CAMRY | 1985 |
| TOYOT | CAMRY | 1986 |
| TOYOT | CAMRY | 1987 |
| TOYOT | CAMRY | 1988 |
| TOYOT | CAMRY | 1989 |
| TOYOT | CAMRY | 1990 |
| TOYOT | CAMRY | 1991 |
| TOYOT | CAMRY | 1992 |
| TOYOT | CAMRY | 1993 |
| TOYOT | CAMRY | 1994 |
| TOYOT | CAMRY | 1995 |
| TOYOT | CAMRY | 1996 |
| TOYOT | CAMRY | 1997 |
| TOYOT | CAMRY | 1998 |
| TOYOT | CAMRY | 1999 |
| TOYOT | CELIC | 1973 |
| TOYOT | CELIC | 1974 |
| TOYOT | CELIC | 1975 |
| TOYOT | CELIC | 1976 |
| TOYOT | CELIC | 1977 |
| TOYOT | CELIC | 1978 |
| TOYOT | CELIC | 1979 |
| TOYOT | CELIC | 1980 |
| TOYOT | CELIC | 1981 |
| TOYOT | CELIC | 1982 |
| TOYOT | CELIC | 1983 |
| TOYOT | CELIC | 1984 |
| TOYOT | CELIC | 1985 |
| TOYOT | CELIC | 1986 |
| TOYOT | CELIC | 1987 |
| TOYOT | CELIC | 1988 |
| TOYOT | CELIC | 1989 |
| TOYOT | CELIC | 1990 |
| TOYOT | CELIC | 1991 |
| TOYOT | CELIC | 1992 |
| TOYOT | CELIC | 1993 |
| TOYOT | CELIC | 1994 |
| TOYOT | CELIC | 1995 |
| TOYOT | CELIC | 1996 |
| TOYOT | CELIC | 1997 |
| TOYOT | CELIC | 1998 |

Figure 3.1.1 Example page of the vehicle target list for LDV/MDV distributed with the brake sampling kits, from the Toyota section.

**Table 3.1.2 Heavy Duty Vehicle* Brake Type for DMV Sample Distribution**

| Model Year | Count | Front Brakes | | | Rear Brakes | | |
|---|---|---|---|---|---|---|---|
| | | Disk | Either** | Drum | Disk | Either** | Drum |
| 1973 | 11 | . | . | 11 | . | . | 11 |
| 1974 | 11 | . | . | 11 | . | . | 11 |
| 1975 | 7 | 1 | . | 6 | . | . | 7 |
| 1976 | 7 | . | . | 7 | . | . | 7 |
| 1977 | 10 | 1 | . | 9 | . | . | 10 |
| 1978 | 11 | . | . | 11 | . | . | 11 |
| 1979 | 13 | 2 | . | 11 | 1 | . | 12 |
| 1980 | 10 | . | . | 10 | . | . | 10 |
| 1981 | 12 | . | . | 12 | . | . | 12 |
| 1982 | 7 | 2 | . | 5 | . | . | 7 |
| 1983 | 8 | 4 | . | 4 | 2 | 2 | 4 |
| 1984 | 12 | 8 | . | 4 | 2 | 3 | 7 |
| 1985 | 11 | 7 | . | 4 | 2 | 2 | 7 |
| 1986 | 17 | 10 | . | 7 | 2 | 3 | 12 |
| 1987 | 14 | 7 | . | 7 | 2 | 1 | 11 |
| 1988 | 16 | 8 | . | 8 | 4 | . | 12 |
| 1989 | 12 | 6 | . | 6 | 3 | . | 9 |
| 1990 | 14 | 3 | . | 11 | 3 | . | 11 |
| 1991 | 5 | . | . | 5 | . | . | 5 |
| 1992 | 10 | 2 | . | 8 | 2 | . | 8 |
| 1993 | 10 | 2 | . | 8 | 1 | . | 9 |
| 1994 | 8 | 2 | . | 6 | 2 | . | 6 |
| 1995 | 10 | 3 | . | 7 | 2 | . | 8 |
| 1996 | 13 | 4 | . | 9 | 2 | . | 11 |
| 1997 | 14 | 5 | . | 9 | 4 | . | 10 |
| 1998 | 11 | 3 | . | 8 | 3 | . | 8 |
| 1999 | 10 | 2 | . | 8 | 2 | . | 8 |
| 2000 | 11 | 3 | . | 8 | 3 | . | 8 |
| 2001 | 13 | 2 | . | 11 | 2 | . | 11 |
| 2002 | 6 | . | . | 6 | . | . | 6 |
| 2003 | 2 | . | . | 2 | . | . | 2 |
| **Total** | **326** | **87** | **0** | **239** | **44** | **11** | **271** |

* Includes EMFAC vehicle codes T4, T5, T6, T7, T8

**Vehicle can be equipped with either drum or disk brakes.

base, included as **Appendix G,** was used as the target list of used BFM field collections.

This process was essential to develop the most reliable estimate of the vehicles currently on the road in California, which could be contributing to asbestos fiber air emissions produced under braking. Refined target vehicle lists were also necessary to narrow the scope of used brake field sampling program, designed to verify the presence of asbestos through the laboratory analysis of the brake ADFM collected.

### 3.2 Brake Friction Material Field Sampling

Monitoring the progress of brake repair shops in properly collecting used BFM and brake dust from target vehicles, according to the written instructions (see Appendix B), proved to be somewhat problematic. Despite repeated assurances from some brake shop managers that they were willing to participate, few brakes were forthcoming during the over nine month collection period. Fortunately, several brake shops, which service a wide variety of LDV/MDV, were very conscientious in collecting samples and recording vehicle information. Only about 10% of the field samples had to be discarded because they were incorrectly collected.

For most of the HDV brake repair shops, the necessity of breaking a sample of BFM from the brake shoe core proved to be a major sampling obstacle. Offers to sample the BFM from the shoe core on-site by EHLB laboratory staff were unsuccessful in generating samples from more than one HDV brake shop.

#### 3.2.1 Application of Asbestos BFM Survey Methods

Sample kits containing collected BFM and brake dust were picked up from brake shops on a bi-monthly basis, and returned to the laboratory for asbestos screening. Qualitative screening results, using low power stereo microscope examination followed by PLM dispersion staining, were simply used to detect the chrysotile asbestos used in BFM (see Appendix D2). Since asbestos is known to be present in BFM at high levels (20-60%) in order to be an effective friction modifier, screening results were obtained rapidly.

The vehicle information sheet provided with each brake kit was invaluable in tracking the vehicle make, model year, engine type, and mileage at brake replacement. Although included in the information sheet, as well, the fields intended to identify information about the used brake shoe removed (installation mileage and manufacturer part number) were usually not provided. Interestingly, the manufacturer’s part numbers for the new replacement brake shoes installed was often provided, and identified the BFM as asbestos-free. This is consistent with the new packaging for brake shoes and pads currently sold by the major auto parts suppliers including NAPA, which indicates that the asbestos BFM versions have recently been replaced with asbestos-free versions.

#### 3.2.2 Asbestos Content of Field Collected BFM

BFM screened from target list vehicle brake shoes which contained asbestos were analyzed by NIOSH Method 9002, to quantify the mass percentage of chrysotile present. Analysis results for the BFM from the rear brake shoes of a 1985 Chevrolet G20, on the target list, is given in **Figure 3.2.1**. Using PLM following ashing treatment to remove organic binder material, the analysis indicated that the BFM was 60% chrysotile asbestos. The results of the analysis shown are given in the format devised to track the sample pre-treatment conducted before analysis, and the asbestos results obtained with each of the PLM measurements techniques. It was important to note that the mass fraction of asbestos found to be present in brake BFM was unaffected by the ashing treatment used to remove the BFM organic binder matrix from the fibers for more accurate PLM analysis. Additional analysis using scanning electron microscopy (SEM), employing EDS, was used to determine that the asbestos fibers were typically present in large bundles protruding from the friction surface of the BFM, as shown in **Figures 3.2.2a, and 3.2.2b.**

Screening and analysis results for all the BFM collected in the field study are listed in **Table 3.2.1.** Of the 38 vehicles screened for asbestos BFM in the used brake shoes collected from brake repair shops, the eight vehicles not on the target list contained no detectable asbestos, and four of the 31 vehicles that were on the target list were found to have high level asbestos BFM. All chrysotile asbestos BFM levels were between 20-60% in agreement with the associated MSDS, which was essentially the same for each vehicle, and was included previously as **Figure 2.3.1.** A common MSDS for these vehicles is not surprising, since their asbestos BFM was produced by Allied Signal Corporation, which was the largest manufacturer of asbestos BFM, with over 60% of the domestic market (S. Braun, 2000). The highest level of asbestos BFM was collected from the rear drum brake shoes of the Chevrolet G20 Van, owned by EHLB. The EHLB G20 van was included in **Table 3.2.1**, since the same protocol employed by the participating brake shops to identify and collect samples was applied to this vehicle as well.

Unfortunately, the only BFM samples obtained from HDV brake repair shops were collected from a pool of used brake shoe cores with no record of the vehicle make, model year or weight class. The local Kenworth Truck Dealer that removed BFM samples from the brake shoe cores, did confirm that all make and model year HDV routinely receive brake service in their shop. The dealer indicated that the BFM samples were collected from the brake shoes of different vehicles, which is consistent with the difference in physical appearance between samples (size, shape, rivet hole pattern). In any case, this assumed random sampling of the BFM from the brake shoes of 15 HDV, revealed no detectable asbestos using the same screening method employed for LDV/MDV.

### 3.2.3 Asbestos Fiber Characterization in Deposited Brake Dust

Using the analysis protocol detailed in **section 2.6,** dust samples collected from the rear brake drum of the four vehicles identified with asbestos BFM shoes, were characterized for chrysotile asbestos fibers by TEM. Gravimetric analysis under tightly controlled conditions (40 $\pm$ 3% RH, 21 $\pm$ 1 $^{o}$C), provided accurate mass determinations for the sub-samples prepared for analysis, which were typically < 6 mg. TEM analysis results for

**TREATED SAMPLE WORKSHEET**

Laboratory Sample #: ____________ Analyst: jwagner

Client Sample ID: CV-85-G20-S2

| | | | | | |
|---|---|---|---|---|---|
| **Composition of Treated Sample (NIOSH Method 9002)** | Method: ashing treatment | | | | |
| 1. Gravimetic Analysis | Substrate [crucible, filter, etc.] (g) | | | | 15.2561 |
| | Before treatment: Substrate + sample (g) | | | | 15.2838 |
| | After treatment: Substrate + sample (g) | | | | 15.276 |
| -->> % of bulk material removed = | 28 % | | | | |
| 2. Type(s) of Asbestos and % of each in TREATED sample: or: ☐ none | ☐ Asbestos - ACTN | % | ☑ Asbestos - CHRY | 75 | % |
| | ☐ Asbestos - AMOS | % | ☐ Asbestos - CROC | | % |
| | ☐ Asbestos - ANTH | % | ☐ Asbestos - TREM | | % |
| 3. Type(s) of non-Asbestos fibers and % of each in TREATED sample: or: ☐ none | ☐ Fibers - CELL | % | ☐ Fibers - OTHR: | | % |
| | ☐ Fibers - FBGL | % | specify: | | |
| | ☐ Fibers - SYNT | % | | | |
| 4. Matrix material(s) and % of each in TREATED sample: | ☐ Non-fiber - ACID | % | ☐ OTHR: org. binder | | % |
| | ☐ Non-fiber - MICA | % | ☑ OTHR: opaque PM | 25 | % |
| | *[ Non-fiber - OTHR (total) ]* 25 | % | ☐ OTHR: | | % |
| | | | specify: | | |

| **-->>implied % in bulk:** | | | **FINAL ANSWER:** | | |
|---|---|---|---|---|---|
| Asbestos - ACTN | | % | Asbestos - ACTN | | % |
| Asbestos - AMOS | | % | Asbestos - AMOS | | % |
| Asbestos - ANTH | | % | Asbestos - ANTH | | % |
| Asbestos - CHRY | 54 | % | Asbestos - CHRY | 60 | % |
| Asbestos - CROC | | % | Asbestos - CROC | | % |
| Asbestos - TREM | | % | Asbestos - TREM | | % |
| Fibers – CELL | | % | Fibers – CELL | | % |
| Fibers – FBGL | | % | Fibers – FBGL | | % |
| Fibers – SYNT | | % | Fibers – SYNT | | % |
| Fibers – OTHR | | % | Fibers – OTHR | | % |
| Non-fiber – ACID | | % | Non-fiber – ACID | | % |
| Non-fiber – MICA | | % | Non-fiber – MICA | | % |
| Non-fiber – OTHR | 18 | % | Non-fiber – OTHR | 40 | % |
| Removed by treatment: | 28 | % | | | |

Figure 3.2.1 Asbestos analysis results for 1985 Chevrolet G20 used brake shoe on the target list (brake part RS473).

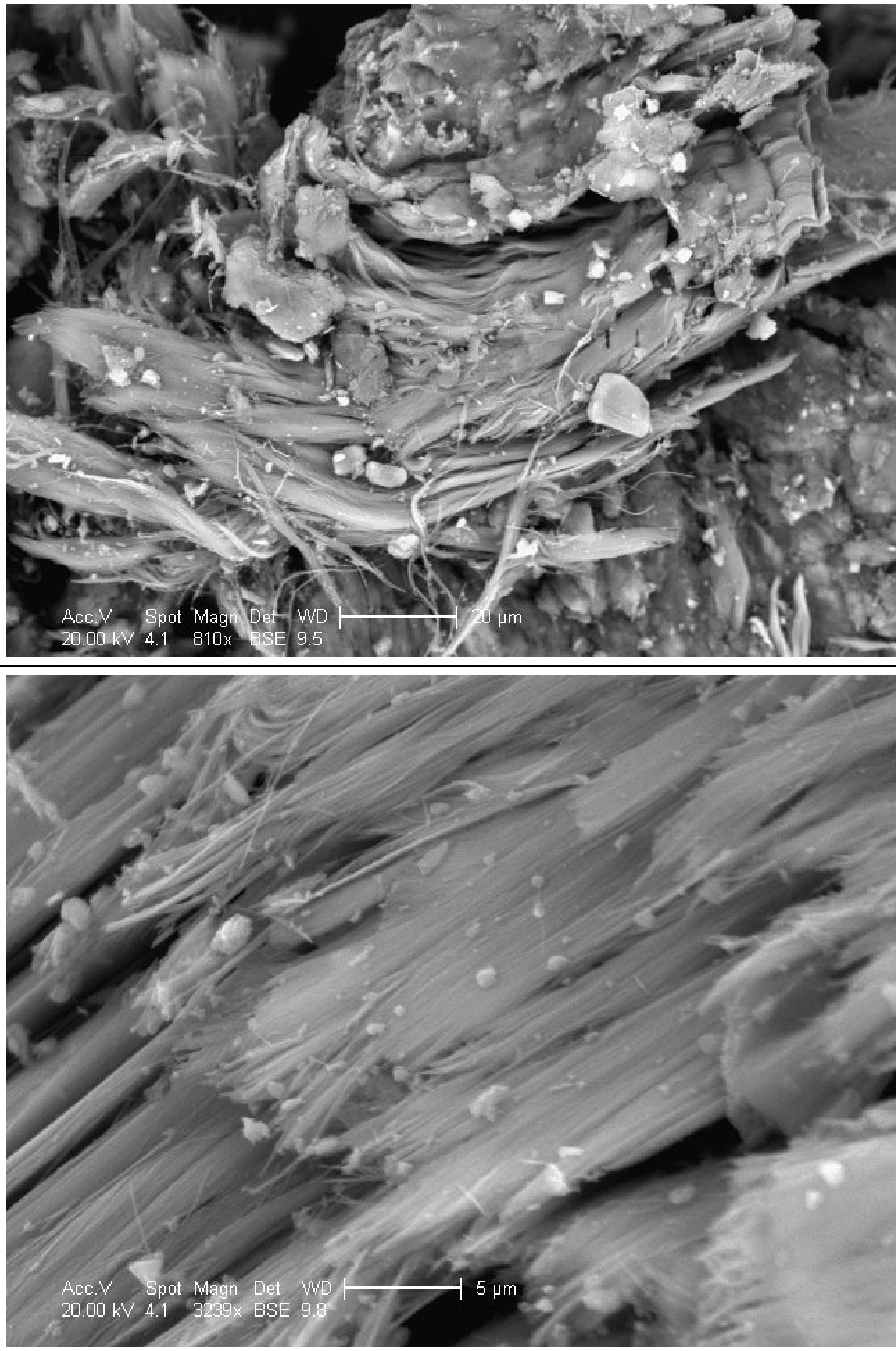



Figure 3.2.2 (a) Asbestos fiber bundles (wavy strands) within matrix material of the RS473 brake shoe from EHLB van. (b) higher magnification of asbestos fiber bundles.

**Table 3.2.1 Asbestos Content of Field Collected Rear Drum Brake Friction Material and Deposited Brake Dust Determined by PLM**

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| **Target Vehicles with Asbestos Brake Friction Material** | | | | | | |
| **60%** | **<1%** | **Chevy** | **1985** | **G20 Van[a]** | **5L V8** | **61,090** |
| **26%** | **<1%** | **Pontiac** | **1996** | **Grand AM** | **(2.4L4/3.1V6)** | **102,303** |
| **40%** | **<1%** | **Pontiac** | **1998** | **Sunfire** | **2.4L** | **73,270** |
| **30%** | **<1%** | **Volks** | **1992[b]** | **Jetta** | **2.0L L4** | **188,457** |
| **Target Vehicles without Asbestos Brake Friction Material** | | | | | | |
| ND | --- | Buick | 1994 | LeSab | 3.8L V6 | 95,133 |
| ND | --- | Chevy | 1997 | S10 | 2.2L L4 | 116,467 |
| ND | --- | Ford | 1985 | Mustang | 5.0L V8 | 69,981 |
| ND | --- | Ford | 1993 | Ranger | 3.0L V6 | 129,337 |
| ND | --- | Ford | 1989 | Taurus | 3.8L V6 | 114,878 |
| ND | --- | Ford | 1999 | Windstar | 3.0/3.8L V6 | 122,188 |
| ND | --- | GMC | 1997 | Yukon | 5.7L V8 | 189,364 |
| ND | --- | Honda | 1993 | Civic | 1.5/1.6L L4 | 143,170 |
| ND | --- | Honda | 1995 | Civic | 1.5/1.6L L4 | 149,049 |
| ND | --- | Mazda | 1991 | MX-6 | 2.2L L4 | 104,680 |
| ND | --- | Mercury | 1998 | Sable | 3.0L V6 | 148,426 |
| ND | --- | Mercury | 1995 | Cougar | 3.8L V6 | 134,341 |
| ND | --- | Nissan | 1993 | Altima | N/A | 141,586 |
| ND | --- | Nissan | 1997 | Quest | 3.0L V6 | 118,306 |
| ND | --- | Nissan | 1991 | Sentra | 1.6L L4 | 127,621 |
| ND | --- | Toyota | 1985 | Camry | 2.0L L4 | 130,679 |
| ND | --- | Toyota | 1994 | Corolla | 1.6/1.8L L4 | 140,405 |
| ND | --- | Toyota | 1999 | Camry | 2.2L4/3.0V6 | 99,031 |
| ND | --- | Toyota | 1999 | Corolla | 1.8L L4 | 81,678 |
| ND | --- | Toyota | 1997 | Corolla | 1.6/1.8L L4 | 75,133 |
| ND | --- | Toyota | 1992 | Corolla | 1.6L L4 | 194,414 |
| ND | --- | Toyota | 1994 | Corolla | 1.6/1.8L L4 | 184,838 |
| ND | --- | Toyota | 1990 | Corolla | N/A | 95,763 |
| ND | --- | Toyota | 1992 | Corolla | 1.6L L4 | 111,376 |
| ND | --- | Toyota | 1996 | Corolla | 1.8L L4 | 65,000 |
| ND | --- | Toyota | 1996 | Corolla | 1.6/1.8L L4 | 94,465 |
| ND | --- | Toyota | 1998 | Corolla | 1.8L L4 | 96,708 |
| **Non-Target Vehicles without Asbestos Brake Friction Material** | | | | | | |
| ND | --- | Chevy | 1999 | Tahoe[c] | 5.7L V8 | 75,438 |
| ND | --- | Oldsm | 2000 | Alero[c] | 2.4L L4 | 65,058 |
| ND | --- | Ford | 2001 | Windstar | 3.8L V6 | 58,277 |
| ND | --- | Ford | 1996 | Ranger | 3.0/4.0L V6 | 132,234 |
| ND | --- | GEO | 1995 | Prizm | 1.6L L4 | 175,176 |
| ND | --- | GEO | 1994 | Prizm | 1.6/1.8L L4 | 68,368 |
| ND | --- | GMC | 1999 | Sonoma | N/A | 68,879 |
| ND | --- | Toyota | 2001 | Sienna | 3.0L V6 | 61,523 |

a. Not brake shop collected, rather EHLB vehicle identified and sampled per standard sampling kit
b. Corrected from originally reported model year (1995) based on drum brake compatibility
c. Rear disc brake pads were collected by the brake shop for vehicle not on the target list

the counting and sizing of individual asbestos fibers present in the brake dust according to the stop counting rules developed (see **section 2.6.3**), are given in dust mass normalized fiber length distributions for number of fibers, **Figure 3.2.3a,** and fiber mass, **Figure 3.2.3b.**

For all brake drum deposited brake wear dust samples, the fiber number distribution exhibits a single sub-micrometer fiber length mode, with the fibers distributed toward smaller lengths for the VW Jetta and Pontiac Sunfire, and larger lengths for Chevrolet G20 and Pontiac Grand AM. The largest number concentration of fibers by dust mass was observed for the Chevrolet G20 Van used for the air emission sampling measurements.

Since the mass concentration is most influenced by the relative number of larger fibers, the mass distributions extend well into the micrometer fiber lengths, with the Chevrolet G20 and Pontiac Sunfire displaying multi-modal fiber length distributions. The single mode in fiber mass concentration near 1 um observed for the Pontiac Grand AM, was an order of magnitude larger than the single mode for the VW Jetta. The mass distribution for the Chevrolet G20 was tri-modal, with mass peaks in the sub-micrometer, micrometer, and super-micrometer size ranges.

Calculated from the sum of the individual fiber masses, the percent chrysotile asbestos per unit mass for deposited brake dust, collected from the brake drum of each of these four target vehicles with asbestos BFM, is provided in **Figure 3.2.4**. In general, the level of asbestos in the brake dust was < 0.1% for all vehicles, with the lowest levels of < 0.01% observed for the Pontiac Sunfire and the VW Jetta.

### 3.3 Airborne Brake Dust Emission Measurements

As described in **section 2.5**, a split dilution tunnel was used to collect air samples of the brake dust emitted from the 1985 Chevrolet G20 test vehicle, known to employ asbestos BFM in the rear drum brakes. The samples collected from the dilution tunnel with the cyclone train included both coarse 2.5 – 10 um aerodynamic diameter (Da) and fine ($\leq$ 2.5 um Da) PM10 particle size fractions. Samples collected with the cyclone train were intended only for TEM analysis, which requires low mass loadings in order to identify, count, and size individual asbestos fibers, unhindered by the larger background of non-asbestos collected mass. Accordingly, the total filter sampler operating at well over two orders of magnitude higher flow rate was utilized to calculate the vehicle brake dust mass emission rate.

### 3.3.1 Dynamometer Sampling Runs

A summary of the three dynamometer test days including: the driving cycle type, number of emission driving cycles over which a set of cyclone and total filter samples were collected, and elapsed sampling time is given in **Table 3.3.1.** Note that dynamic blanks were run to correct for the intrusion of ambient particle laden air into the split dilution tunnel, inherent in use of a free air section to allow a more realistic air stream dispersal of the brake wear generated dust. As can be noted from **Table 3.3.1**, these dynamic blank samples were collected for about the same duration as one

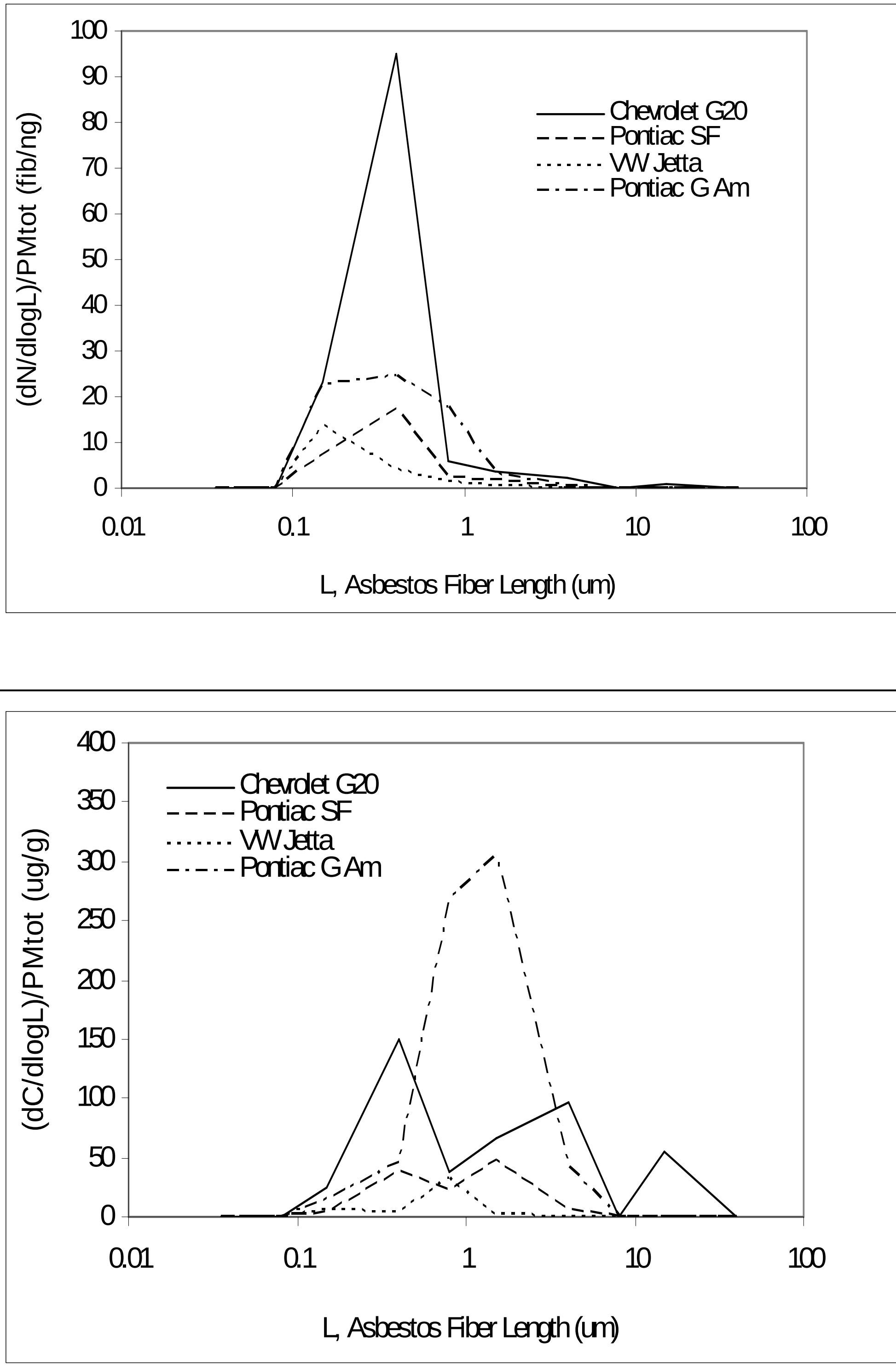



Figure 3.2.3 (a), Top frame: mass normalized fiber length distributions for the number of asbestos fibers and (b), Bottom frame: asbestos fiber mass, from rear drum brake dust analysis for vehicles with asbestos BFM.

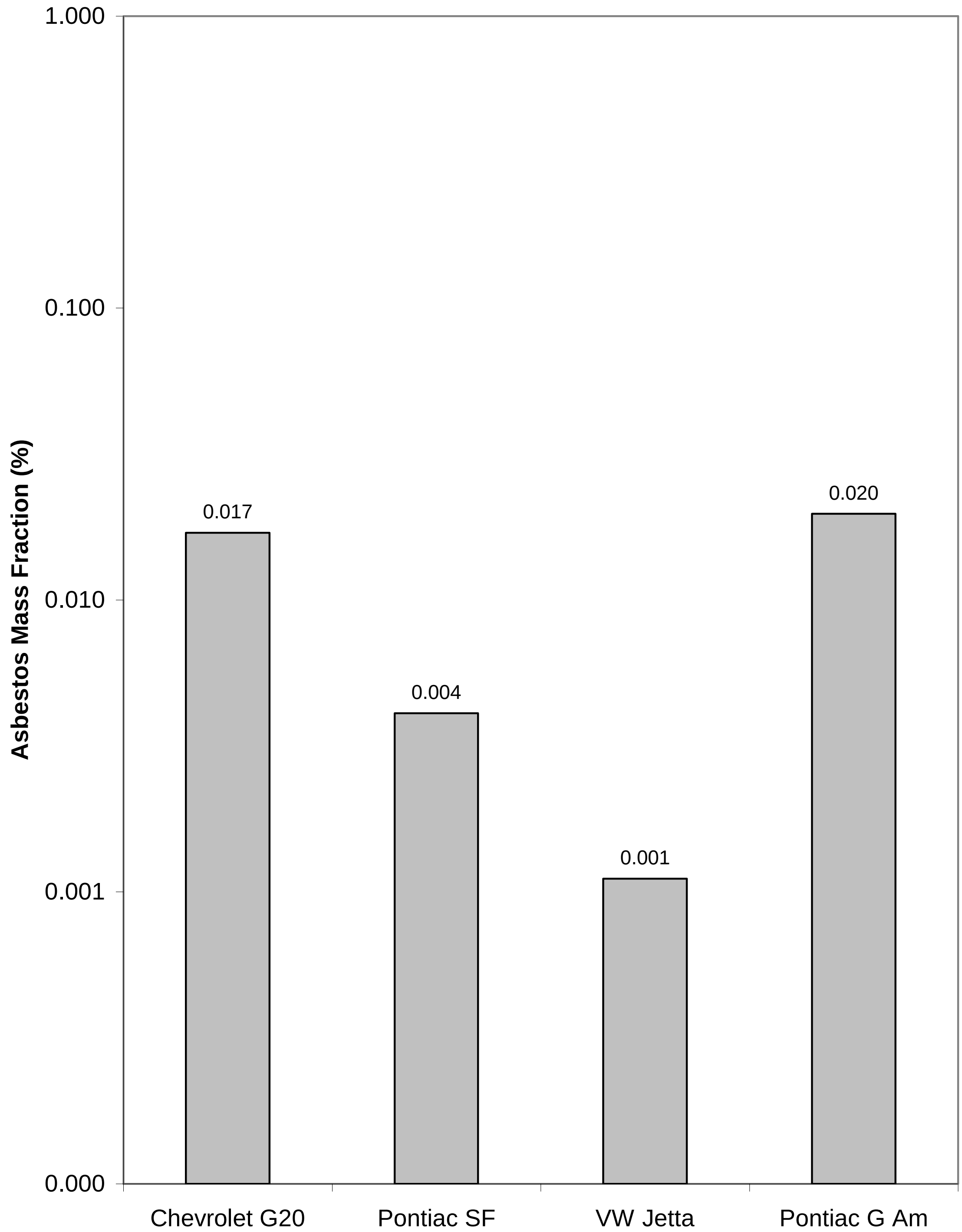



Figure 3.2.4 Chrysotile asbestos percent mass fraction for deposited brake dust, collected from the brake drum of each of the four target vehicles with asbestos BFM.

Table 3.3.1 Summary of the Air Sampling Runs Conducted for a Series of Dynamometer Driving Cycles Over the Three Test Days Including BFM Mass Emission Rate Measurements Based on the Total Filter (1985 Chevrolet G20 Van)

| Dyno Test | Driving Cycle | Driving Cycle[a] | Filter Set | Sampling Time | Collected Mass[d] | Sample Volume | Airborne Level | Corrected Air Level | Total Distance | Total Mass Emission[e,f,g] |
|---|---|---|---|---|---|---|---|---|---|---|
| Day No. | Type | Run Nos. | Run No. | (min) | $M_C$ (mg) | $V_S$ (m3) | (ug/m3) | $L_A$ (ug/m3) | $D_T$ (Miles) | $M_{TE}$ (mg/axle-mile) |
| 1 | UC/LA92 | 1 - 2 | E3 | *51.83* | 11.40 | 91.1 | 124.2 | 113.4 | 19.84 | 2.86 |
| 1 | - | Dyna Blank[b] | E4 | *25.00* | 0.57 | 44.7 | 10.7 | --- | --- | --- |
| 2 | UC/LA92 | 1 - 3 | E5 | *78.83* | 5.47 | 142.7 | 37.7 | 26.6 | 29.62 | 0.71 |
| 2 | UC/LA92 | 4 - 6 | E6 | *76.33* | 3.52 | 137.3 | 25.0 | 13.9 | 29.52 | 0.36 |
| 2 | - | Dyna Blank[b] | E7 | *18.83* | 0.47 | 34.3 | 11.1 | --- | --- | --- |
| 3 | Fed/LA4 | 1 - 4 | E8 | 101.00 | 3.30 | 175.4 | 18.3 | 7.5 | 29.60 | 0.25 |
| 3 | Fed/LA4 | 5 - 8 | E9 | *99.17* | 3.79 | 171.0 | 21.6 | 10.9 | 29.62 | 0.35 |
| 3 | - | Dyna Blank[b] | E10 | *19.50* | 0.47 | 34.9 | 10.8 | --- | --- | --- |
| 3 | - | Static Blank[c] | E11 | --- | 0.09 | --- | --- | --- | --- | --- |

a. Driving cycle run numbers are given to be consistent with real-time sensor data format.

b. Dynamic blanks were collected under the same conditions as the emission samples, except the vehicle was stationary with the engine at idle.

c. Static blanks were collected by mounting and unmounting the filter in the same manner as for emission samples, but without applying air flow.

d. Total filter mass was collected from a portion of the total dilution tunnel flow, and was increased by a flow factor of 2.75 to calculate $M_{TE.}$

e. Total vehicle mass emission ($M_{TE}$) is for the rear axle of the test vehicle, determined by doubling the emission rate for the drum brake sampled.

f. Total vehicle emission rate, including both front disc and rear drum brakes, can be estimated by applying a factor of 2.45 derived from Cha et al.(1983), which includes an adjustment for the differential wear between disc and drum brakes.

g. Total mass emission calculation: $L_{A,E3} = 1000 * ((M_{C,E3} - M_{C,E11}) / V_{S,E3} - (M_{C,E4} - M_{C,E11})/V_{S,E4})$

$$M_{TE,E3} = L_{A,E3} * 2 * 2.75 * V_{s,E3} / 1000 / D_{T,E3}$$

dynamometer cycle, and always collected approximately the same mass loading on each day.

Accordingly, the airborne mass concentration determined from these dynamic blanks was assumed to be constant, and was used to calculate a corrected mass emission concentration. Interestingly, based on subsequent SEM analysis of the cyclone air samples, an unexpected background of air borne mold spores in the SRI dynamometer facility was the major contribution to the dynamic blank mass. Based on the blank corrected total mass collected over the course of the dynamometer cycles and the mass of brake dust collected from the brake drum, one third of the brake wear generated mass was present in the air emission.

Using the total miles traveled for each air sampling run, which varied depending on the number and type of driving cycles employed, a mass emission source strength in mg/axle-mile (two drum brakes) could be determined. From these values given in **Table 3.3.1**, the source strength, on a per-vehicle basis, can be calculated using a factor of 2.45, based on the approach of Cha et al., to account for the different emission rates expected for the front disc and rear drum brakes. The resulting emission rates were all less than half of the classical value, 12.8 ug/mile, estimated by these previous researchers for a 1972 Chevrolet Impala, operated over a non-standard driving cycle.

These source strength measurements were considerably higher for the first day sampling period (E3), when the surfaces inside the brake drum, including the brake shoe friction surface, had been freshly cleaned. The only other difference was the addition, starting with run E5, of a quarter round section of 6” diameter PVC between the two halves of the dilution tunnel, to act as shield against turbulence produced by the dynamometer rollers below the vehicle tire. However, as will be shown in the next section, the addition of this shield did not appear to significantly alter the optical particle counter data, especially when compared to differences in particle size distribution between the different driving cycles.

### 3.3.2 Real-time Sensor Data

The characteristics of the emission driving cycles performed on the chassis dynamometer were monitored with real-time sensors for vehicle velocity, brake fluid hydraulic pressure, brake drum friction surface temperature, and the size distribution of emitted particles. As representative examples, the variations of these parameters with time during the second emission cycle for each of the three sampling days, are given in **Figures 3.3.5, 3.3.6, and 3.3.7.** Notable is the difference in the vehicle velocity profile between the UC/LA92 driving cycle used on the first two days (**Figures 3.3.5, 3.3.6)** and the LA4 cycle (**Figure 3.3.7)**, as expected from the discussion in **section 2.5**. For each driving cycle conducted, the actual vehicle velocity closely matched the driving cycle target speed, as shown in the bottom most trace in these figures.

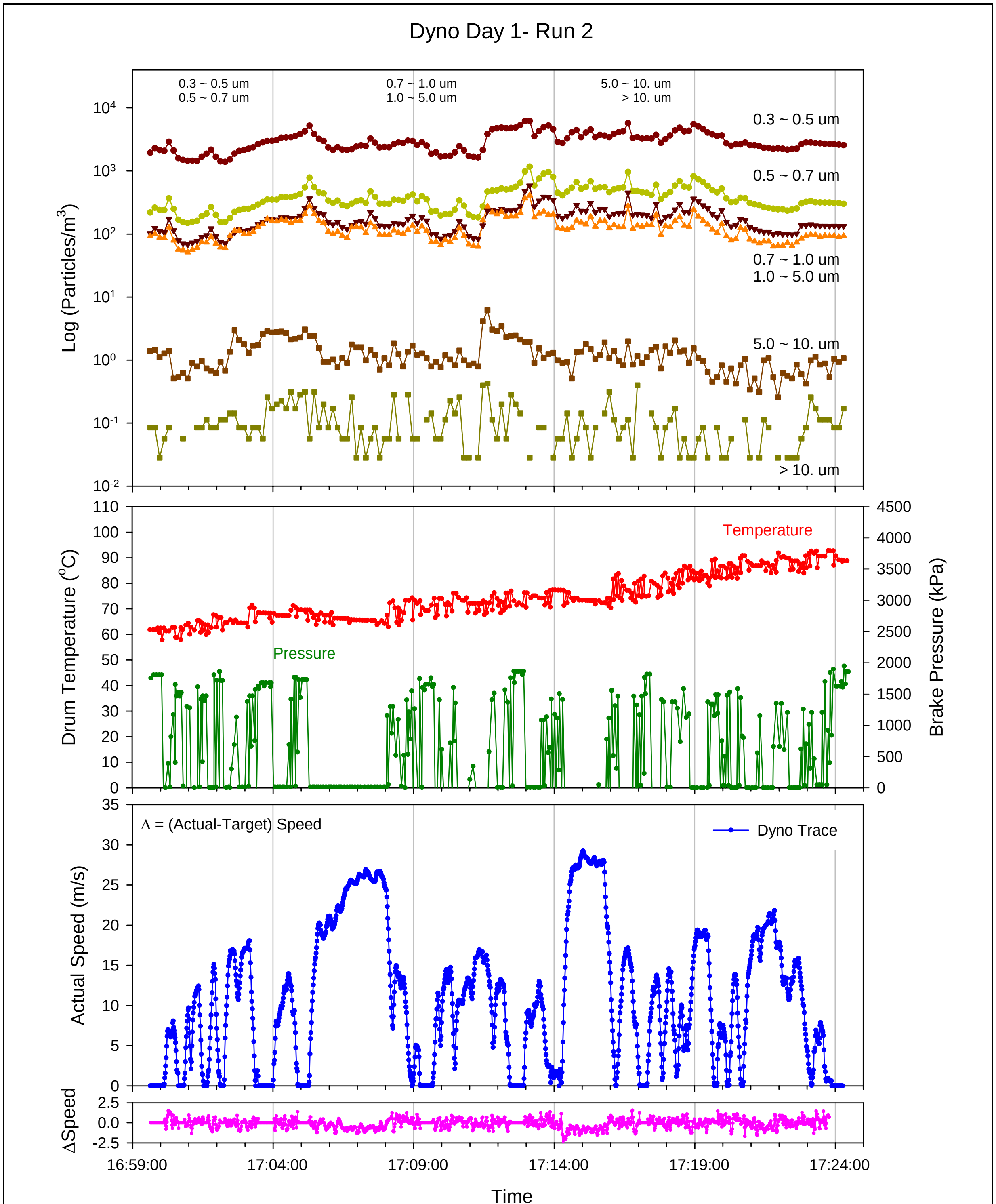



Figure 3.3.5 Test vehicle (1985 Chevrolet G20 Van) chassis dynamometer time series Day1 – Run2 for LA92 driving cycle showing (top) particle size fraction counts, (center) brake drum temperature and hydraulic pressure, and (bottom) actual velocity compared with target velocity.

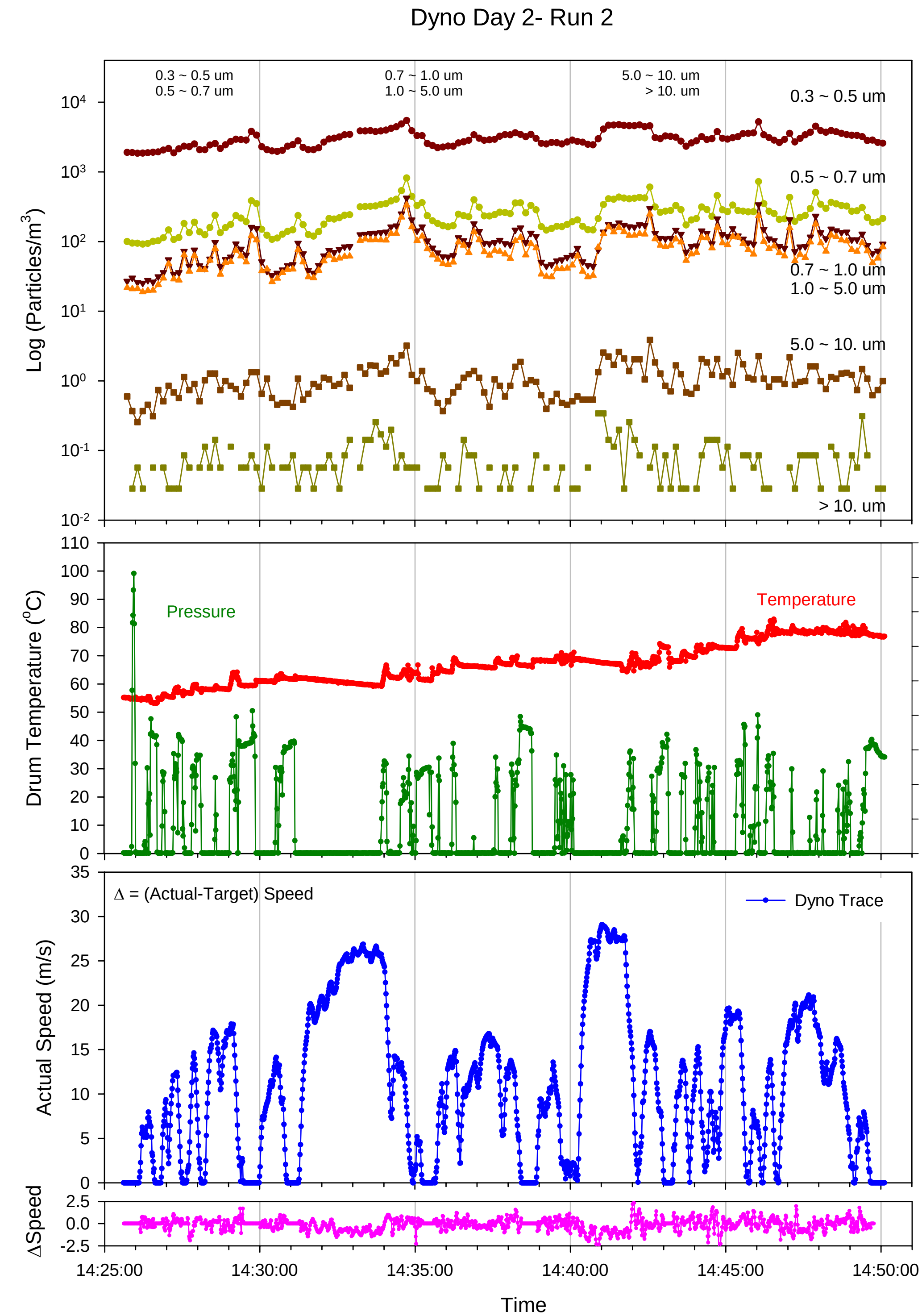



Figure 3.3.6 Test vehicle (1985 Chevrolet G20 Van) chassis dynamometer time series Day2 – Run2 for LA92 driving cycle showing (top) particle size fraction counts, (center) brake drum temperature and hydraulic pressure, and (bottom) actual velocity compared with target velocity.

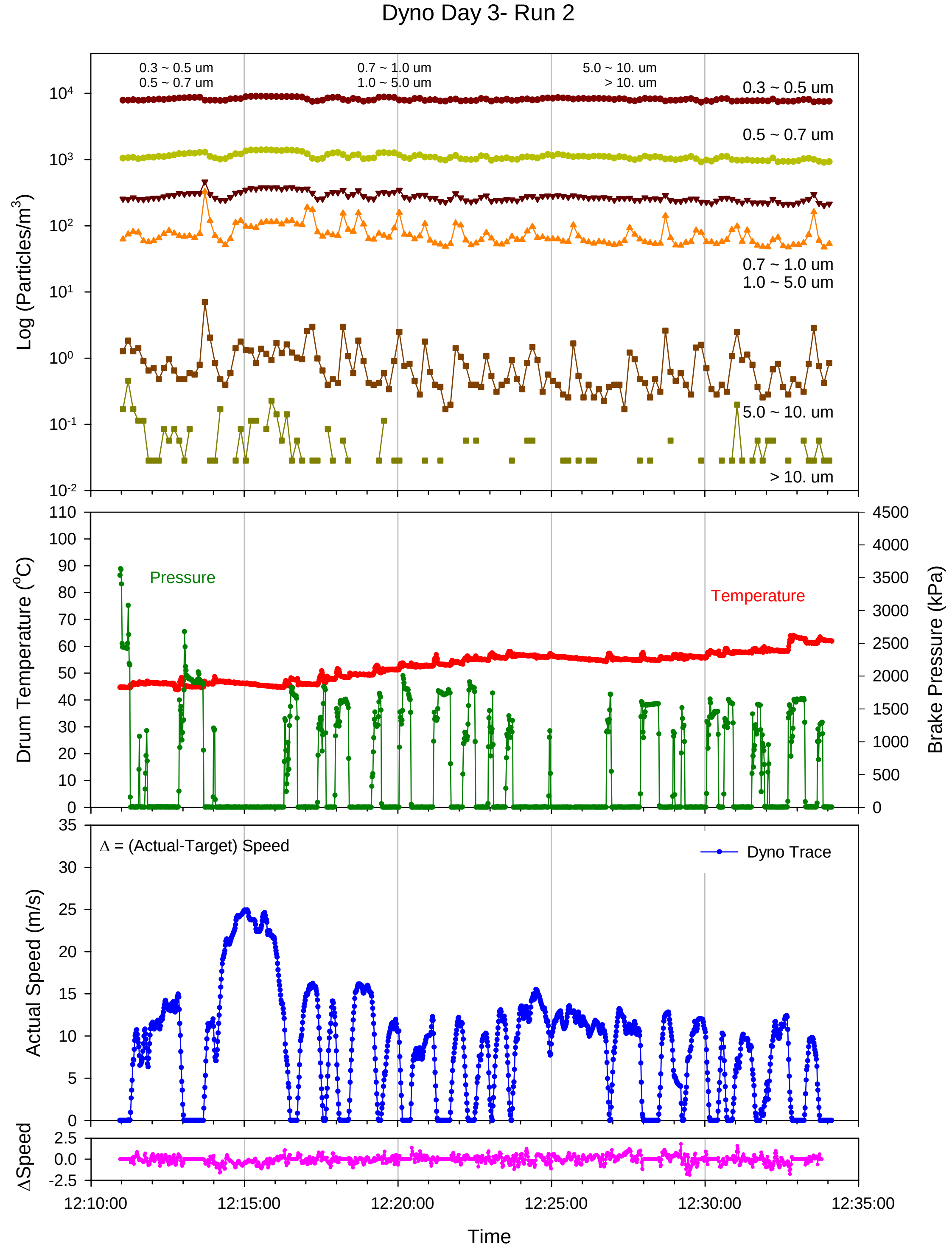



Figure 3.3.7 Test vehicle (1985 Chevrolet G20 Van) chassis dynamometer time series Day3 – Run2 for LA4 driving cycle showing (top) particle size fraction counts, (center) brake drum temperature and hydraulic pressure, and (bottom) actual velocity compared with target velocity.

The brake pressure trace, which rarely exceeded 2,500 kPa (360 psi), shows a considerable amount of fine structure, produced by the application of brakes for the fine speed adjustments necessary to match the driving cycle. Although the brake drum friction surface temperature increased with braking during a driving cycle, the high thermal mass of the braking system prevented the temperature from ever rising above 140°C, even after a series of four driving cycles run in quick secession. Remarkable are the similarities in the OPC particle size traces for the first two sampling days, which both employed the UC/LA92 driving cycle, despite the introduction of the additional turbulence shield discussed above. Distinctly different are the particle size traces for the LA4 driving cycle used on the last sampling day, consistent with generation of far fewer sub-micrometer particles than observed for the UC/LA92 driving cycle. Note that the OPC particle distributions given here have not been corrected for dynamic blank levels and are intended to display the fine structure of the particle emissions. A complete set of real-time sensor time series data for all the dynamometer driving cycles and dynamic blank runs is provided in **Appendix H**. The applicable dynamic blank OPC data is shown to be relatively constant, especially for particles < 5 µm. A dynamic blank (Day1, blank run 1) taken hours before the emission testing began, reflects the decay of the particle background after the dynamometer and all sampling equipment was started for the first time.

### 3.3.3 Airborne Asbestos Fiber Length Distributions

TEM analysis using fiber counting and sizing techniques as described in **section 2.6.3**, were applied to two of the five cyclone air samples of brake dust emissions due to project resource limitations. The cyclone air samples were chosen from one sampling period for each of the two different driving cycles investigated. Since asbestos fibers can be converted to a non-hazardous form due to the heat evolved in frictional braking, the analysis scheme included quality control measures to ensure the identification and quantification of hazardous asbestos fibers in the collected samples.

Fiber length distributions for the coarse (2.5 -10 um) and fine (<2.5 um) aerodynamic size fractions collected with the cyclone sampler are given in **Figures 3.3.8 and 3.3.9**, for the UC/LA92 and Federal LA4 emissions driving cycles respectively. Distributions are displayed for both asbestos fiber number (N) and mass (C) air concentrations, since both measures are potential exposure markers for human respiratory disease. The TEM fiber counting data for both the cyclone air samples and dust sample, collected during the dynamometer driving cycles, as well as, the field collected asbestos BFM dust samples collected by brake shops, are included in **Appendix I.**

The most striking feature of the fiber length distributions are the large differences in air concentration between these different driving cycles for both fiber number and fiber mass. Much higher levels were observed for the UC/LA92 cycle, which is characterized by harder braking events from higher velocities than the urban street circuit used for the Federal/LA4 cycle. For the UC/LA92 cycle, considered to be more representative of typical driving behavior, the PM10 fiber number and mass concentration is dominated by sub-micron length fibers, which are collected in the PM2.5 fraction. Although the primary mode of the mass and number fiber length distributions coincide, the mass

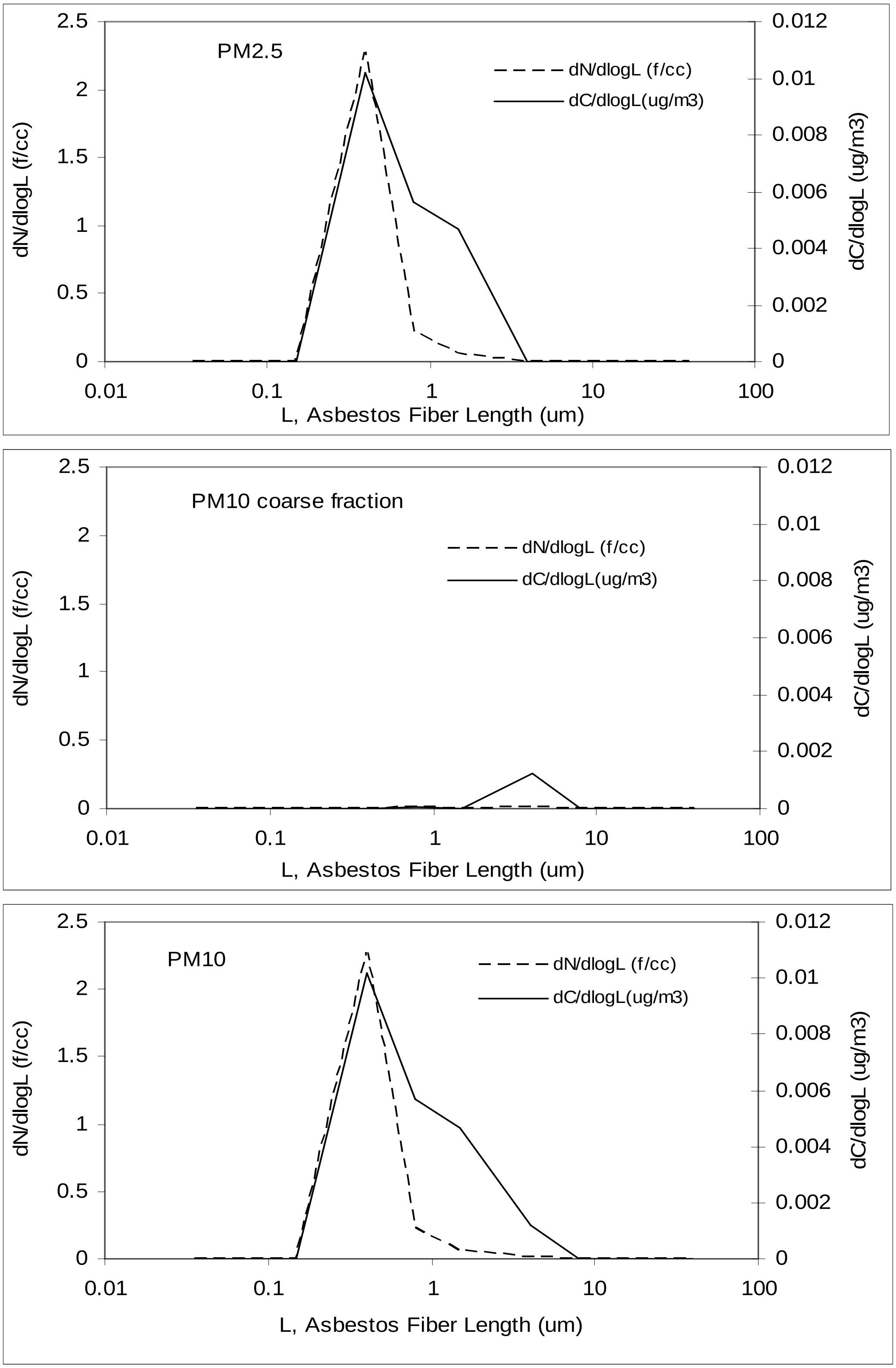



Figure 3.3.8 Airborne fiber length distributions for the coarse (2.5 -10 um) and fine (< 2.5 um) aerodynamic size fractions collected with the cyclone sampler from the 1985 Chevrolet G20 test vehicle for the UC/LA92 driving cycles.

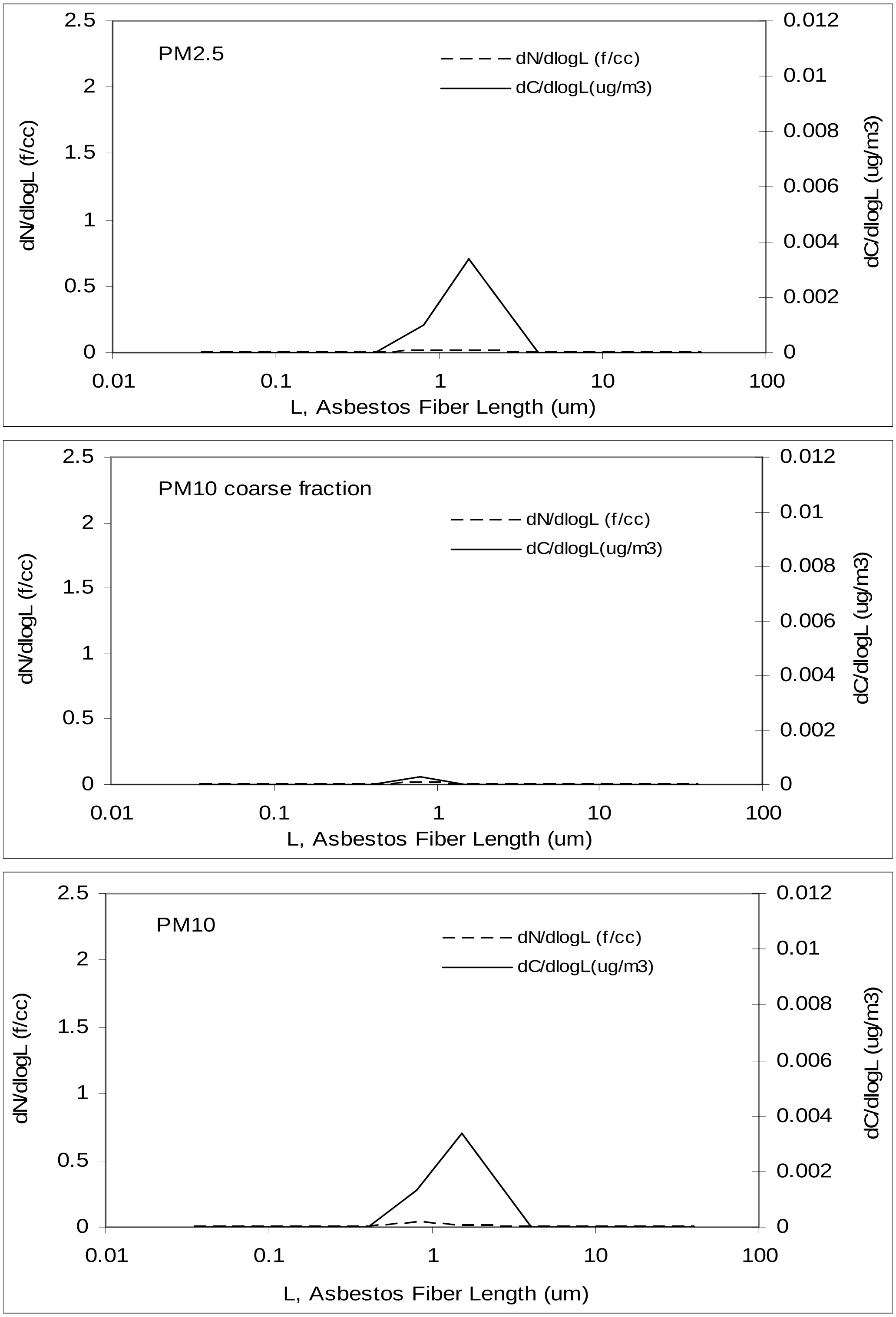



Figure 3.3.9 Airborne fiber length distributions for the coarse (2.5 -10 um) and fine (< 2.5 um) aerodynamic size fractions collected with the cyclone sampler from the 1985 Chevrolet G20 test vehicle for the Federal LA4 emissions driving cycle.

peak is asymmetrical with a shoulder extending to larger fiber length, consistent with a bi-modal distribution. Although the coarse fraction contributes little to the magnitude of the PM10 asbestos fiber mass, the coarse fraction mass mode extends the PM10 distribution to fiber lengths near 10 um.

In contrast, for the Federal/LA4 cycle considered to have more urban surface street driving character, the lower absolute PM10 fiber mass concentration is dominated by super-micrometer length fibers, which are collected in the fine fraction as PM2.5 aerosol. Similar to the LA92 cycle, most of the PM10 asbestos fiber mass is contributed by the fine fraction. Interestingly, the small contribution to PM10 asbestos fiber mass from the coarse fraction occurs for fiber lengths in the sub-micrometer range indicating that shorter fiber length does not always correlate with smaller aerodynamic size.

### 3.3.4 Airborne and Deposited Asbestos Fibers

Of particular interest was the relationship between the characteristics of the brake dust asbestos fibers deposited inside the brake drum, with the fugitive asbestos fibers dispersed from the braking system as an airborne emission. Such a relationship would offer the capability to estimate the source strength of the asbestos fiber air emission based on the analysis of deposited dust, which is significantly easier to collect. Accordingly, the airborne asbestos fiber length distributions were normalized by the total collected mass (rather than air volume sampled) for comparison with the deposited dust results, as shown in **Figures 3.3.10 and 3.3.11** for the UC/LA92 and Federal/LA4 driving cycles respectively.

The fiber length distribution by asbestos mass and fiber number for the deposited brake dust is the same in each figure since the brake drum dust sample collected represents the brake wear produced by all of the driving cycles listed previously in **Table 3.3.1.** Although this became a necessary constraint in order to complete the required sampling schedule, fortuitously the deposited brake dust distribution generated during dynamometer testing was not dissimilar to on-road generated dust sampled before the driving cycles began. For the airborne asbestos distributions derived from the cyclone train, the normalization mass was obtained from the total filter for the corresponding sampling period, corrected for the much higher flow rate of the total filter sampler.

Comparing the mass normalized asbestos fiber number distributions for the UC/LA92 and Federal/LA4 driving cycles, the deposited dust and air emissions from both cycles primarily contained fibers in the sub-micrometer length range, although the smaller peak in the air emission for the Federal/LA4 cycle extended to longer fiber lengths. This single sub-micrometer fiber length mode, although larger for the more aggressive UC/LA92 driving cycle, was over half an order of magnitude smaller for the air samples relative to the deposited dust per unit of sampled mass. For the less aggressive Federal/LA4 cycle, this difference was substantially greater.

Unlike the fiber length number distributions, the mass distribution for the airborne fibers normalized to total sample mass is quite different for the two driving cycles. For the

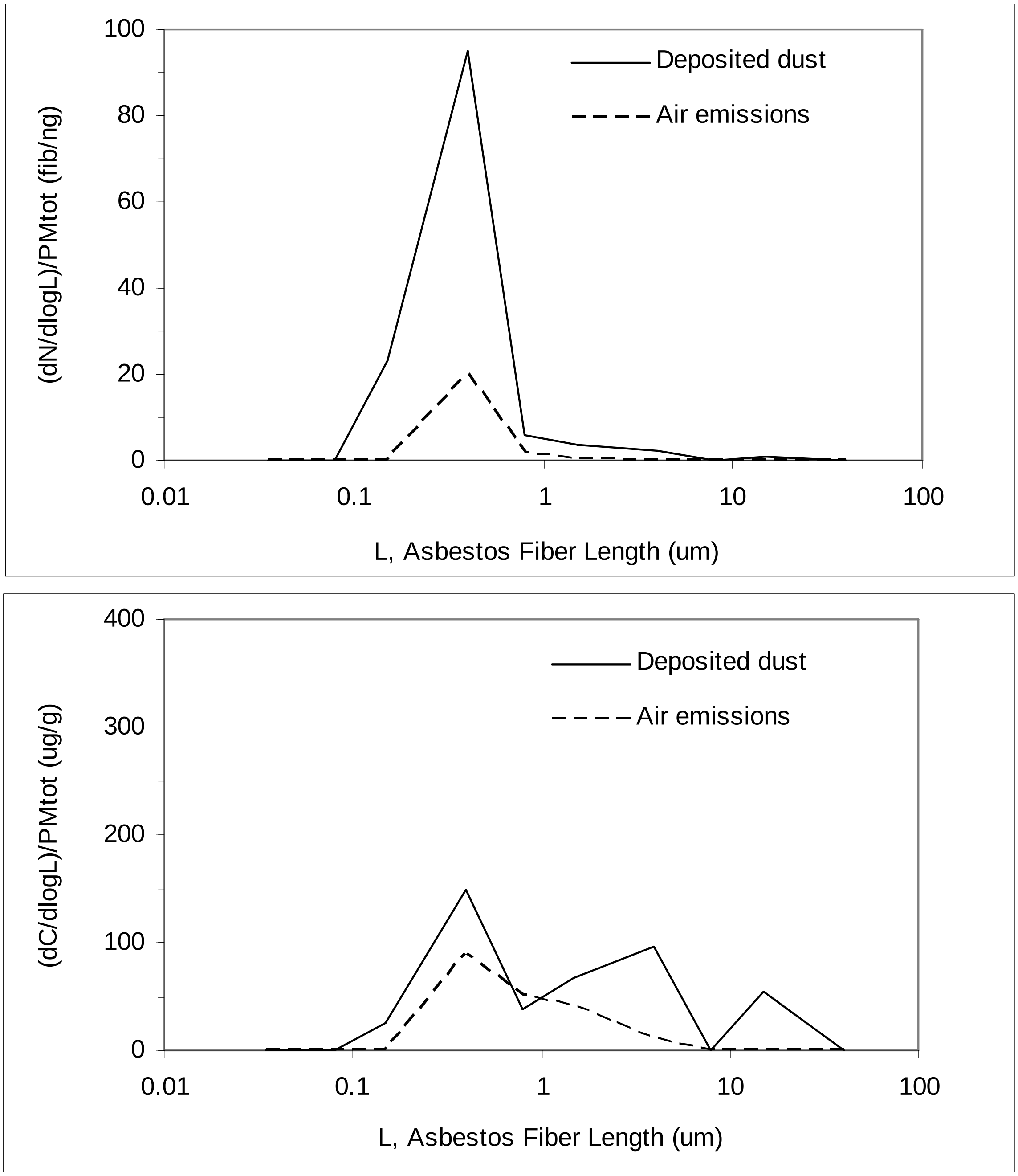



Figure 3.3.10 Airborne asbestos fiber length distributions normalized by the total collected mass for comparison with the deposited dust results from the 1985 Chevrolet G20 test vehicle for the UC/LA92 driving cycle.

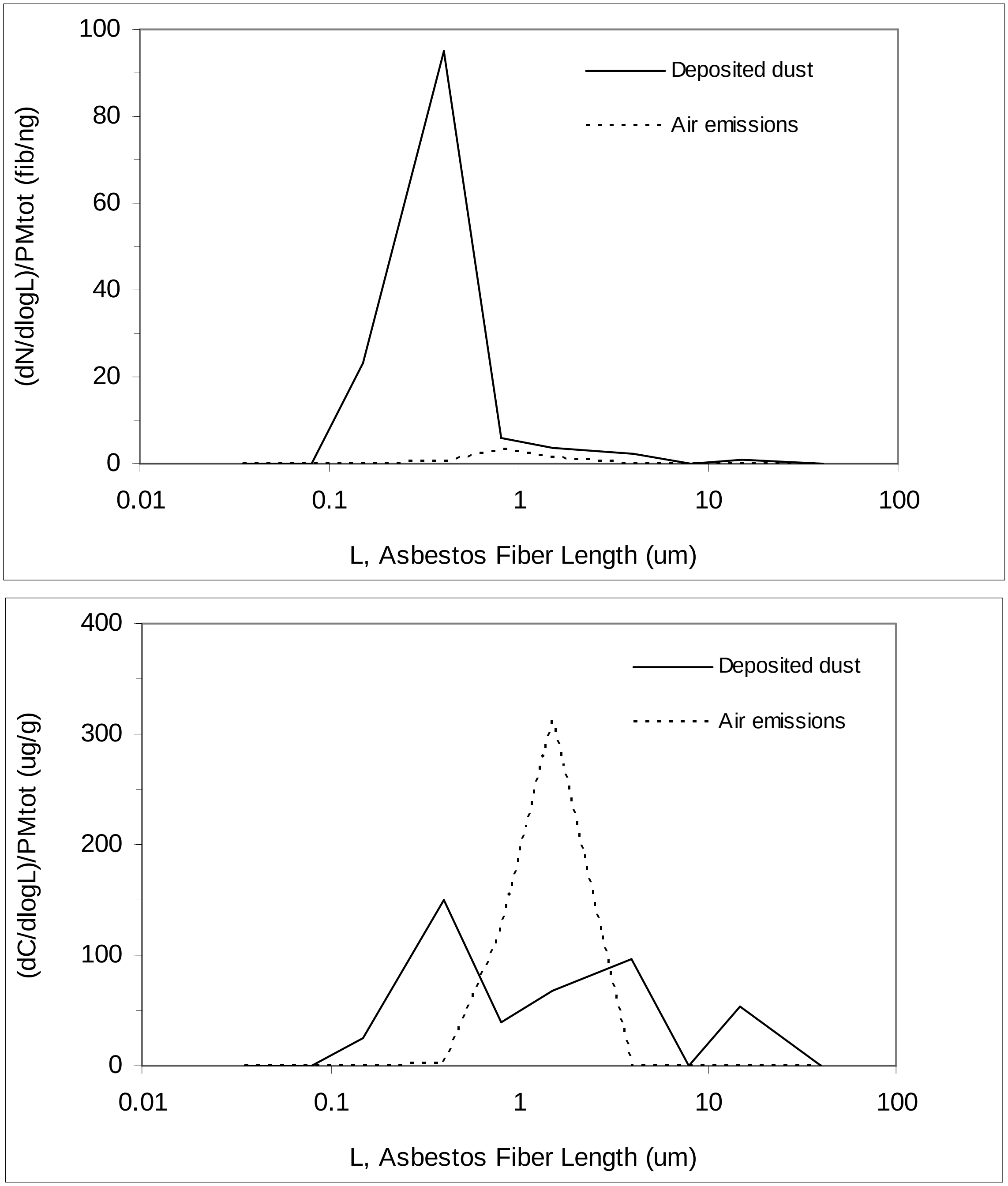



Figure 3.3.11 Airborne asbestos fiber length distributions normalized by the total collected mass for comparison with the deposited dust results from the 1985 Chevrolet G20 test vehicle for the Federal/LA4 driving cycle.

more aggressive UC/LA92 cycle, the asbestos fiber mass exhibits a broad distribution with a peak in the sub- micrometer range, and extends through the super-micrometer fiber lengths. Although the magnitude of the air emission sub-micrometer asbestos mass peak is similar to that of the deposited dust, the asbestos fiber mass in the air emission decreases for larger fiber lengths, and does not display the super-micrometer modes present in the deposited dust. This would be consistent with a smaller transmission efficiency expected for the larger length asbestos fibers from the space inside the brake drum to the ambient air.

The modal distribution of airborne asbestos mass from the less aggressive Federal/LA4 cycle occurs at a larger fiber size and is significantly greater in magnitude than for the UC/LA92 cycle. However, as observed for the UC/LA92, the airborne asbestos mass distribution for the Federal/LA4 cycle does not extend to the longest fiber lengths (> 10 um), which are present in the deposited dust.

To underscore the similarity in the nature of the chrysotile asbestos fibers of similar size observed in the air emission and the deposited brake dust, electron micrographs taken with the SEM are included as **Figures 3.3.12 and 3.3.13.** Morphology for the super-micrometer length asbestos fibers observed in the deposited brake dust and airborne fibers collected in the coarse fraction (2.5 -10 um aerodynamic diameter) are shown in the top and bottom frames of **Figure 3.3.12,** respectively**.** Similarly, the sub-micrometer length asbestos fibers observed in the deposited brake dust and fibers collected in the fine cyclone fraction (PM2.5) are shown in the top and bottom frames of **Figure 3.3.13.** The airborne asbestos fibers shown were all collected in the cyclone sampling train during UC/LA92 driving cycles. Note that in these examples, the airborne fibers occur as single fibers, while the deposited dust fibers can be associated with other fibers or brake dust matrix particles.

### 3.3.5 Asbestos Mass Fraction in Aerosol and Dust

As described above, the cyclone sampler was operated to collect light mass loadings in order to prevent co-collected brake dust matrix from interfering with the counting and sizing of the individual asbestos fibers and fiber bundles. Since this precluded gravimetric analysis on the cyclone samples, the distribution of total mass collected between the PM10 coarse fraction and the PM2.5 fraction was conducted by CCSEM single particle image analysis and converted to mass fraction, as previously described in **section 2.6.4**. The resulting aerodynamic size distributions are provided for the cyclone samples collected during the California UC/LA92 and Federal/LA4 driving cycles under consideration in **Appendix J.** Using this method, the mass present in the coarse and fine PM10 fractions was determined to be 56% and 44% respectively for the UC/LA92 driving cycle (sample set E3), and 59% and 41% respectively for the Federal/LA4 driving cycle (sample set E9).

This mass ratio for the two size fractions was applied to the air emission mass concentration measured by the total filter, and was used to estimate the mass collected on each stage of the cyclone sampler as follows:

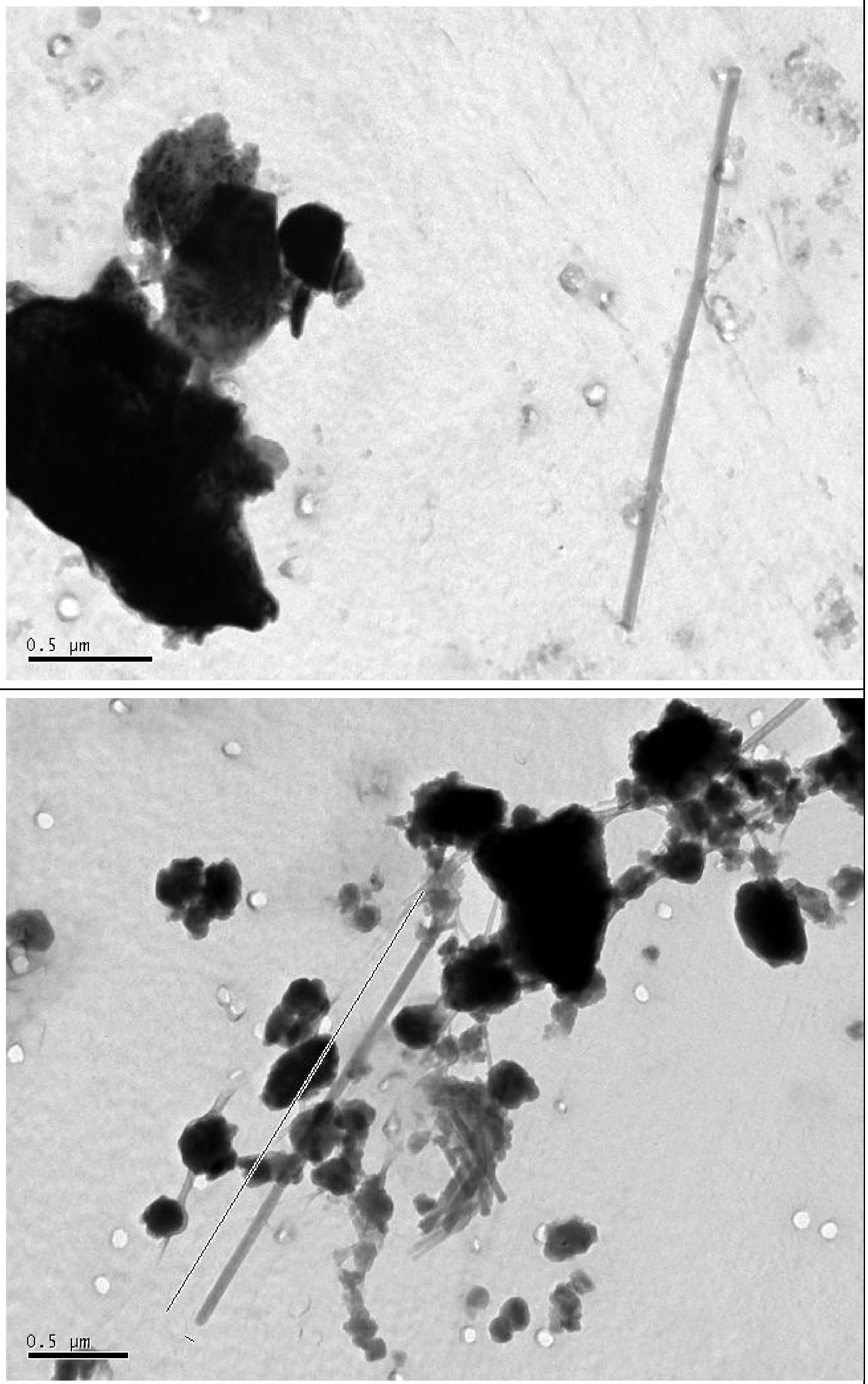
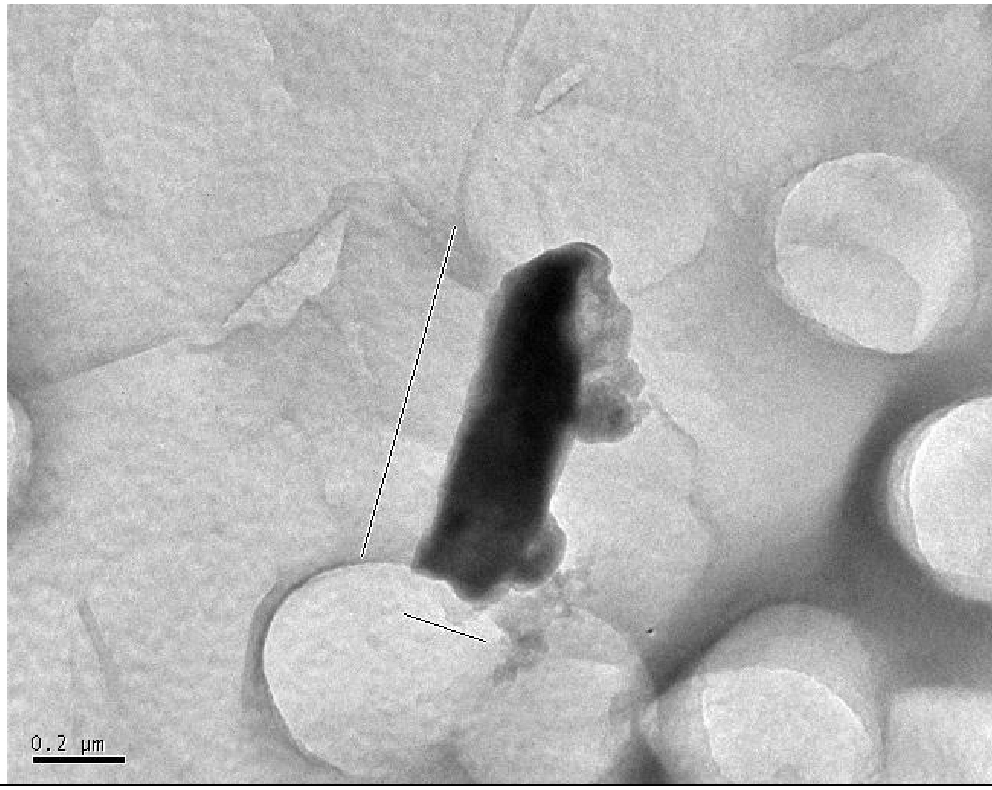



Figure 3.3.12 (Top) Airborne chrysotile asbestos (rods) collected in PM2.5-PM10 cyclone fraction during two consecutive LA92 driving cycles with the 1985 Chevrolet G20 test vehicle, and (Bottom) residual brake dust collected from inside the brake drum.



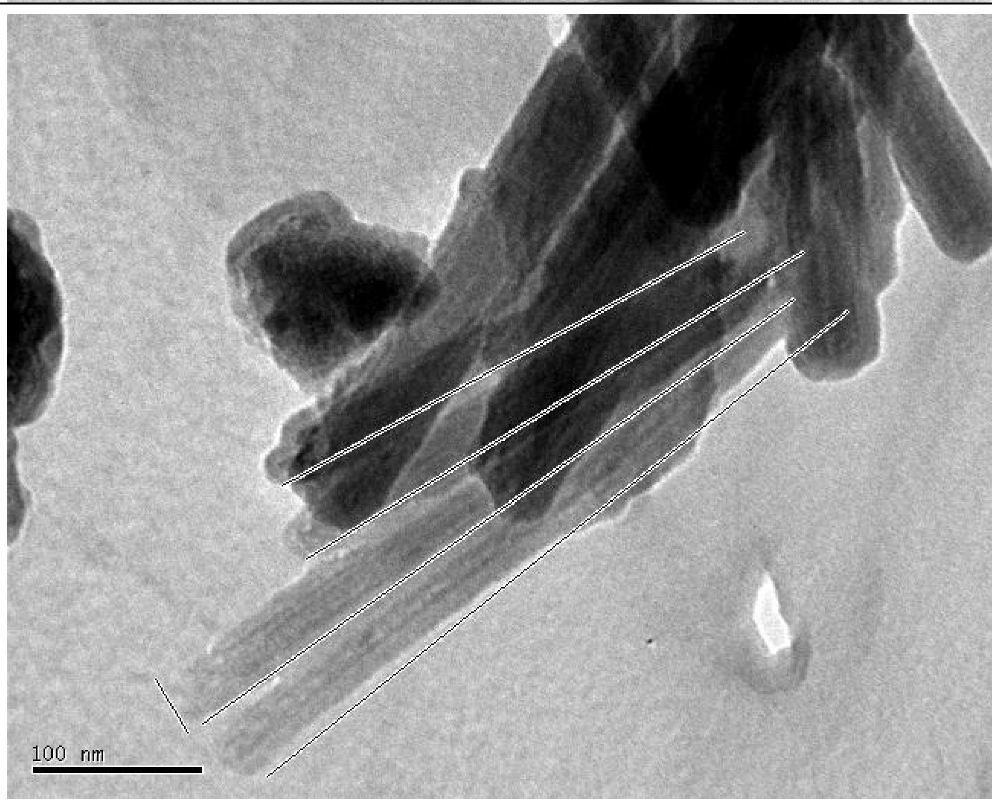




Figure 3.3.13 (Top) Airborne chrysotile asbestos (rods) collected in PM2.5 cyclone fraction during two consecutive LA92 driving cycles with the 1985 Chevrolet G20 test vehicle, and (Bottom) residual brake dust collected from inside the brake drum.

1) The analysis automatically excludes particles with Dp >13.3um (Da >12.6um), since these large particles were determined to be either background spores present in the dynamometer facility or stainless steel fragments from the cyclone sampler threads,

where: Dp = physical particle diameter and
Da = aerodynamic particle diameter

2) The coarse fractions were determined by subtracting the non-brake blank value and the sampler blank value for each of nine size bins “i” for the range 0.12 to 13.3 um and summing the results:

$$L_{A,E3,coarse} = 1000 \times [\Sigma_i (M_{C,E3} - M_{C,E11})_i / V_{S,E3} - \Sigma_i (M_{C,E4} - M_{C,E11})_i / V_{S,E4}]$$
$$L_{A,E9,coarse} = 1000 \times [\Sigma_i (M_{C,E9} - M_{C,E11})_i / V_{S,E9} - \Sigma_i (M_{C,E10} - M_{C,E11})_i / V_{S,E10}]$$

The fine fractions were determined the same way, but since E11 had zero mass in the fine fraction, the equations simplify:

$$L_{A,E3,fine} = 1000 \times [\Sigma_i (M_{C,E3})_i / V_{S,E3} - \Sigma_i (M_{C,E4})_i / V_{S,E4}]$$
$$L_{A,E9,fine} = 1000 \times [\Sigma_i (M_{C,E9})_i / V_{S,E9} - \Sigma_i (M_{C,E10})_i / V_{S,E10}]$$

Where the symbol nomenclature is similar to that defined in **Table 3.3.1;** however here the mass measurements ($M_c$) were conducted by CCSEM image analysis (section 2.6.4) on samples collected with the cyclone (section 2.5.1) for the air volume sampled ($V_s$).

Accordingly, using the mass of asbestos determined by TEM analysis for each cyclone stage, the percent asbestos by mass in the coarse and fine aerodynamic size fractions was determined, as given in **Figure 3.3.14.** As shown, the amount of asbestos in the air emissions and deposited dust was well under 1% by mass. The asbestos level for PM10, expected to represent most of the airborne mass emission mass, was appreciably less for both emission cycles than the level determined for the deposited brake dust collected over all emission cycles. In general, the percent asbestos in the air emission from the more aggressive UC/LA92 driving cycle was significantly less than generated from the Federal/LA4 cycle. In the air emission from both cycles, the percent asbestos was substantially greater in the PM2.5 fraction than in the PM10 coarse fraction. This has important public health implications for respiratory exposure assessment due to the distinctly different lung deposition and clearance regimes for these different aerodynamic size fractions of PM10.

Asbestos fiber emission factors for the aerodynamic PM2.5 and PM10 coarse fractions are given in **Table 3.3.2**. Emission factors for three classifications of fiber length are employed to reflect the different definitions of health relevant fibers. As discussed in **section 4.3** considering the health implications of asbestos fiber length, a prudent approach would include fibers of all lengths. The federal AHERA action level of 0.03 fibers/cc includes fibers $\geq$ 0.5 µm length, and was exceeded by a wide margin for the PM2.5 fraction collected during the UC/LA92 driving cycle. Fibers greater than 5 um in length, as specified in classical industrial hygiene microscopy methods, were not

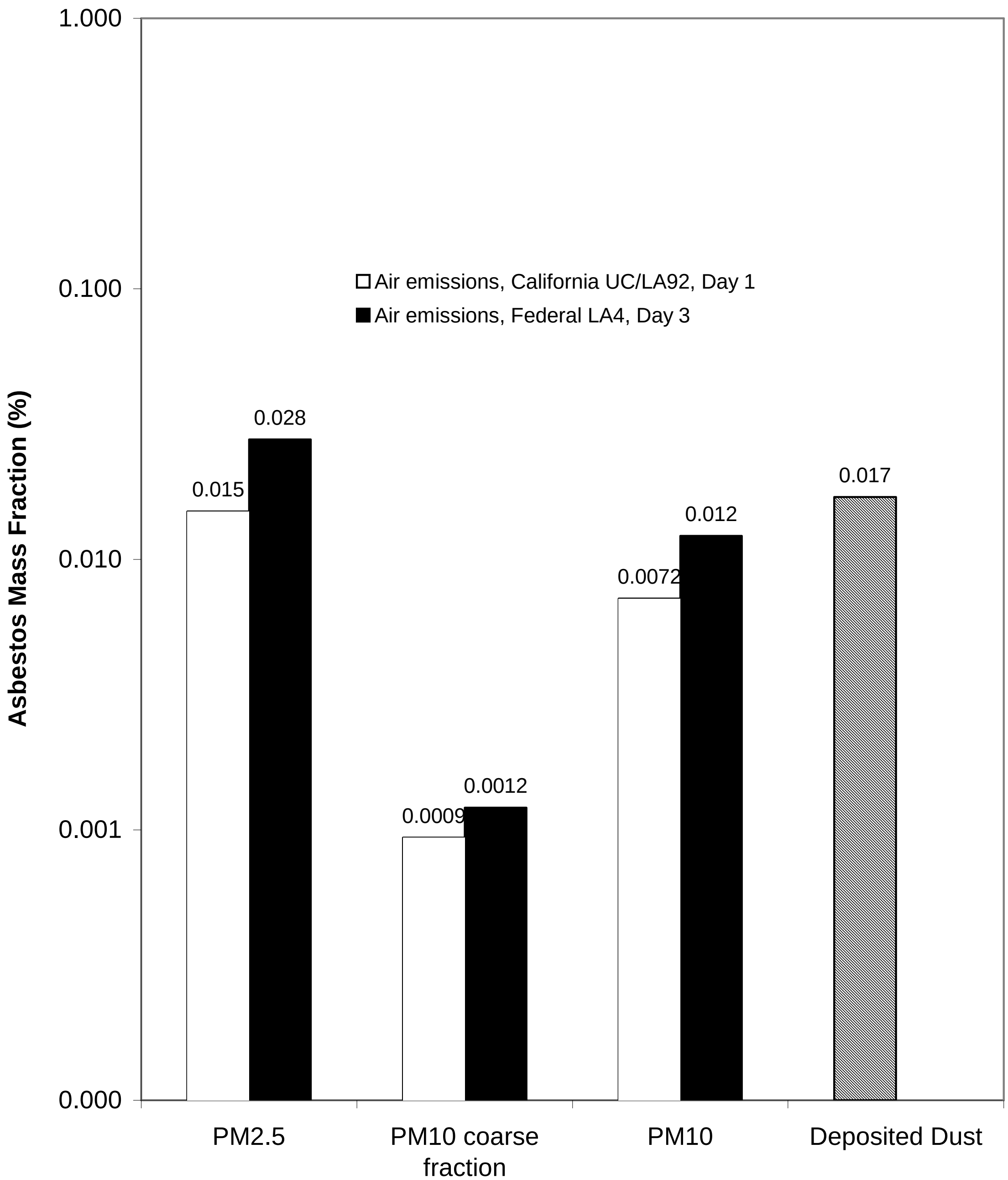



Figure 3.3.14 Asbestos percent mass fraction for the 1985 Chevrolet G20 test vehicle in the coarse and fine aerodynamic size fractions of the air emission, compared to the level in the deposited dust.

Table 3.3.2 Asbestos Fiber Emission Factors Normalized to Brake Wear Mass and Sampled Air Volume for Rear Axle Drum Brakes.

| | Airborne Brake Wear | | | | Deposited Brake Wear |
|---|---|---|---|---|---|
| Test | LA92 (Day 1) | | LA4 (Day 3) | | (All tests) |
| Collected particle size fraction | PM2.5 | PM10 coarse | PM2.5 | PM10 coarse | (All fractions) |
| **fibers / [ng brakewear][a,b]** | | | | | |
| all fibers | 10.142 | 0.062 | 0.702 | 0.484 | 55.999 |
| fibers with L $\geq$ 0.5 um | 0.570 | 0.062 | 0.702 | 0.323 | 7.177 |
| fibers with L > 5.0 um | 0.000 | 0.000 | 0.000 | 0.000 | 0.217 |
| **fibers / [cc air] rear axle[c]** | | | | | |
| all fibers | 2.300 | 0.014 | 0.015 | 0.011 | -- |
| fibers with L $\geq$ 0.5 um | 0.129 | 0.014 | 0.015 | 0.007 | -- |
| fibers with L > 5.0 um | 0.000 | 0.000 | 0.000 | 0.000 | -- |

a. Derived from emission measurements on one rear drum brake of the chassis dynamometer mounted 1985 Chevrolet G20 Van test vehicle.

b. Fractions normalized to total (rather than fraction-specific) PM mass for direct comparison with the brake drum dust normalized to total drum deposited mass.

c. Measured emission factor normalized to air volume has been doubled to yield the rear axle emission factor.

detected in any of the air samples for either driving cycle, and represented a minor fraction of the fibers found in the deposited brake drum dust.

Noteworthy is the comparison of the number of asbestos fibers normalized to collected mass for the air sample and brake drum deposited dust given in the upper portion of **Table 3.3.2.** For both California UC/LA92 and Federal/LA4 driving cycles, the PM2.5 fraction contained a higher proportion of asbestos fibers than the PM10 coarse fraction for all fiber length classifications, although this difference was substantially larger for the California UC/LA92 cycle. Unlike the PM2.5 fraction collected for the Federal/LA4 cycle with most asbestos fibers lengths between 0.5 and 5 um, the UC/LA92 cycle PM2.5 fraction consisted primarily of fibers < 0.5 um length. Considering all asbestos fiber lengths, the airborne mass represented by the PM10 fraction for the UC/LA92 cycle contained approximately 1/5$^{th}$ of the asbestos fibers present in the deposited dust. For the Federal/LA4 cycle, the level of asbestos fibers of all sizes in the PM10 fraction was another order of magnitude lower than in the deposited dust.

Although the BFM undergoing wear during the braking process contains between 20 - 60% chrysotile asbestos by mass, previous researchers have also found surprisingly low levels of asbestos that survive in the BFM emissions. Although Anderson et al. (1973) proposed a mechanism involving sufficiently high temperatures developed at the friction surface asperities, no direct evidence has been provided for the conversion of the crystalline structure of chrysotile asbestos fibers to a different mineral form. A preliminary discussion of direct evidence of this conversion, derived from electron microscopy images and SAED spot patterns of fibers collected in this study, is given in **Appendix K.** As indicated in the **Appendix K** figures, the TEM analyses of brake shoe surface material revealed magnesium silicate particles that had both fibrous and non-fibrous regions with different SAED spot patterns, suggesting the transition of chrysotile asbestos to another non-fibrous crystalline form, consistent with localized frictional heating to high temperatures.

# 4. Discussion

## 4.1 Initial Assessment of the Prevalence of Asbestos in ADFM

A primary intent of this study was to provide an initial assessment of the prevalence of asbestos in ADFM utilized in the braking systems of PC, LDT, MDT, and a representative set of HDT, currently on the road in California. Due to the limited scale of the project, emphasis was placed on devising an approach to identify make and model year vehicles currently on the road which were likely to employ braking systems asbestos ADFM. Due to the secretive nature of the friction materials industry discussed by Brauer (1998), a novel approach using MSDS to identify asbestos ADFM brake parts and reverse search brake part data base, was necessary to develop a LDV/MDV target list to better focus the investigation.

Since an MSDS would be required for any asbestos ADFM, due to OSHA regulations, this approach was also useful in determining that most replacement brakes currently available appear to be asbestos free. Unlike LDV/MDV, the absence of asbestos in MSDS associated with ADFM specific to HDV for a number of years, coupled with the high frequency of brake replacement for this vehicle class, suggests that asbestos emissions may not be important for HDV.

As late as 1998, the most comprehensive report on the friction product and materials market (Brauer, 1998) indicated that the largest market for asbestos was in the production of ADFM by a few large brake manufacturers. Brauer (1998) also stated that friction material manufacturers were considering an increase in the production of asbestos-based products. However, it is unknown whether or not this increase has materialized. The report also suggested that, unlike disc brake linings which were formulated more recently, there were no ready substitutes for the classic asbestos formulation of drum brake linings. Brauer also reports that even for the 1998 model year, one quarter of the LDV/MDV utilized rear drum brakes and one quarter of these contained asbestos BFM. Accordingly, the target list developed for the used BFM collected in the field program focused on brake shoes.

A unique feature of this study was the development of a limited scale used brake shoe collection program, using laboratory analysis to investigate the prevalence of asbestos BFM for target vehicles still on the road. The brake shoe and drum dust collection kit developed proved to be easy to use, and generally provided good quality samples for laboratory analysis. Although brake shop participation was not always consistent, since there were no real incentives to invest the extra shop time to collect and document the samples, the target vehicles sampled by the independent and national chain shops suggest BFM wear cannot as yet be dismissed as an asbestos air emission source.

In the limited BFM sampling by brake shops, consisting of 31 target vehicles, BFM from the brake shoes of 4 vehicles or 13% contained significant quantities of chrysotile asbestos in the range 26 – 60% by mass. This is consistent with the associated MSDS, which listed a similar substantial chrysotile asbestos content of between 20 – 50% by mass. Anderson et al. (1973) reported the chrystotile asbestos composition range in BFM to be 25 – 65 % by mass, while more recently Garg et al. (2000) listed the chrysotile asbestos content to be > 50% in BFM produced by Dephi, as OEM equipment for 1998 General Motors cars. Although there is no known direct historical information on the prevalence of asbestos BFM in the on the road vehicle fleet, notable is the report by MarketScope Research (Blau, 2001) that indicates asbestos brake linings were still being installed on 10% of the vehicles serviced by their readers in 1996. Approximately 25% of the drum brakes sold by OEMs came equipped with asbestos at the time the Brauer report was written.

Consistent with most previous asbestos brake emissions research, analysis of the deposited brake dust collected from target vehicles with asbestos BFM contained less than 1% asbestos by mass. The range of values for this study from near 0.02% for the Chevrolet Van and Pontiac Grand AM to less than 0.005% for the Pontiac Sunfire and VW Jetta, compare favorably with the range of values from 0.002-0.2% and a mean level of 0.031% reported by Williams and Muhlbaier (1980) for drum brake wear emissions. Anderson et al. (1973), Williams and Muhlbaier (1980), and Cha et al.

(1983) all reported similar mean asbestos levels in brake wear emissions of between 0.02-0.03%.

Unlike previous research investigations, in this study the deposited brake dust asbestos fibers, which were counted and sized to calculate their contribution to total mass, were also classified into fiber length size ranges. Length size ranges were utilized, since the health effects of asbestos have been most closely linked with number and mass distributions of airborne fiber length. The single mode in the asbestos fiber number distribution for brake dust from the Pontiac Grand AM, Sunfire, and Chevrolet Van which occurred near 0.5 um fiber length, was in close agreement with the 0.59 um mean fiber length reported by Cha et al. (1983) and the 0.50 um median length given by Williams and Muhlbaier (1980) for airborne emissions.

These results suggest that the level of asbestos in the brake dust collected during brake replacement for a large number of target vehicles would be useful in estimating emission source strength. When compared with the measurements of airborne asbestos fibers produced under standard emissions driving cycles, easily collected deposited brake wear dust may also offer a simplified strategy for predicting the air emission fiber distribution, which may be most closely related to health effects.

### 4.2 Test Vehicle Emissions of Asbestos BFM dust

Previous investigators have devised a number of different approaches to collect and characterize the air borne emissions from full size brake systems with asbestos BFM. Jacko et al. installed a shroud around disc and drum brakes to collect deposited and emitted asbestos brake dust during on the road operation. Although this approach had the advantage of employing on road travel through real traffic conditions, the results were subject to heating and brake dust deposition artifacts produced by the shroud.

Williams and Muhlbaier (1980) investigated the emissions of both drum and disc brakes that were removed from parent vehicles and mounted inside the containment of a dilution tunnel. Although this containment appears to have been sufficiently large to allow air flow around the brake system, the air flow rate was only 1 m/sec (2 mph), and was not subject to the fluid dynamic effects of a tire rotating on a surface. The brake sampling was conducted for non-standard emission cycles using a brake dynamometer to produce controlled braking decelerations from fixed velocities. Cascade impactor and open face samples were used for air borne emission mass size distributions and asbestos fiber counting, respectively. A similar arrangement was employed by Cha et al. (1983), except the disc brake remained mounted on the axle of a 1972 Chevrolet Impala and was housed inside a transparent plastic box, which served as the dilution tunnel. As with Williams and Muhlbaier, the air flow past the brake system was quite low, producing a residence time of 20 seconds and was not subject to the flow effects introduced by a rotating tire. Unlike previous research, the brake cycles employed by Cha et al. were based on a statistical analysis of actual on the road driving conditions; however, they cannot be easily related to the standard vehicle emission cycles currently in use.

Most closely related to the free air brake emissions zone provided in the split dilution tunnel design used in the current study, was the brake emissions sampling configuration of Anderson et al. (1973). This study utilized a tire mounted brake system rotating in free air, with a pseudo-split dilution tunnel arrangement with realistic air velocity. However, the use of unfiltered ambient source air created a high background contamination of particles and asbestos fibers, which had to be subtracted from the collected brake emission samples.

The current study had the benefit of incorporating information about the advantages and disadvantages of previous research into the design of the emissions sampling system. Key elements included: the use of the unaltered brake system of a real vehicle, operation of the vehicle through standard emission cycles on a chassis dynamometer, and the use of a clean air split dilution tunnel operated at realistic air velocities to collect BFM wear dust emitted into a free air flow regime. Although a significant improvement over previous sampling systems, the split section dilution tunnel was not designed to simulate the variation in dilution air velocity produced by changes in vehicle speed or to reproduce the complex nature of the undercarriage air turbulence produced in on road driving.

Additional advantages were the use of real-time monitors to continuously record those parameters considered to be important in characterizing the nature of brake emissions produced, including optical particle size distributions. The use of a total filter for reliable mass measurements, and a cyclone to collect both coarse and fine PM10 aerodynamic size fractions for TEM counting and sizing of asbestos fibers, provided new information about the character of the brake wear source emission for both particle mass and asbestos fibers.

The source strength measured in the typical units of mass per mile derived from this study cannot be directly compared to previous measurements, which are typically in mass per braking event. In order to report emission results per mile, both Williams and Muhlbaier, and Cha et al. were required to derive the factors of 5.1 and 2.0 braking events per mile, respectively. In determining the brake wear emission factor currently employed by CARB in the EMFAC2000 mobile source emission model, Cha et al. used a factor of 1.69 derived from the measurements of Williams and Muhlbaier to calculate a mass emission rate for the entire test vehicle from the measurements conducted on one of the front disc brakes. The factor was necessary to account for the smaller emission rate measured for drum brakes, yielding 12.8 mg/vehicle-mile (3.8 mg/disc-brake mile x 1.69 x 2) for the 1972 Chevrolet Impala test vehicle. A similar calculation, applied to our mass emission per axle mile given in **Table 3.3.1** for the 1985 Chevrolet G20 Van test vehicle, yields values for the California UC/LA92 driving cycle of 7.03 mg/vehicle-mile (first test day) to 1.73 and 0.87 (second test day). Calculated in the same manner, the results for the Federal LA4 driving cycle yielded values of 0.60 and 0.85 mg/vehicle-mile (third test day). Although the mass emission rate appears to be higher for the more aggressive braking in the California cycle, there is a decreasing trend in the emission rate with the number of driving cycles sampled, as seen in the differences in the first and second test day results.

In general agreement with the three previous studies (Jacko, et al., Williams and Muhlbaier, and Cha et al.), airborne particle emissions represented approximately one-third of the total brake wear mass, with the remainder consisting of particles deposited in the braking system. From the TEM analysis for asbestos fibers in the brake wear emissions, estimates of the asbestos present in the airborne and deposited particulate fractions were considered to be similar to the distribution of total brake wear generated mass in these fractions. Accordingly, from Cha et al., 11.9 ug/mi of total asbestos emissions is comprised of one-third airborne emissions (3.82 ug/mi), with the difference present in the deposited particles (8.08 ug/mi).

From the results for the current study (**see Figure 3.3.14**), the level of asbestos in the deposited dust collected from the test vehicle and the PM10 air emissions from the Federal LA 4 driving cycle were comparable at under 0.02% by mass, yielding an asbestos air emission rate of 42 ng/mile for the rear drum brake axle and 103 ng/mile using the scaling factor 2.45 for a vehicle with both front disc and rear drum brakes with asbestos. Although the asbestos mass fraction in the PM10 air emissions for the California driving cycle was significantly lower (0.007%), the higher air borne brake wear mass produced, yielded a much higher asbestos air emission rate of 205 ng/mile-drum brake axle or 503 ng/mile-disc and drum brake axles. Of particular note was the PM2.5 fraction, which contained the highest asbestos levels as a percentage of mass for both driving cycles. Due to the difference in mass emissions for these driving cycles, the PM2.5 asbestos emission rate for the Federal driving cycle was almost a factor of five lower at 40 ng/mile-drum brake axle or 97 ng/mile-disc and drum brake axles when compared with the California driving cycle with 190 ng/mile-drum brake axle or 466 ng/mile-disc and drum brake axles.

### 4.3 Health Effect Implications for Asbestos Fiber Brake Emissions

Motor vehicle brake dust emission rates and brake friction material inventories of asbestos, a known carcinogen, are currently largely unknown. Assessment of the potential health effect consequences from asbestos BFM requires the identification of the asbestos fiber type and classification of fiber size, as well as, the determination of the asbestos concentration in brake dust emissions. Although historically only asbestos fibers greater than 5 um in length and visible by light microscopy have been considered to be associated with health effects, this long held assumption has been brought into question for some time (Lippy et al., 1989). As can be noted from the asbestos air analysis references included in **Appendix C**, several methods based on TEM analysis count fibers an order of magnitude smaller ($\geq$ 0.5 um). Also, the USEPA 600/R-93/116 requires all fibers observed by high magnification TEM to be sized and counted.

It must be recognized that the original air quality standards and the underlying methods were developed to monitor relatively large fibers in industrial environments known to have high levels of asbestos. As asbestos sources have been removed from the environment and evidence of the health hazard associated with inhaled asbestos has grown, the action level for air borne asbestos has been lowered. Over the last 36 years, the action level has decreased by three orders of magnitude to the current action level of 0.1 fiber/cc. This standard considers only fibers greater than 5 um in length, since these longer fibers are associated with asbestosis, but not necessarily tumor formation.

There is some evidence that although fibers greater than 5 um in length are cleared more slowly from the lung, thereby increasing the probability of disease initiation, clearance rate also decreases for fiber lengths shorter than 1 um (Coin et al.1992). As reported by Oberdorster (2001), at the USEPA Asbestos Conference, although the longer fibers are often associated with lung cancer, fibers of all lengths must be considered in the initiation of tumor formation. The health effects data strongly suggest that both short and long asbestos fibers are biologically active (Libby et al. 1989), and according to Peters in the Source Book on Asbestos Diseases (1980), public health measures should assume both may be injurious to human health. Accordingly, the most prudent approach would be to conduct asbestos analysis at the high magnifications available by TEM, such that all fibers present can be counted and sized. In this way, distributions of fiber length by both number and mass need to be determined as potential causative factors in human lung disease.

## 5. Summary and Conclusions

Although the USEPA instituted a ban on the production of most products containing asbestos in 1989, ADFM including disc brake pads, and drum brake linings were subsequently exempted from the ban in 1991. It has been 20-30 years since landmark studies were conducted on brake wear emissions, which was during an era before the 1989 ban, when asbestos was a preferred ingredient in vehicle brakes. Accordingly, the proportion of vehicle brakes containing asbestos, as well as, the composition of asbestos in the brake lining material formulation for vehicles still on the road, is currently unknown. More importantly, a thorough characterization of the asbestos fibers present in the brake dust, released from the variety of different ADFM currently available, has not been conducted. Accordingly, an assessment of the current contribution of motor vehicles to the statewide emission inventory of asbestos is required for the CARB to consider the necessity for regulatory control.

Through this project, representative information on the nature and use of current automotive brake lining products containing asbestos was investigated and verified by applying direct laboratory analysis of ADFM. Characterization of the form, size, and levels of asbestos present in brake dust generated from ADFM was sought to provide the background necessary to consider regulatory control to protect the public health. Brake wear asbestos emission rates as a fraction of total brake dust, were also investigated to allow an estimate of the PM inventory contribution from brake wear asbestos emissions statewide.

Collection of used drum brake linings and the associated brake wear dust was conducted in the field from local brake repair facilities, which agreed to cooperate in the study. These facilities were provided a watch list of target vehicles identified to have a high probability of utilizing asbestos-containing ADFM in their braking systems. Using a novel research approach, the list of target vehicles for the LDV/MDV and HDV classes was developed based on knowledge of the vehicle specific brake application and associated BFM composition. Simple to use kits were developed for brake shop use in the collection of target vehicle brake shoes, and brake dust from surfaces inside the associated brake drums were collected to minimize contamination from other sources.

To determine the prevalence of asbestos BFM in vehicles still on the road, used brake shoes were analyzed by PLM, which was well adapted to detect the large asbestos fiber bundles characteristic of this material. Unlike previous research, in this study the collected brake drum dust from vehicles found to employ asbestos BFM was analyzed by high magnification TEM to count and size the individual asbestos fibers. The intent was to explore the easily collected dust sample asbestos fiber characteristics as a predictive tool for estimating the airborne emissions. Assessment of the potential health effects consequences requires the identification of the asbestos fiber type and classification of fiber size, as well as, the determination of the asbestos concentration in brake dust emissions.

Previous investigators have devised a number of different approaches to collect and characterize the air borne emissions from full size brake systems with asbestos BFM. This study had the benefit of incorporating knowledge about the advantages and disadvantages of previous research approaches into the design of the emissions sampling system. Key elements included: the use of the unaltered brake system of a real vehicle, operation of the vehicle through standard emission cycles on a chassis dynamometer, and the use of a clean air split dilution tunnel operated at realistic air velocities to collect BFM wear dust emitted into a free air flow regime. Additional advantages were the use of real-time monitors to continuously record those parameters considered to be important in characterizing the nature of brake emissions produced, including brake drum temperature, brake pressure, and optical particle size distribution. The use of a total filter for reliable mass measurements, and a cyclone to collect both coarse and fine PM10 aerodynamic size fractions for TEM counting and sizing of asbestos fibers, provided new information about the character of the brake wear source emission for both particle mass and asbestos fibers.

In the limited BFM sampling conducted by brake shops, consisting of 31 target vehicles, BFM from the brake shoes of four vehicles or 13% contained significant quantities of chrysotile asbestos in the range 26 – 60% by mass. This is consistent with the associated MSDS, which listed a similar substantial chrysotile asbestos content of between 20 – 50% by mass. Anderson et al. (1973) reported the chrystotile asbestos composition range in BFM to be 25 – 65 % by mass, while more recently Garg et al. (2000) listed the chrysotile asbestos content to be > 50% in BFM produced by Dephi, as OEM equipment for 1998 General Motors cars.

In determining the brake wear emission factor currently employed by CARB in the EMFAC2000 mobile source emission model, Cha et al. used a factor of 1.69 derived from the measurements of Williams and Muhlbaier, to calculate a mass emission rate for the entire test vehicle from the measurements conducted on one of the front disc brakes. The factor was necessary to account for the smaller emission rate measured for drum brakes, yielding 12.8 mg/vehicle-mile (3.8 mg/disc-brake mile x 1.69 x 2) for the

1972 Chevrolet Impala test vehicle driven over a non-standard emissions cycle. A similar calculation applied to our drum brake mass emission per axle mile for the 1985 Chevrolet G20 Van test vehicle (2.86 mg drum-brake axle mile x 2.45), yields values for the California UC/LA92 driving cycle of 7.03 mg/vehicle-mile (first test day) to 1.73 and 0.87 (second test day). Calculated in the same manner the results for the Federal LA4 driving cycle yielded values of 0.60 and 0.85 mg/vehicle-mile (third test day). Although the mass emission rate appears to be higher for the more aggressive braking in the California cycle, there is a decreasing trend in the emission rate with the number of driving cycles sampled, as seen in the differences in the first and second test day results.

From the results for the current study, the level of asbestos in the deposited dust collected from the test vehicle and the PM10 air emissions from the Federal LA4 driving cycle were comparable at under 0.02% by mass, yielding an asbestos air emission rate of 42 ng/mile for the rear drum brake axle and 103 ng/mile using the scaling factor 2.45 for a vehicle with both front disc and rear drum brakes with asbestos. Although the asbestos mass fraction in the PM10 air emissions for the California driving cycle was significantly lower (0.007%), the higher air borne brake wear mass produced, yielded a much higher asbestos air emission rate of 205 ng/mile-drum brake axle or 503 ng/mile-disc and drum brake axles. Of particular note was the PM2.5 fraction, which contained the highest asbestos levels as a percentage of mass for both driving cycles. Due to the difference in mass emissions for these driving cycles, the PM2.5 asbestos emission rate for the Federal driving cycle was almost a factor of five lower at 40 ng/mile-drum brake axle or 97 ng/mile-disc and drum brake axles when compared with the California driving cycle with 190 ng/mile-drum brake axle or 466 ng/mile-disc and drum brake axles.

These levels were significantly lower than the asbestos air emission value of 3820 ng/mile calculated by Cha et al. for the 1972 Chevrolet Impala, which was operated over repetitive braking cycles rather than a standard emissions cycle. Although the repetitive braking events from fixed vehicle speeds used by Cha et al. where based on a statistical sampling of on the road driving, this does not reflect the realistic sequence of brake applications from different speeds found in standard emission cycles. For the standard emission cycles employed in this study, the California UC/LA92 driving cycle produced significantly higher levels of airborne mass and asbestos derived from BFM wear than the Federal/LA4 driving cycle. The more aggressive driving style of California UC/LA92 cycle, derived from chase car data, is considered to be more representative of typical driving behavior than the Federal/LA4 cycle.

There is some evidence that although fibers greater than 5 um in length are cleared more slowly from the lung, increasing the probability of disease initiation, clearance rate also decreases for fiber lengths shorter than 1 um (Coin et al. 1992). As reported by Gunter (2001), at the USEPA Asbestos Conference, although the longer fibers are often associated with lung cancer, fibers of all lengths must be considered in the initiation of tumor formation. The health effects data strongly suggest that both short and long asbestos fibers are biologically active, and according to Peters in the Source Book on Asbestos Diseases (1980), public health measures should assume both may be injurious to human health. Accordingly, the most prudent approach would be to conduct asbestos analysis at high magnifications available by TEM, such that all fibers present can be counted and sized. In this way, distributions of fiber length by both number and mass need to be determined as potential causative factors in human lung disease.

Notable is the requirement of CARB 427, which provides for the counting and sizing of all fibers observed by TEM at high magnification (20,000-50,000x) for emission source stack sampling. The fiber sizing and counting data are used to determine the airborne asbestos fiber mass concentration, as well as, the fiber count concentration. Although there are no standards for asbestos emissions, screening levels have been identified by USEPA using the AHERA permissible air limits of 0.01 fibers/cc for asbestos fibers > 5 um length, and 0.03 fibers/cc for asbestos fibers $\geq$ 0.5 um length. In the current study, the mode for the concentration of airborne asbestos fibers emitted during both the California and Federal driving cycles, for the 1985 Chevrolet G20 van test vehicle occurred at 0.5 um. From **Table 3.3.2**, the airborne PM10 concentration measured for the 1985 Chevrolet G20 van test vehicle for fibers $\geq$ 0.5 µm length, exceeded the AHERA standard by nearly a factor of five (0.14 fibers/cc) on the UC/LA92 driving cycle. A considerably lower PM10 emission of fibers $\geq$ 0.5 um length (0.022 fibers/cc) for the Federal LA4 cycle was 2/3 of the AHERA action level. For both emission cycles, the PM 2.5 fraction contained most of the asbestos fibers both when all fibers lengths were included and only fibers $\geq$ 0.5 µm in length.

## 6. Recommendations

The objective of this study was to assess the prevalence of asbestos in automotive brakes, and to obtain information that can be used to determine asbestos emission rates due to brake wear from vehicles currently on the road in California. The key elements of the objective include the identification of asbestos-containing ADFM currently utilized in braking systems, and the determination of the asbestos composition of dust produced by vehicle brake wear from these ADFM. From a public health perspective, this study provided a preliminary assessment of the need to allocate further resources to the investigation of asbestos from ADFM.

Considerable project resources were dedicated to developing the innovative methodologies necessary to identify target vehicles still on the road, collect and screen BFM from these vehicles, and to conduct single fiber TEM analysis to characterize the asbestos present in deposited and airborne dust generated from brake wear. These investigations were successful in establishing that BFM containing a high concentration of asbestos is still present in the vehicle fleet currently; however, a much larger sample size, using the same techniques, would be required to provide a comprehensive assessment of the prevalence of asbestos BFM in each vehicle class. This would be especially important for HDV, since the lack of brake participation by truck repair facilities produced a limited number of BFM samples with uncertain vehicle identifications.

Although over the last few years domestic manufacturers have apparently eliminated asbestos as an ingredient in BFM formulations, there must be a comprehensive verification based on laboratory analysis. Brauer (1998) also stated that friction material manufacturers were considering an increase in the production of asbestos-based products. However, it is unknown whether or not this increase has materialized. In addition, the asbestos-free BFM formulations need to be thoroughly investigated to determine the presence of substitute friction modifiers, such as crystalline silica or carbon fiber, which may present as great a health hazard as asbestos. Mitigation of the current health hazard associated with airborne asbestos exposure could utilize an early brake replacement program for target vehicles likely to employ asbestos BFM.

More comprehensive investigations of the nature of the particulate matter generated from brake wear under standard emission cycles are needed to assess the potential impact of these unregulated fugitive emissions on the public health. Using the sample collection and analysis methodology for deposited and airborne emissions developed in this study, additional research can be conducted to further elucidate the relationship between the composition of BFM and the health hazard characteristics of the brake wear generated dust, including asbestos fibers, as well as, other materials of concern in non-asbestos BFM.

Specifically for this study, in order to commit the resources necessary to thoroughly characterize the asbestos fibers present in the PM2.5 and PM10 mass emissions over California and Federal driving cycles, TEM analysis was limited to two of the five air sample sets collected. Accordingly, completion of the TEM analysis for these remaining sets would be a first priority in any future research plan.

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## Glossary

ADFM = Automotive Dry Friction Material
AHERA = Asbestos Hazard Emergency Response Act
BFM = brake friction material
BSE = back scatter electron
CARB = California Air Resources Board (ARB)
CCSEM = computer controlled scanning electron microscopy
CFM = cubic foot per minute
Da = aerodynamic particle diameter
DBD = deposited brake dust
DI = deionized
Dp = physical particle diameter
DMV = Department of Motor Vehicles (California)
EDS = energy-dispersive x-ray spectroscopy
EHLB = Environmental Health Laboratory
EMFAC2000 = Emission Factor Model 2000 series
FMSI = Friction Materials Standards Institute
GM = General Motors Corporation
GVW = gross vehicle weight
HDT = heavy duty trucks
HDV = heavy duty vehicle
HEPA = high efficiency particulate air filters
ICAP/AES = inductively coupled axial plasma/atomic emission spectroscopy
ID = internal diameter
IPA = isopropyl alcohol
LDT = light duty trucks
LDV/MDV = light duty vehicle/medium duty vehicle (EMFAC codes PC, T1, T2, T3)
MCE = mixed cellulose ester
MDT = medium duty trucks
NIOSH = National Institute for Occupational Safety and Health
OEM = original equipment manufacturer
OPC = optical particle counter
OSHA = Occupational Safety and Health Administration
PC = passenger cars
PCM = phase contrast microscopy
PLM = polarized light microscopy
PM10 = particulate matter less than 10 um in aerodynamic diameter
PM2.5 = particulate matter less than 2.5 um in aerodynamic diameter
PVC = polyvinyl chloride
RH = relative humidity
SAED = selected area electron diffraction
SEM = scanning electron microscopy
SRI = Sierra Research Incorporated
SUV = sport utility vehicle

TEM = transmission electron microscopy
TFE = tetrafluoroethylene
TSI = Thermo Systems Incorporated
USEPA = United Sates Environmental Protection Agency
VIN = vehicle identification number

## Appendix A: Project Facilities

### Environmental Health Laboratory, California Department of Health Services

The Microscopy Unit of the Outdoor Air Quality Group was equipped with state-of-the-art optical and electron microscopes. Optical microscopes for conducting phase contrast (PCM) and polarized light microscopy (PLM) were equipped with Nikon DXM-1200 digital cameras. The cameras allow real-time image field searching and provide digital image capture and photographic quality image reproduction using a Fuji Pictography 3500 printer. Scanning electron microscopy was conducted with a Philips XL30 ESEM with single particle elemental analysis provided by a Noran Vantage EDS system. Transmission electron microscopy was conducted with a Philips TECNAI 12 equipped with a Noran EDS system for single particle elemental analysis and a Gatan 780 CCD camera for capturing electron diffraction patterns.

### Sierra Research Incorporated

The facilities of the subcontractor, Sierra Research Inc., specific to the project proposal include extensive computer hardware and software capability to construct databases for the organization and assessment of emissions survey data, and a chassis dynamometer cell with instrumented test vehicles to conduct brake wear emissions testing. A Clayton DC-100 chassis dynamometer provides both mechanical and electric simulation, allowing for the testing of vehicles ranging from 1,000 to 9,000 lbs. loaded vehicle weight under a variety of conditions using standard and custom driving cycles. The fully instrumented dynamometer incorporates a constant volume sampling system, and instrumented test vehicles provide a variety of brake system configurations.

**Appendix B: Vehicle Information Sheet and the Sample Collection Instructions**
**<u>INFORMATION-Vehicle Must be on Target List</u>**

**Brake Shop**

| | |
|---|---|
| Name | |
| Phone | |
| Mechanic | |
| Date | |

**Target Vehicle**

| | |
|---|---|
| Make | |
| Year | |
| Model | |
| Vin# | |
| Engine | |
| Miles Now | |
| Miles, last R/R | |
| Date, last R/R | |

**Brake Sample**

| | | | |
|---|---|---|---|
| Sample # | | | |
| | Manufacturer | Part Number | Edge Code |
| **Brake Removed** | | | |
| Rear Shoe | | | |
| | | | |
| Front Shoe | | | |
| | | | |
| Brake Installed | | | |
| Rear Shoe | | | |
| | | | |
| Front Shoe | | | |
| | | | |

**INSTRUCTIONS-Collecting Brake Shoes and Drum Dust**
(During scheduled brake replacement)
Determine that the vehicle is on the target list provided, which is arranged by make, model, and year. Only collect brake shoes and brake dust from vehicles on the target list. Please use the items in the sealed collection kit to collect brake dust from one brake drum and to collect both brake shoes from the same drum as follows:

1. Once the brake drum is removed, use the plastic razor blade in the plastic tube inside the zip lock bag, to scrape brake dust from the braking surface at the interior edge of the brake drum.

2. Use the same plastic razor blade to scoop the brake dust into the green-topped plastic tube, which originally contained the razor blade.

3. Scoop as much dust as possible into the tube and finally drop the razor blade into the same tube, screw the top on securely, and return to the zip lock bag.

4. Remove both brake shoes from the same wheel where the brake dust was collected, and place into the sampling kit bag.

5. Remove this instructional sheet from the protective plastic sleeve and complete each section of the informational sheet located on the back including the shop, vehicle, and brakes

6. Place the sheet back in the plastic sleeve, seal the sleeve in the zip lock bag with the plastic tube, and place in the kit bag along with the brake shoes. Seal the kit bag with the original bag clip.

***THANK YOU FOR YOUR HELP***

**<u>INFORMATION-Vehicle Must be on Target List</u>**

**Brake Shop**

| | |
|---|---|
| Name | |
| Phone | |
| Mechanic | |
| Date | |

**Target Vehicle/Weight Class (circle): T4 T5 T6 T7 T8**

| | |
|---|---|
| Make | |
| Year | |
| Model | |
| Vin# | |
| Engine | |
| Miles Now | |
| Miles, last R/R | |
| Date, last R/R | |

**Brake Sample**

| | | | |
|---|---|---|---|
| Sample # | | | |
| | Manufacturer | Part Number | Edge Code |
| **Brake Removed** | | | |
| Rear Shoe | | | |
| | | | |
| Front Shoe | | | |
| | | | |
| Brake Installed | | | |
| Rear Shoe | | | |
| | | | |
| Front Shoe | | | |
| | | | |

**INSTRUCTIONS-Collecting HDV Friction Material and Drum Dust (During scheduled brake replacement)**

Determine that the vehicle is on the target list provided, which is arranged by make, model, and year. Only collect brake shoes and brake dust from vehicles on the target list. Please use the items in the sealed collection kit to collect brake dust from one brake drum and to collect both brake shoes from the same drum as follows:

7. Once the brake drum is removed, use the plastic razor blade in the plastic tube inside the zip lock bag, to scrape brake dust from the braking surface at the interior edge of the brake drum.

8. Use the same plastic razor blade to scoop the dry brake dust (use no solvents) into the green-topped plastic tube, which originally contained the razor blade.

9. Scoop as much dust as possible into the tube and finally drop the razor blade into the same tube, screw the top on securely, and return to the zip lock bag.

10. Remove one brake shoe from the same wheel where the brake dust was collected. Break off a sizable piece (approximately 2” x 2”) of brake shoe friction material and place in the plastic bag. Retain the brake shoe core to return for relining.

11. Remove this instructional sheet from the protective plastic sleeve and complete each section of the informational sheet located on the back including the shop, vehicle, and brakes.

12. Place the sheet back in the plastic sleeve, seal the sleeve in the zip lock bag with the plastic tube, and place in the kit bag along with the brake shoes. Seal the kit bag with the original bag clip.

***THANK YOU FOR YOUR HELP***

# Appendix C: Summary of Existing TEM Methods for Asbestos Fiber Analysis

Comparison of TEM Analyses used in Nine Different Asbestos Analytical Methods

| Method | Sample Type | Sample Preparation | Parameters to be Counted [c] | Count magnif. | # of SAED inspec-tions required | # of EDS analyses required | # of zone-axis SAED analyses required | Other measurements required |
|---|---|---|---|---|---|---|---|---|
| ISO 10312 | Air filter | Mount on grid, dissolve filter | Primary fibrous structures > 0.5 um long:<br>1) fibers > 5:1<br>2) bundles of [1]<br>3) disperse clusters of [1] or [2]<br>4) compact clusters of [1] or [2]<br>5) disperse matrices attached to [1] or [2]<br>6) compact matrices attached to [1] or [2]<br>Subcomponent structures > 0.5 um long:<br>7) [1] within clusters<br>8) [2] within clusters<br>9) residual components of clusters<br>10) [1] within matrices<br>11) [2] within matrices<br>12) residual components of matrices | 20kx | 1 per fiber[d] | 1 per fiber[d] | if amphi-boles present, 1 per sample[d] | 1) Length, width of each structure<br>2) # of structures > 5 um long<br>3) # of fibers and bundles of fibers > 5:1, > 5 um<br>4) # of structures > 3:1, > 5 um length, 0.2-3 um width<br>5) # of particles with parallel sides, > 3:1, > 5um length, 0.2-3 um width |
| EPA 100.1 | Water sample | Filter, mount on grid, dissolve filter | Fibers > 0.5 um long, > 3:1 | 20kx | 1 per fiber[d] | 1 per fiber[d] | if amphi-boles present, 1 per sample[d] | 1) Length, width of each fiber<br>2) estimated mass[a] |
| EPA 100.2 [g] | Water sample | Filter, mount on grid, dissolve filter | Fibers > 10 um long, > 3:1 | 10kx-20kx | NONE[e] | 1 per fiber[e] | NONE[e] | Length, width of each fiber |
| ARB 427 | Air filter from station-ary source | mount on grid, dissolve filter | HIGH-MAG (structure sizes not specified):<br>1. fibers<br>2. bundles<br>3. mats<br>4. particles attached to fibrous structures<br>LOW-MAG:<br>5. fibers > 5 um long, >3:1, > 0.2 um wide | HIGH-MAG: 20kx-50kx<br>LOW-MAG: 400-4kx; | NONE[e] | 1 per fiber[e, f] | NONE[e] | Length, width of each structure |
| NIOSH 7402 | Air filter | Mount on grid, dissolve filter | Fibers > 5 um long, > 3:1, > 0.25 um wide | 500-1kx | 1 per fiber | 5-10, plus 1 per every addition-al 10 fibers | NONE | 1) Length, width of each fiber<br>2) fraction of all fibers which are asbestos |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| AHERA | Air filter | Mount on grid, dissolve filter | 1. Fibers ≥ 0.5 um long, > 5:1<br>2. Bundles of [1]<br>3. Clusters of [1] or [2]<br>4. Matrices with embedded [1] or [2] | 15kx-20kx | 4 [b] | 1 per fiber [b] | NONE | 1) # of structures < 5um long<br>2) # of structures > 5um long |
| EPA 540/2-90/005a, super-fund | Air filter from ambient sample | (redisperse on filter), mount on grid, dissolve filter | HIGH-MAG (> 0.5 um long):<br>1) fibers > 5:1<br>2) bundles of [1]<br>3) fibrous clusters with no ends visible<br>4) fibrous clusters with ends visible<br>5) matrices with no fiber ends visible<br>6) matrices with fiber ends visible<br>7) [1] within clusters<br>8) [2] within clusters<br>9) [1] within matrices<br>10) [2] within matrices<br>11) residual 'submatrix' components<br>LOW-MAG:<br>12) fibers > 5 um long, > 5:1 | HIGH-MAG: 20kx<br>LOW-MAG: 10kx | 1 per fiber[d] | 1 per fiber[d] | if amphi-boles present, 1 per sample[d] | Length, width of each structure |
| EPA 600/R-93/116, build-ing material | Bulk build-ing Material | Matrix reduction / homogeniza-tion, disperse on filter, mount on grid, dissolve filter | All visible asbestos structures | (Mag. at which largest bundle fills screen) | (not specified) | (not speci-fied) | (not spec-fied) | 1) Volume of each structure<br>2) % asbestos by mass[a] |
| OSHA 191 | Bulk material | (not specified) | Visual estimation of % asbestos | (not specified) | (not specified) | (not speci-fied) | (not spec-fied) | NONE |

[a] must convert to % mass using assumed size and density factors.
[b] corresponds to 70 structures/mm$^2$, the critical level up to which all fibers must be identified by SAED. The AHERA Method is ambiguous about whether EDS is necessary for amphiboles beyond this level.
[c] For all methods except NIOSH 7402, "fiber" refers to asbestos fibers only, and separate counts are maintained for each asbestos type. For NIOSH 7402, non-asbestos fiber types are counted as well.
[d] for routine samples with *unknown* asbestos content. (For routine samples with *well-characterized* asbestos content, lower levels of analysis may be acceptable, *e.g.*, zone-axis SAED not required, or EDS not required. In contrast, for non-routine samples where precise ID of all fibers is necessary, zone-axis SAED should be obtained for *all* fibers. For each fiber, note which of the 3 ID data types [SAED, EDS, and zone-axis SAED] were successfully obtained, so that the appropriate fibers may be tallied for a given level of analysis.)
[e] acquisition of SAED patterns is encouraged, but EDS alone is sufficient. Alternatively, for chrysotile, SAED alone is also sufficient. For amphiboles, SAED alone is not sufficient unless it is performed on multiple zone axes (not recommended due to difficulty).
[f] for "positive" ID. If EDS cannot be obtained but morphology is consistent with asbestos, denote ID as "tentative".
[g] EHLB maintains a certification for EPA 100.2 analysis (US EPA).

(SAED = selected-area electron diffraction; EDS = energy-dispersive x-ray spectroscopy)

## Appendix D1: Detailed Protocol to Prepare Samples for TEM Asbestos Analysis

1. Determine the number and type of samples to be prepared
   1.1. This procedure covers the preparation of the following types of samples:
      1.1.1. brake dust samples
      1.1.2. cyclone final filter (PM2.5) samples
      1.1.3. cyclone middle stage rinse (PM10 coarse) samples
   1.2. A maximum of 4 samples per preparation session is recommended

2. Assemble the following equipment and supplies
   2.1. Cahn microbalance in controlled temperature/RH room
   2.2. turbo evaporative carbon coater and carbon thread
   2.3. proSONIK™ ultrasonic cleaner (Ney Ultrasonic, Inc.)
   2.4. stereozoom microscope (optional)
   2.5. 1 50mL graduated cylinder – 1 for each dust sample
   2.6. glass, 25mm vacuum filtration apparatuses - 1 for each PM10 coarse or dust sample
   2.7. 25mm Nuclepore (polycarbonate) filters, 0.1um pore size – 1 for each PM10 coarse or dust sample
   2.8. 25mm HA (MCE) backup filters, 0.45um pore size - 1 for each PM10 coarse or dust sample
   2.9. 10 mL volumetric pipets - 1 for each PM10 coarse or dust sample
   2.10. plastic Petri dishes with covers, 47mm - 1 for each PM10 coarse or dust sample
   2.11. glass slides or plastic Petri dishes - 1 for each PM2.5, PM10 coarse, or dust sample
   2.12. glass Petri dish bottoms, 47mm (optional)- 1 for each PM2.5, PM10 coarse, or dust sample
   2.13. 47mm filter papers cut into quarter-filter wedges- 1 for each PM2.5, PM10 coarse, or dust sample
   2.14. 1 glass Petri dish bottom, 125mm (top is optional)
   2.15. rubber bulb or electric pipettor
   2.16. flat tweezers
   2.17. sharp-pointed tweezers
   2.18. Scotch tape
   2.19. Razor blade
   2.20. foam cubes
   2.21. small glass bottle with stopper for dispensing chloroform
   2.22. AHERA/200 mesh TEM grids
   2.23. 0.1-um filtered deionized water and squeeze bottle
   2.24. Chloroform, reagent grade
   2.25. isopropyl alcohol in squeeze bottle

3. Prepare glassware (for PM10 coarse or dust samples)
   3.1. A maximum of 4 samples per preparation session, and thus 4 sets of filtration glassware, is recommended.

3.2. Clean 1000mL beaker using the following procedure
    3.2.1. Clean with soap and tap water.
    3.2.2. Rinse with IPA.
    3.2.3. Ultrasonicate with DI, 0.1um-filtered water for 10 min in ProSONIK$^{TM}$
3.3. Repeat steps 3.2.1-3.2.3 for the filtration apparatus tops, glass stopper, and 50mL graduated cylinder. Use the clean 1000mL beaker to hold the apparatus tops, cylinder, and stopper during sonication.
3.4. Discard the water in the beaker and flask, refill each with DI, 0.1um-filtered water, and sonicate again for 6 minutes.
3.5. Connect house vacuum to filter apparatuses and turn vacuum lines ON. Rinse fritted bottoms of each with squeeze bottle of DI, 0.1um-filtered water.
3.6. Clamp apparatus tops to filtration apparatuses and cover top with aluminum foil.
3.7. Record filtration apparatus IDs.

4. Preparation of Brake Dust for TEM
    4.1. Weigh 5-6 mg dust and record exact mass.
    4.2. Add 45 mL filtered, deionized water to 50 mL graduated cylinder.
    4.3. Add 0.5 mL 0.1% OT (detergent).
    4.4. Remove 1 mL for blank.
    4.5. Transfer brake dust to graduated cylinder.
    4.6. Bring up to 50 mL.
    4.7. Briefly ultrasonicate graduated cylinder (6 minutes) in precision waveform proSONIK$^{TM}$ ultrasonic cleaner (Ney Ultrasonic, Inc.) to disperse loose clumps.
    4.8. Assemble filter funnel using 0.45 um MCE filter for backing and 0.1 um Nuclepore filter.
    4.9. Pretreat filter assembly with 10 mL water.
    4.10. Shake sample. Do not use magnetic stirring bar!
    4.11. Add 10 mL water and 1 mL sample from graduated cylinder to filter funnel.
    4.12. Apply vacuum to filter funnel to collect sample on filter.
    4.13. Transfer filter to Petri dish.
    4.14. Measure the inside diameter of filter funnel to determine filter deposit diameter.

5. Preparation of Cyclone Samples for TEM
    5.1. Obtain filter weights.
        5.1.1. For PM2.5 fractions (direct on filter)
            5.1.1.1. Tare Cahn microbalance.
            5.1.1.2. Calibrate microbalance using 20mg standard weight.
            5.1.1.3. Pre-weigh polycarbonate filter(s) for sample collection, after passing through $Po^{210}$ static discharge device twice and store in sealed Petri dish with ID label.
            5.1.1.4. After sample collection, pass loaded filter, deposit side face-up, through a $Po^{210}$ static discharge device twice.
            5.1.1.5. Re-weigh loaded filter.

5.1.1.6. Use previously recorded filter pre-weight to determine mass gained during sampling.

5.1.2. For PM10 coarse fractions (liquid extract filtration)

5.1.2.1. Follow steps of section 5.1.1 using 0.1um polycarbonate filter used for extract filtration of section 5.2.

5.1.2.2. Follow steps 5.2.1.1-5.2.1.12 to generate filter deposit from the PM10 coarse sample liquid extract.

5.2. Filtration of PM10 coarse fractions

5.2.1. For each PM10 coarse sample:

5.2.1.1. Unclamp filtration unit and remove top.

5.2.1.2. Using flat tweezers, place a 0.45um MCE filter on fritted bottom. This works best when frit is dry.

5.2.1.3. Using flat tweezers, place the 0.1um polycarbonate filter weighed in step 5.1.2 on top of the MCE filter.

5.2.1.4. Turn on vacuum to flatten filter.

5.2.1.5. Guide apparatus top straight down onto filter so that the filter does not wrinkle. Replace clamp and turn off vacuum.

5.2.1.6. Agitate PM10 coarse sample tube by hand with a swirling motion to disperse gross agglomerates. (Uniform dispersal of particulates within liquid is not critical, as entire contents of tube will be filtered.)

5.2.1.7. Wet filter with 5 mL IPA.

5.2.1.8. Add 10 mL DI water.

5.2.1.9. Using a 10mL volumetric pipet and bulb or electric pipettor, progressively transfer entire sample from tube into filtration apparatus. Do not allow the water level in the filtration funnel to drop below 10 mL at any time during the filtration.

5.2.1.10. Rinse sample tube with 10 mL water or IPA and filter this rinse.

5.2.1.11. When filter is relatively dry, unclamp top and turn off vacuum.

5.2.1.12. Return polycarbonate filter to plastic Petri dish.

5.2.2. Allow filters to equilibrate overnight with covers slightly ajar in controlled temperature/RH room.

5.2.3. Reweigh all PM10 coarse filters, refer to 5.1.2.1

5.2.4. Determine filtered masses using the pre- and post-filtration weights.

5.2.5. Measure the inside diameter of filter funnel to determine filter deposit diameter.

6. Carbon coat each of the filters from Steps 4 and 5 as follows

6.1. Tape filter edges to inside of Petri dish, taking care not to wrinkle filter.

6.2. Place filter/Petri dish in carbon coater chamber.

6.3. Mount double carbon thread (X) and rotate shield in over one of the threads. Connect electrodes across the appropriate terminals.

6.4. Close chamber and pump down to $<10^{-4}$ mbar.

6.5. Turn process ON.

6.6. Degas carbon thread and then rotate shield out.
6.7. Coat using short pulses of high current until slide appears relatively dark, making sure to minimize the heat generated. Overheating the filter will increase dissolution time in Jaffe washer.
6.8. Turn process OFF and switch electrodes across second thread.
6.9. Repeat steps 6.5-6.7.
6.10. Vent chamber, return sample to Petri dish, and cover Petri dish.

7. Prepare Jaffe washer:
   7.1. Fill small glass bottle with chloroform (use exhaust fan whenever chloroform is open to air).
   7.2. The design of the Jaffe washer is not critical as long as it maintains a saturated chloroform atmosphere. Two suggested designs:
      7.2.1. [simplest design] Fill a large glass Petri dish bottom with foam cubes. Place 1 filter paper wedge on top of the cubes in each Petri dish and label each with the corresponding filtration number. Using the small bottle of chloroform, fill the large Petri dish half full, so that the cubes and filter paper are just soaked. Leave dish uncovered.
      7.2.2. [uses fewer cubes and chloroform, possibly produces a higher vapor concentration] Arrange small glass Petri dish bottoms in large glass Petri dish bottom. Fill each small Petri dish with foam cubes. Place 1 filter paper wedge on top of the cubes in each small Petri dish and label each with the corresponding filtration number. Using the small bottle of chloroform, fill each small Petri dish half full, so that the cubes and filter paper are just soaked. Cover the large Petri dish with its cover.

8. Dissolve filters onto TEM grids using one of the following 2 methods (can be performed with or without the aid of a stereozoom microscope):
   8.1. Method 1:
      8.1.1. Place 1 AHERA/200 mesh TEM grid onto the slide next to the filter. (For EMS grids, place dark/dull side up so that letters/numbers are backwards).
      8.1.2. Use razor to cut small square (~1mm$^2$) from center of filter.
      8.1.3. Place filter square on top of TEM grid using sharp-pointed tweezers.
      8.1.4. Using sharp-pointed tweezers, place grid-plus-filter “sandwich” on top of the appropriate chloroform-soaked filter paper in the Jaffe washer. The filter square will instantly ‘melt’ onto the grid.
      8.1.5. Prepare at least 3 grids per sample by repeating steps (1)-(4).
   8.2. Method 2:
      8.2.1. Place 1 AHERA/200 mesh TEM grid onto the appropriate chloroform-soaked filter paper in the Jaffe washer. (For EMS grids, place dark/dull side up so that letters/numbers are backwards).
      8.2.2. Use razor to cut small square (~1mm2) from center of filter.
      8.2.3. Place filter square on top of TEM grid in Jaffe washer using sharp-pointed tweezers. The filter square will instantly ‘melt’ onto the grid.

8.2.4. Prepare at least 3 grids per sample by repeating steps (1)-(3).

9. Clear filters in Jaffe washer:
    9.1. Place Jaffe washer inside a glass desiccator that is as small as possible. No desiccant is required; the desiccator is simply used to contain the chloroform vapors. Cover desiccator.
    9.2. Check chloroform levels daily. If any Petri dish is less than half full, remove from desiccator and refill with chloroform, then replace inside desiccator.
    9.3. After 1-2 days in Jaffe washer, choose a test grid and inspect in TEM. If no polycarbonate filter pores are visible and fibers are clearly resolved, grids are ready for analysis. If grid is not yet ready, then return to Jaffe washer (may require 4 days or more; if filters were severely overheated during coating, they may not ever completely dissolve).

**Appendix D2. Brake Shoe Asbestos Screening Protocol Using Polarized Light Microscopy (PLM)**

1. Brake Shoe Sample Login
   1.1. Login each sample through the Laboratory Information System (LIMS) using the existing pre-logged sample ID for the collected brake shoe.
   1.2. Record the vehicle year, make, and model, as well as, the brake shop shoe collector, date collected, and date received in the laboratory.

2. BFM Sub-Sampling and PLM Slide Preparation
   2.1. Inside a chemical fume hood and wearing vinyl gloves, remove the brake shoe from the sealed plastic collection bag.
   2.2. Break off several 1 $cm^2$ pieces of brake friction material (BFM) from the brake shoe, using 10" End Cutting Nippers and store in a sealed Petri dish labeled with the sample ID
   2.3. While still in the fume hood, place the brake shoe back into the sealed plastic sampling kit collection bag and place in sample archive storage.
   2.4. In the fume hood, open the labeled Petri dish containing the friction material and examine under a stereoscope for identify the presence of fibers and fiber bundles.
   2.5. Apply a drop of 1.550 refractive index oil, used to identify chrysotile asbestos fibers on a clean slide.
   2.6. Using sharp tweezers, pull out fibers from the BFM and place in the drop of refractive index oil on the slide
   2.7. Re-examine the BFM for other types of fibers and repeat step (6) to transfer all the types of fibers observed in the BFM sample to the oil drop on the slide.
   2.8. Seal the sampled portion of slide with a micro cover glass.
   2.9. Label the slide with the sample ID, insert the slide horizontally into a 50 mL centrifuge tube, and store centrifuge tube in a horizontal position to prevent the oil drop from flowing off the slide.

3. Chrysotile Screening using PLM
   3.1. Power up the PLM, with digital camera, and perform those pre-screening analysis checks from NIOSH Method 9002, required to yield unambiguous identification of chrysotile asbestos in a standard reference sample.
   3.2. Place a prepared BFM sample slide to be screened on the PLM stage.
   3.3. Record the results of the following Asbestos Sample Screening Schema used to confirm the presence of chrysotile asbestos fibers (expected to be 20-60% of the BFM mass):
      3.3.1. Under plain light (no polarization), with 10X objective, observe the color of the fiber. (**chrysotile displays a clear color**).
      3.3.2. Under plain light, pull the analyzer slider out (with polarization on, the background turns to pink). Observe if the colors of the fiber disappear when it is parallel to both the horizontal and vertical axes of the cross hair. (**If YES, then this is a chrysotile trait**).

3.3.3. With the same setting as the previous step, check if the fibers at, \\\ (upper left to lower right diagonal) direction on the cross hair, appears to be yellow color **<u>and</u>**, /// (upper right to lower left) direction on the cross hair, appears to be blue color. (**If YES, this positive sign of elongation, is a chrysotile trait**).

3.3.4. Using the Dispersion Staining objective, and push the analyzer slider in (polarization turned off), and turn the condenser aperture diaphragm ring all the way to the right (reduce the amount of light going through). Check the field of view for the horizontal fibers displaying a magenta color, **<u>and</u>** a blue color in the vertical direction, both relative to the cross hairs. (**If YES, this is a chrysotile trait**).

3.4. If **<u>all</u>** of the above PLM screening test characteristics are observed, the BFM is considered to contain **chrysotile asbestos fibers**.

3.5. If only **<u>one or none</u>** of the above sub-steps matches the trait of chrysotile, the BFM is considered to **NOT** to contain **chrysotile asbestos fibers**.

3.6. If chrysotile fibers cannot be confirmed as present or absent, then fresh BFM samples can be ashed (NIOSH method 9002) to remove any matrix material coating the fibers and re-examined by the above PLM schema. Ashing is not usually required for BFM screening to confirm the presence or absence of chrysotile asbestos fibers, due to the high level expected (20-60% of BFM mass).

3.7. Record the screening results in the LIMS for the sample under examination.

**Appendix E: Representative Fleet Brake Type Distribution for LDV/MDV**
(Summary, vehicle make and model year specific listing available on CD-R)

| EMFAC Vehicle Code | | Front Brake Type | | | Rear Brake Type | | |
|---|---|---|---|---|---|---|---|
| | **Model Year** | **Disk** | **Either** | **Drum** | **Disk** | **Either** | **Drum** |
| | 1973 | 299 | 66 | 25 | 73 | . | 317 |
| | 1974 | 239 | 57 | . | 64 | 2 | 230 |
| | 1975 | 251 | 13 | . | 62 | 1 | 201 |
| | 1976 | 483 | 1 | . | 131 | 33 | 320 |
| | 1977 | 674 | . | . | 115 | 39 | 520 |
| | 1978 | 926 | . | . | 146 | 58 | 722 |
| | 1979 | 1269 | . | . | 309 | 68 | 892 |
| | 1980 | 1547 | . | . | 221 | 142 | 1184 |
| | 1981 | 2995 | . | . | 335 | 68 | 2592 |
| | 1982 | 3748 | . | . | 660 | 264 | 2824 |
| | 1983 | 5083 | . | . | 507 | 825 | 3751 |
| | 1984 | 7875 | . | . | 1013 | 1229 | 5633 |
| | 1985 | 10031 | . | . | 1813 | 1057 | 7161 |
| **PC*** | 1986 | 11577 | . | . | 2555 | 900 | 8122 |
| | 1987 | 13264 | . | . | 2594 | 1169 | 9501 |
| | 1988 | 10695 | . | . | 1830 | 1305 | 7560 |
| | 1989 | 11163 | . | . | 1852 | 3353 | 5958 |
| | 1990 | 10933 | . | . | 2390 | 2850 | 5693 |
| | 1991 | 14386 | . | . | 2950 | 4387 | 7049 |
| | 1992 | 12053 | . | . | 2751 | 5559 | 3743 |
| | 1993 | 11731 | . | . | 2184 | 7015 | 2532 |
| | 1994 | 9899 | . | . | 2346 | 5670 | 1883 |
| | 1995 | 13167 | . | . | 3322 | 7945 | 1900 |
| | 1996 | 14533 | . | . | 3675 | 8645 | 2213 |
| | 1997 | 16058 | . | . | 3907 | 9763 | 2388 |
| | 1998 | 14229 | . | . | 3722 | 7338 | 3169 |
| | 1999 | 13869 | . | . | 3911 | 8081 | 1877 |
| | **Total** | 212977 | 137 | 25 | 45438 | 77766 | 89935 |

* PC = Passenger Cars, all vehicle weights.

| EMFAC Vehicle Code | Model Year | Front Brake Type | | | Rear Brake Type | | |
|---|---|---|---|---|---|---|---|
| | | Disk | Either | Drum | Disk | Either | Drum |
| T1-T3* | 1973 | 402 | 78 | 17 | . | . | 497 |
| | 1974 | 324 | 44 | 21 | . | . | 389 |
| | 1975 | 192 | 47 | 21 | . | . | 260 |
| | 1976 | 506 | . | 5 | . | . | 511 |
| | 1977 | 776 | . | . | . | . | 776 |
| | 1978 | 826 | . | . | . | . | 826 |
| | 1979 | 970 | . | . | . | . | 970 |
| | 1980 | 606 | . | . | . | . | 606 |
| | 1981 | 700 | . | . | . | . | 700 |
| | 1982 | 904 | . | . | . | . | 904 |
| | 1983 | 1223 | . | . | . | . | 1223 |
| | 1984 | 2035 | . | . | . | . | 2035 |
| | 1985 | 2304 | . | . | . | . | 2304 |
| | 1986 | 3133 | . | . | . | 225 | 2908 |
| | 1987 | 3097 | . | . | 3 | . | 3094 |
| | 1988 | 2830 | . | . | 3 | 53 | 2774 |
| | 1989 | 3582 | . | . | 6 | 17 | 3559 |
| | 1990 | 3437 | . | . | 5 | 299 | 3133 |
| | 1991 | 3994 | . | . | 2 | 461 | 3531 |
| | 1992 | 3839 | . | . | 5 | 393 | 3441 |
| | 1993 | 4444 | . | . | 7 | 295 | 4142 |
| | 1994 | 4733 | . | . | 7 | 260 | 4466 |
| | 1995 | 5243 | . | . | 468 | 586 | 4189 |
| | 1996 | 5169 | . | . | 694 | 546 | 3929 |
| | 1997 | 6519 | . | . | 1046 | 617 | 4856 |
| | 1998 | 6604 | . | . | 1159 | 1449 | 3996 |
| | 1999 | 7218 | . | . | 1383 | 1664 | 4171 |
| | **Total** | 75610 | 169 | 64 | 4788 | 6865 | 64190 |
| **Total** | **LDV/MDV**** | 288587 | 306 | 89 | 50226 | 84631 | 154125 |

* See Table 2.3.1 for a complete list of EMFAC Vehicle Code specifications.

** LDV/MDV includes PC, T1, T2, and T3.

| EMFAC Vehicle Code | | Front Brake Type | | | Rear Brake Type | | |
|---|---|---|---|---|---|---|---|
| | | Disk | Either | Drum | Disk | Either | Drum |
| T1* | 1973 | 211 | 71 | 13 | . | . | 295 |
| | 1974 | 170 | 42 | 18 | . | . | 230 |
| | 1975 | 67 | 45 | 21 | . | . | 133 |
| | 1976 | 201 | . | 5 | . | . | 206 |
| | 1977 | 340 | . | . | . | . | 340 |
| | 1978 | 216 | . | . | . | . | 216 |
| | 1979 | 371 | . | . | . | . | 371 |
| | 1980 | 287 | . | . | . | . | 287 |
| | 1981 | 325 | . | . | . | . | 325 |
| | 1982 | 551 | . | . | . | . | 551 |
| | 1983 | 748 | . | . | . | . | 748 |
| | 1984 | 1441 | . | . | . | . | 1441 |
| | 1985 | 1559 | . | . | . | . | 1559 |
| | 1986 | 1988 | . | . | . | 225 | 1763 |
| | 1987 | 2084 | . | . | . | . | 2084 |
| | 1988 | 1708 | . | . | . | . | 1708 |
| | 1989 | 1807 | . | . | . | . | 1807 |
| | 1990 | 1582 | . | . | . | 244 | 1338 |
| | 1991 | 1694 | . | . | . | 161 | 1533 |
| | 1992 | 1201 | . | . | . | . | 1201 |
| | 199 | 1196 | . | . | . | . | 1196 |
| | 1994 | 1380 | . | . | . | . | 1380 |
| | 1995 | 739 | . | . | 79 | . | 660 |
| | 1996 | 1175 | . | . | 73 | 197 | 905 |
| | 1997 | 1386 | . | . | 72 | . | 1314 |
| | 1998 | 849 | . | . | 32 | 281 | 536 |
| | 1999 | 915 | . | . | . | 124 | 791 |
| | **Total** | 26191 | 158 | 57 | 256 | 1232 | 24918 |

* T1 = Light-duty trucks 0 - 3,750 lbs.

| EMFAC Vehicle Code | Model Year | Front Brake Type | | | Rear Brake Type | | |
|---|---|---|---|---|---|---|---|
| | | Disk | Either | Drum | Disk | Either | Drum |
| T2* | 1973 | 191 | 7 | 4 | . | . | 202 |
| | 1974 | 154 | 2 | 3 | . | . | 159 |
| | 1975 | 125 | 2 | . | . | . | 127 |
| | 1976 | 305 | . | . | . | . | 305 |
| | 1977 | 436 | . | . | . | . | 436 |
| | 1978 | 610 | . | . | . | . | 610 |
| | 1979 | 599 | . | . | . | . | 599 |
| | 1980 | 319 | . | . | . | . | 319 |
| | 1981 | 375 | . | . | . | . | 375 |
| | 1982 | 353 | . | . | . | . | 353 |
| | 1983 | 475 | . | . | . | . | 475 |
| | 1984 | 594 | . | . | . | . | 594 |
| | 1985 | 745 | . | . | . | . | 745 |
| | 1986 | 1145 | . | . | . | . | 1145 |
| | 1987 | 1013 | . | . | 3 | . | 1010 |
| | 1988 | 1122 | . | . | 3 | 53 | 1066 |
| | 1989 | 1775 | . | . | 6 | 17 | 1752 |
| | 1990 | 1855 | . | . | 5 | 55 | 1795 |
| | 1991 | 2300 | . | . | 2 | 300 | 1998 |
| | 1992 | 2638 | . | . | 5 | 393 | 2240 |
| | 1993 | 3248 | . | . | 7 | 295 | 2946 |
| | 1994 | 3353 | . | . | 7 | 260 | 3086 |
| | 1995 | 4504 | . | . | 389 | 586 | 3529 |
| | 1996 | 3994 | . | . | 621 | 349 | 3024 |
| | 1997 | 5098 | . | . | 974 | 617 | 3507 |
| | 1998 | 5712 | . | . | 1100 | 1168 | 3444 |
| | 1999 | 6006 | . | . | 1354 | 1540 | 3112 |
| | **Total** | 49044 | 11 | 7 | 4476 | 5633 | 38953 |

* T2 = Light-duty trucks 3,751 - 5,750 lbs.

| EMFAC Vehicle Code | Model Year | Front Brake Type | | | Rear Brake Type | | |
|---|---|---|---|---|---|---|---|
| | | Disk | Either | Drum | Disk | Either | Drum |
| T3* | 1997 | 35 | . | . | . | . | 35 |
| | 1998 | 43 | . | . | 27 | . | 16 |
| | 1999 | 297 | . | . | 29 | . | 268 |
| | **Total** | 375 | 0 | 0 | 56 | 0 | 319 |

* T3 = Medium-duty trucks, 5,751 - 8,500 lbs.

## Appendix F: Distribution of LDV/MDV on Target List for Field Brake Sampling

(Example Target List, full listing available on CD-R)

| Make | Model | Year | Class | Frequency | Bendix Field |
|---|---|---|---|---|---|
| BUICK | APOLL | 1973 | PC | 0.0010% | BUICK 1973 APOLLO FRONT DRUM BRAKE B - 246 S - RS246 |
| BUICK | APOLL | 1974 | PC | 0.0007% | BUICK 1974 APOLLO FRONT DRUM BRAKE B - 246 S - RS246 |
| BUICK | APOLL | 1975 | PC | 0.0003% | BUICK 1975 APOLLO FRONT DISC BRAKE B - 245 S - RS245 |
| BUICK | CENTU | 1973 | PC | 0.0017% | BUICK 1973 CENTURY (RWD) 9 1/2 X 2 REAR BRAKE B - 245 S - RS245 |
| BUICK | CENTU | 1974 | PC | 0.0003% | BUICK 1974 CENTURY (RWD) 9 1/2 X 2 REAR BRAKE B - 245 S - RS245 |
| BUICK | CENTU | 1975 | PC | 0.0010% | BUICK 1975 CENTURY (RWD) 9 1/2 X 2 REAR BRAKE B - 245 S - RS245 |
| BUICK | CENTU | 1977 | PC | 0.0007% | BUICK 1977 CENTURY (RWD) REAR DRUM BRAKE B - 462 S - RS462 |
| BUICK | CENTU | 1978 | PC | 0.0014% | BUICK 1978 CENTURY (RWD) REAR DRUM BRAKE B - 514 S - RS514 |
| BUICK | CENTU | 1980 | PC | 0.0062% | BUICK 1980 CENTURY (RWD) 9 1/2 X 2 REAR BRAKE B - 514 S - RS514 |
| BUICK | CENTU | 1981 | PC | 0.0173% | BUICK 1981 CENTURY (RWD) 9 1/2 X 2 REAR BRAKE B - 514 S - RS514 |
| BUICK | CENTU | 1985 | PC | 0.0772% | BUICK 1985 CENTURY (FWD) STATION WAGON JA-2, JA-8 ($) BRAKE SYSTEM B - 552 S - RS552 |
| BUICK | CENTU | 1986 | PC | 0.0751% | BUICK 1986 CENTURY (FWD) STATION WAGON JA-2, JA-8 ($) BRAKE SYSTEM B - 552 S - RS552 |
| BUICK | CENTU | 1987 | PC | 0.0616% | BUICK 1987 CENTURY (FWD) STATION WAGON JA-2, JA-8 ($) BRAKE SYSTEM B - 552 S - RS552 |
| BUICK | CENTU | 1988 | PC | 0.0256% | BUICK 1988 CENTURY (FWD) STATION WAGON JA-2, JA-8 ($) BRAKE SYSTEM B - 552 S - RS552 |
| BUICK | CENTU | 1989 | PC | 0.0436% | BUICK 1989 CENTURY (FWD) STATION WAGON JA-2, JA-8 ($) BRAKE SYSTEM B - 552 S - RS552 |
| BUICK | CENTU | 1990 | PC | 0.0360% | BUICK 1990 CENTURY (FWD) STATION WAGON B - 552 S - RS552 |
| BUICK | CENTU | 1991 | PC | 0.0419% | BUICK 1991 CENTURY (FWD) STATION WAGON B - 552 S - RS552 |
| BUICK | CENTU | 1992 | PC | 0.0311% | BUICK 1992 CENTURY (FWD) STATION WAGON B - 552 S - RS552 |
| BUICK | CENTU | 1993 | PC | 0.0201% | BUICK 1993 CENTURY (FWD) STATION WAGON B - AF636 S - RS636 |
| BUICK | CENTU | 1994 | PC | 0.0270% | BUICK 1994 CENTURY (FWD) STATION WAGON B - AF636 S - RS636 |
| BUICK | CENTU | 1995 | PC | 0.0235% | BUICK 1995 CENTURY (FWD) STATION WAGON B - AF636 S - RS636 |
| BUICK | CENTU | 1996 | PC | 0.0221% | BUICK 1996 CENTURY (FWD) STATION WAGON B - AF636 S - RS636 |
| BUICK | CENTU | 1997 | PC | 0.0208% | BUICK 1997 CENTURY (FWD) REAR DRUM BRAKE B - AF636 S - RS636 |
| BUICK | CENTU | 1998 | PC | 0.0547% | BUICK 1998 CENTURY (FWD) REAR DRUM BRAKE B - AF636 S - RS636 |
| BUICK | CENTU | 1999 | PC | 0.0626% | BUICK 1999 CENTURY (FWD) REAR DRUM BRAKE B - AF636 S - RS636 |
| BUICK | ELECT | 1977 | PC | 0.0031% | BUICK 1977 ELECTRA (RWD) 11 X 2 REAR BRAKE B - 462 S - RS462 |
| BUICK | ELECT | 1978 | PC | 0.0048% | BUICK 1978 ELECTRA (RWD) 11 X 2 REAR BRAKE B - 462 S - RS462 |
| BUICK | ELECT | 1979 | PC | 0.0024% | BUICK 1979 ELECTRA (RWD) 11 X 2 REAR BRAKE B - 462 S - RS462 |
| BUICK | ELECT | 1980 | PC | 0.0017% | BUICK 1980 ELECTRA (RWD) 11 X 2 REAR BRAKE B - 462 S - RS462 |
| BUICK | ELECT | 1981 | PC | 0.0031% | BUICK 1981 ESTATE WAGON 11 X 2 REAR BRAKE B - 462 S - RS462 |
| BUICK | ELECT | 1982 | PC | 0.0048% | BUICK 1982 ELECTRA (RWD) 11 X 2 REAR BRAKE B - 462 S - RS462 |
| BUICK | ELECT | 1983 | PC | 0.0083% | BUICK 1983 ELECTRA (RWD) 11 X 2 REAR BRAKE B - 462 S - RS462 |
| BUICK | ELECT | 1984 | PC | 0.0076% | BUICK 1984 ELECTRA (RWD) 11 X 2 REAR BRAKE B - 462 S - RS462 |
| BUICK | ELECT | 1985 | PC | 0.0408% | BUICK 1985 CENTURY (FWD) STATION WAGON JA-2, JA-8 ($) BRAKE SYSTEM B - 552 S - RS552 |
| BUICK | ELECT | 1986 | PC | 0.0315% | BUICK 1986 ELECTRA (FWD), PARK AVENUE, PARK AVENUE ULTRA 8.86 X 1.77 REAR BRAKE B - 552 S - RS552 |
| BUICK | ELECT | 1987 | PC | 0.0322% | BUICK 1987 LESABRE (FWD) REAR DRUM BRAKE B - 564 S - RS564 |

**Appendix G: Representative Fleet Brake Type Distribution for HDV**
(Summary, Vehicle make and model year specific listing available on CD-R)

| EMFAC Vehicle Code | Model Year | Count | Front Brakes | | | Rear Brakes | | |
|---|---|---|---|---|---|---|---|---|
| | | | Disk | Either | Drum | Disk | Either | Drum |
| T4* | 1985 | 1 | . | . | 1 | . | . | 1 |
| | 1986 | 1 | . | . | 1 | . | . | 1 |
| | 1987 | 1 | . | . | 1 | . | . | 1 |
| | 1988 | 3 | . | . | 3 | . | . | 3 |
| | 1989 | 4 | 1 | . | 3 | 1 | . | 3 |
| | 1990 | 2 | 1 | . | 1 | 1 | . | 1 |
| | 1991 | 1 | . | . | 1 | . | . | 1 |
| | 1992 | 2 | . | . | 2 | . | . | 2 |
| | 1993 | 3 | 1 | . | 2 | . | . | 3 |
| | 1994 | 3 | . | . | 3 | . | . | 3 |
| | 1995 | 4 | 1 | . | 3 | . | . | 4 |
| | 1996 | 4 | 2 | . | 2 | . | . | 4 |
| | 1997 | 4 | 1 | . | 3 | . | . | 4 |
| | 1998 | 3 | 1 | . | 2 | 1 | . | 2 |
| | 1999 | 3 | 2 | . | 1 | 2 | . | 1 |
| | 2000 | 2 | 2 | . | . | 2 | . | . |
| | 2001 | 3 | . | . | 3 | . | . | 3 |
| | 2002 | 3 | . | . | 3 | . | . | 3 |
| | **Total** | 47 | 12 | . | 35 | 7 | . | 40 |
| T5** | 1973 | 2 | . | . | 2 | . | . | 2 |
| | 1974 | 1 | . | . | 1 | . | . | 1 |
| | 1975 | 2 | . | . | 2 | . | . | 2 |
| | 1976 | 2 | . | . | 2 | . | . | 2 |
| | 1977 | 1 | . | . | 1 | . | . | 1 |
| | 1978 | 2 | . | . | 2 | . | . | 2 |
| | 1979 | 1 | . | . | 1 | . | . | 1 |
| | 1981 | 2 | . | . | 2 | . | . | 2 |
| | 1982 | 1 | . | . | 1 | . | . | 1 |
| | 1984 | 1 | 1 | . | . | . | . | 1 |
| | 1986 | 2 | 2 | . | . | . | 1 | 1 |
| | 1987 | 1 | . | . | 1 | . | . | 1 |
| | 1988 | 1 | 1 | . | . | 1 | . | . |
| | 1989 | 1 | . | . | 1 | . | . | 1 |
| | 1993 | 1 | . | . | 1 | . | . | 1 |
| | 1994 | 1 | 1 | . | . | 1 | . | . |
| | 1996 | 1 | . | . | 1 | . | . | 1 |
| | 1998 | 1 | . | . | 1 | . | . | 1 |
| | 2000 | 2 | . | . | 2 | . | . | 2 |
| | 2001 | 3 | 1 | . | 2 | 1 | . | 2 |
| | **Total** | 29 | 6 | . | 23 | 3 | 1 | 25 |

* T4 = Light-heavy duty trucks, 8,501 – 10,000 lbs.
** T5 = Light-heavy duty trucks, 10,001 - 14,000 lbs.

| EMFAC Vehicle Code | Model Year | Count | Front Brakes | | | Rear Brakes | | |
|---|---|---|---|---|---|---|---|---|
| | | | Disk | Either | Drum | Disk | Either | Drum |
| T6* | 1973 | 6 | . | . | 6 | . | . | 6 |
| | 1974 | 7 | . | . | 7 | . | . | 7 |
| | 1975 | 4 | . | . | 4 | . | . | 4 |
| | 1976 | 3 | . | . | 3 | . | . | 3 |
| | 1977 | 5 | . | . | 5 | . | . | 5 |
| | 1978 | 8 | . | . | 8 | . | . | 8 |
| | 1979 | 7 | . | . | 7 | . | . | 7 |
| | 1980 | 3 | . | . | 3 | . | . | 3 |
| | 1981 | 5 | . | . | 5 | . | . | 5 |
| | 1982 | 1 | . | . | 1 | . | . | 1 |
| | 1983 | 5 | 2 | . | 3 | 1 | 1 | 3 |
| | 1984 | 5 | 5 | . | . | 1 | 3 | 1 |
| | 1985 | 3 | 3 | . | . | 1 | 1 | 1 |
| | 1986 | 6 | 5 | . | 1 | 1 | 2 | 3 |
| | 1987 | 4 | 2 | . | 2 | 1 | 1 | 2 |
| | 1988 | 5 | 4 | . | 1 | 2 | . | 3 |
| | 1989 | 2 | 1 | . | 1 | 1 | . | 1 |
| | 1990 | 3 | . | . | 3 | . | . | 3 |
| | 1991 | 2 | . | . | 2 | . | . | 2 |
| | 1992 | 3 | 1 | . | 2 | 1 | . | 2 |
| | 1993 | 2 | 1 | . | 1 | 1 | . | 1 |
| | 1994 | 3 | 1 | . | 2 | 1 | . | 2 |
| | 1995 | 3 | 1 | . | 2 | 1 | . | 2 |
| | 1996 | 2 | 2 | . | . | 2 | . | . |
| | 1997 | 4 | 2 | . | 2 | 2 | . | 2 |
| | 1998 | 2 | 1 | . | 1 | 1 | . | 1 |
| | 1999 | 3 | . | . | 3 | . | . | 3 |
| | 2000 | 4 | 1 | . | 3 | 1 | . | 3 |
| | 2001 | 4 | 1 | . | 3 | 1 | . | 3 |
| | 2002 | 1 | . | . | 1 | . | . | 1 |
| | 2003 | 1 | . | . | 1 | . | . | 1 |
| | **Total** | 116 | 33 | . | 83 | 19 | 8 | 89 |

* T6 = Medium-heavy duty trucks, 14,001 – 33,000 lbs.

| EMFAC Vehicle Code | Model Year | Count | Front Brakes | | | Rear Brakes | | |
|---|---|---|---|---|---|---|---|---|
| | | | Disk | Either | Drum | Disk | Either | Drum |
| T7* | 1974 | 1 | . | . | 1 | . | . | 1 |
| | 1975 | 1 | 1 | . | . | . | . | 1 |
| | 1976 | 1 | . | . | 1 | . | . | 1 |
| | 1978 | 1 | . | . | 1 | . | . | 1 |
| | 1980 | 4 | . | . | 4 | . | . | 4 |
| | 1981 | 2 | . | . | 2 | . | . | 2 |
| | 1982 | 1 | . | . | 1 | . | . | 1 |
| | 1983 | 2 | 2 | . | . | 1 | 1 | . |
| | 1984 | 4 | 1 | . | 3 | 1 | . | 3 |
| | 1985 | 6 | 4 | . | 2 | 1 | 1 | 4 |
| | 1986 | 3 | 3 | . | . | 1 | . | 2 |
| | 1987 | 7 | 4 | . | 3 | 1 | . | 6 |
| | 1988 | 4 | 2 | . | 2 | 1 | . | 3 |
| | 1989 | 2 | 1 | . | 1 | . | . | 2 |
| | 1990 | 7 | 2 | . | 5 | 2 | . | 5 |
| | 1991 | 1 | . | . | 1 | . | . | 1 |
| | 1992 | 4 | 1 | . | 3 | 1 | . | 3 |
| | 1993 | 3 | . | . | 3 | . | . | 3 |
| | 1995 | 2 | 1 | . | 1 | 1 | . | 1 |
| | 1996 | 2 | . | . | 2 | . | . | 2 |
| | 1997 | 3 | 2 | . | 1 | 2 | . | 1 |
| | 1998 | 1 | 1 | . | . | 1 | . | . |
| | 1999 | 2 | . | . | 2 | . | . | 2 |
| | 2003 | 1 | . | . | 1 | . | . | 1 |
| | **Total** | 65 | 25 | . | 40 | 13 | 2 | 50 |

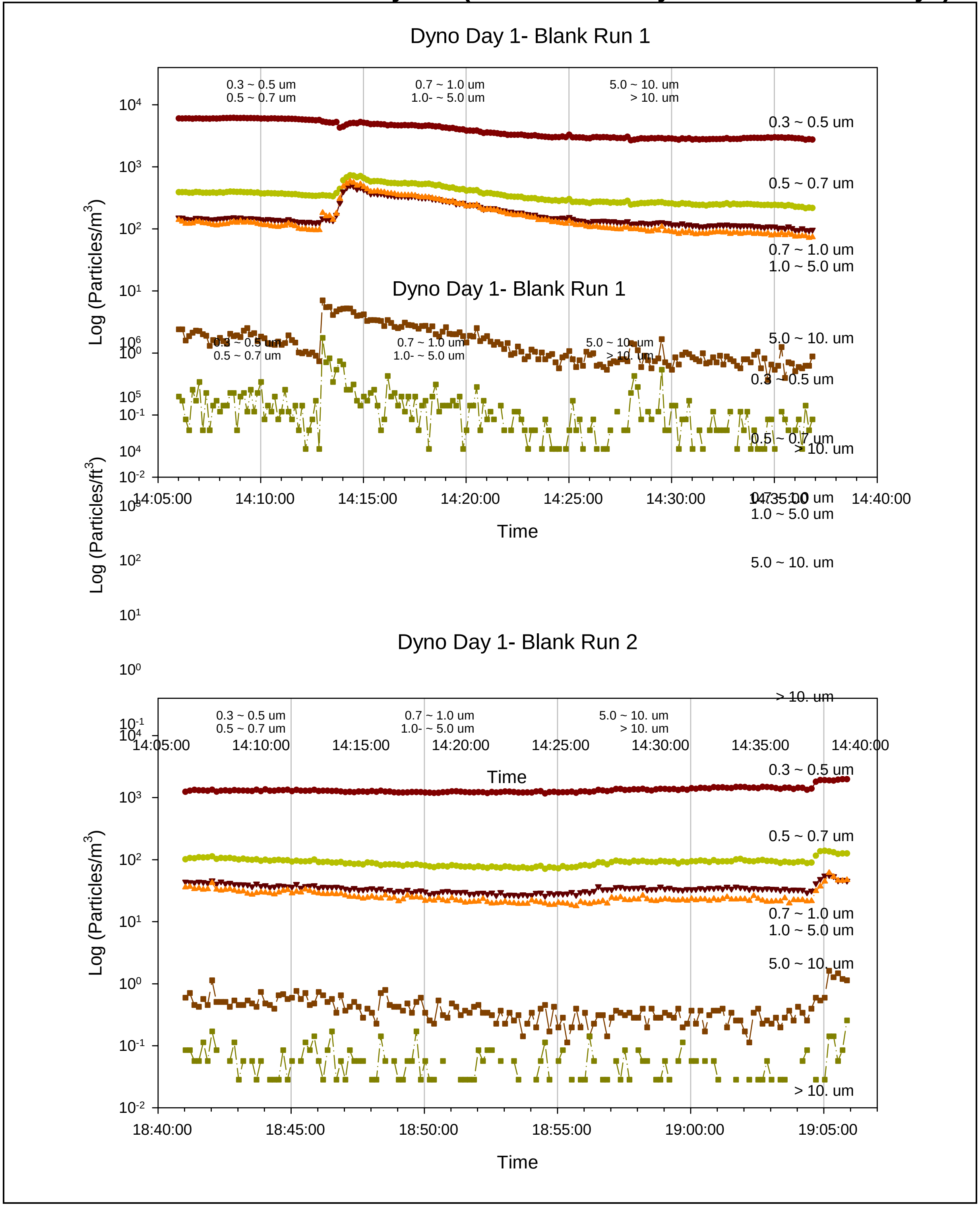
* T7 = Heavy-heavy duty trucks 33,001 – 60,000 lbs.

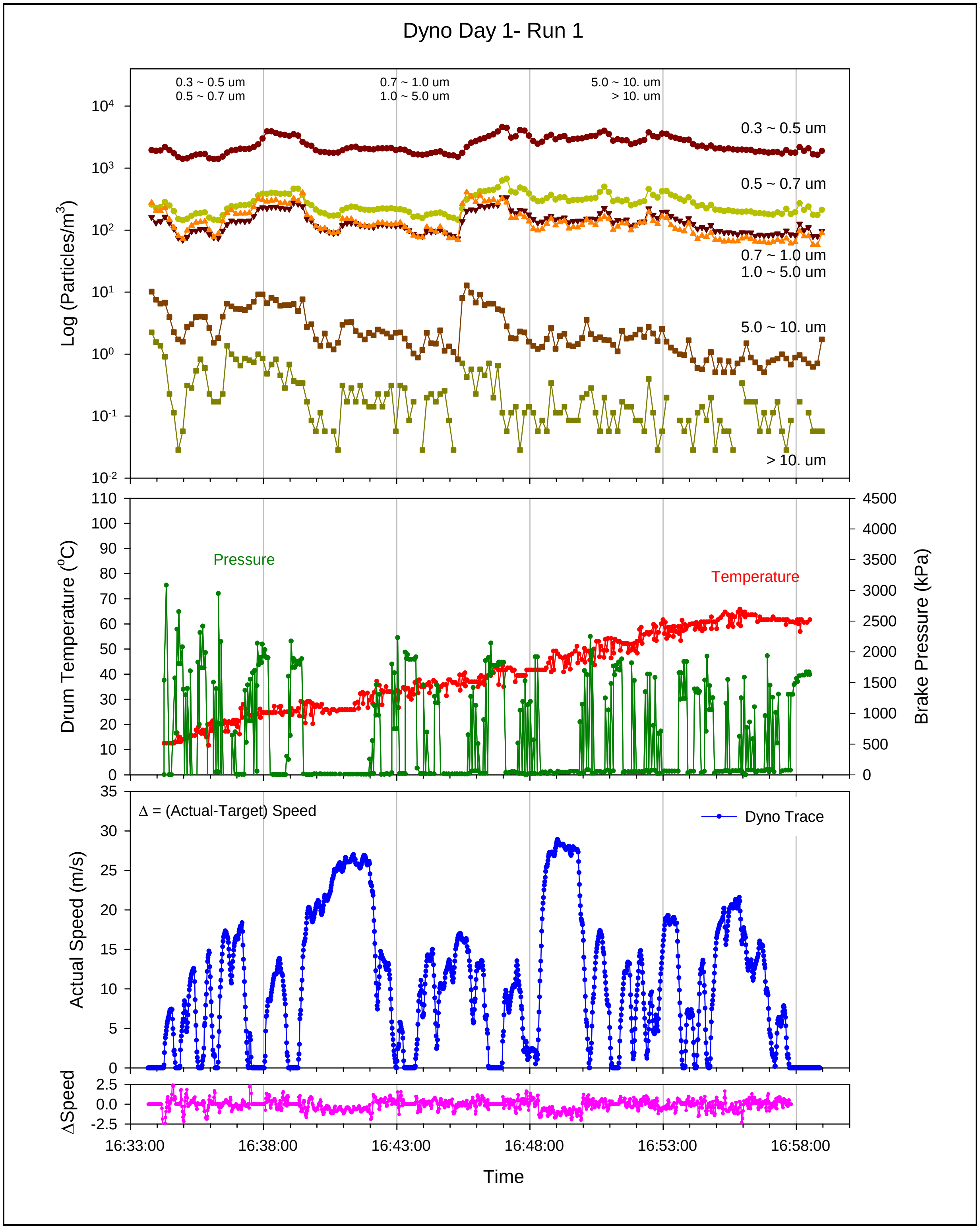
| EMFAC Vehicle Code | Model Year | Count | Front Brakes | | | Rear Brakes | | |
|---|---|---|---|---|---|---|---|---|
| | | | Disk | Either | Drum | Disk | Either | Drum |
| | 1973 | 3 | . | . | 3 | . | . | 3 |
| | 1974 | 2 | . | . | 2 | . | . | 2 |
| | 1976 | 1 | . | . | 1 | . | . | 1 |
| | 1977 | 4 | 1 | . | 3 | . | . | 4 |
| | 1979 | 5 | 2 | . | 3 | 1 | . | 4 |
| | 1980 | 3 | . | . | 3 | . | . | 3 |
| | 1981 | 3 | . | . | 3 | . | . | 3 |
| | 1982 | 4 | 2 | . | 2 | . | . | 4 |
| | 1983 | 1 | . | . | 1 | . | . | 1 |
| | 1984 | 2 | 1 | . | 1 | . | . | 2 |
| | 1985 | 1 | . | . | 1 | . | . | 1 |
| | 1986 | 5 | . | . | 5 | . | . | 5 |
| | 1987 | 1 | 1 | . | . | . | . | 1 |
| | 1988 | 3 | 1 | . | 2 | . | . | 3 |
| **T8*** | 1989 | 3 | 3 | . | . | 1 | . | 2 |
| | 1990 | 2 | . | . | 2 | . | . | 2 |
| | 1991 | 1 | . | . | 1 | . | . | 1 |
| | 1992 | 1 | . | . | 1 | . | . | 1 |
| | 1993 | 1 | . | . | 1 | . | . | 1 |
| | 1994 | 1 | . | . | 1 | . | . | 1 |
| | 1995 | 1 | . | . | 1 | . | . | 1 |
| | 1996 | 4 | . | . | 4 | . | . | 4 |
| | 1997 | 3 | . | . | 3 | . | . | 3 |
| | 1998 | 4 | . | . | 4 | . | . | 4 |
| | 1999 | 2 | . | . | 2 | . | . | 2 |
| | 2000 | 3 | . | . | 3 | . | . | 3 |
| | 2001 | 3 | . | . | 3 | . | . | 3 |
| | 2002 | 2 | . | . | 2 | . | . | 2 |
| | **Total** | 69 | 11 | . | 58 | 2 | . | 67 |
| **Total** | **HDV**** | **326** | **87** | **.** | **239** | **44** | **11** | **271** |

* T8 = Line-haul trucks 60,000+ lbs.

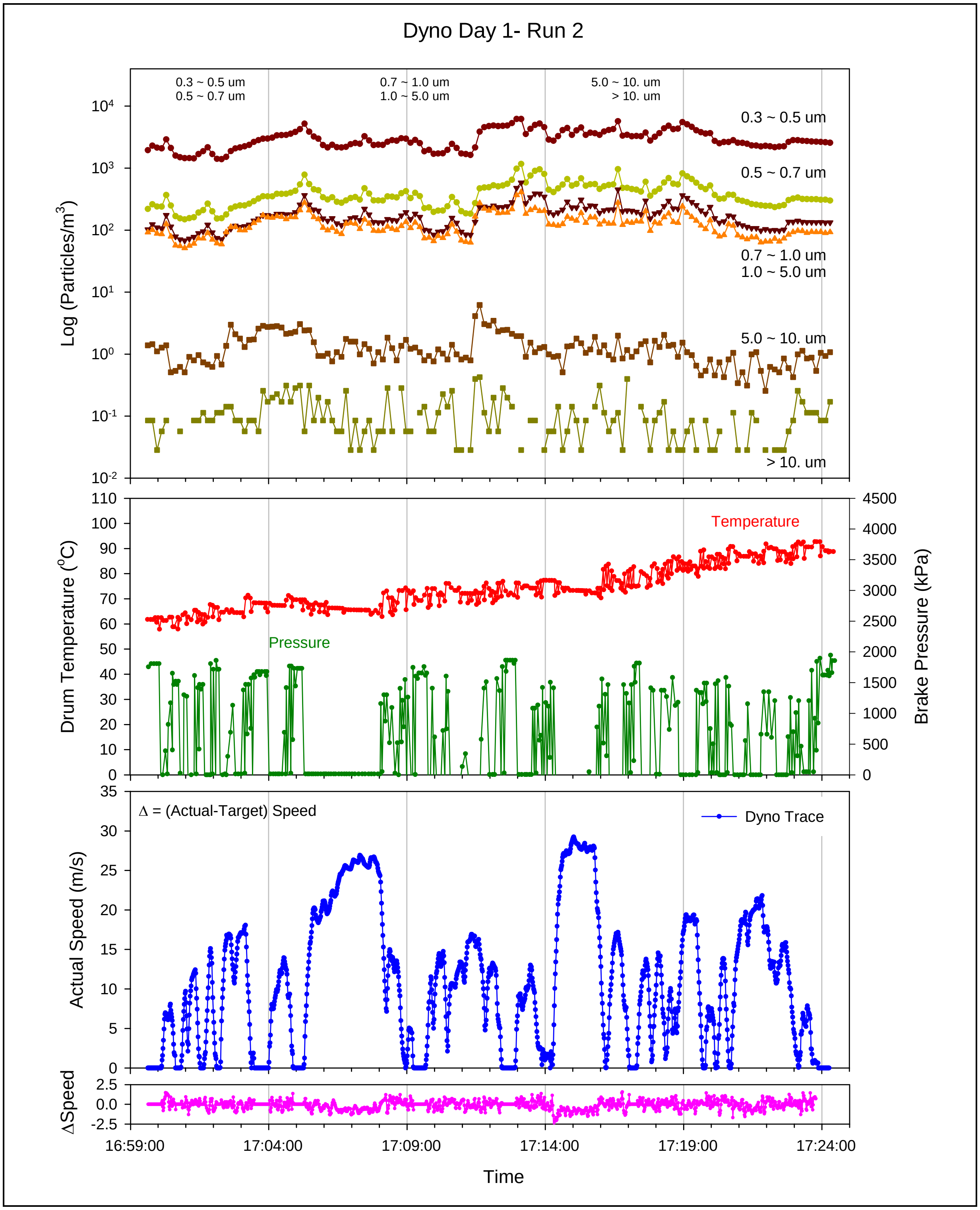
** HDV includes T4, T5, T6, T7, and T8.

## Appendix H: Real-time Sensor Measurements for Test Vehicle Dynamometer Brake Emission Cycles (LA92 ran on Days 1-2 and LA4 on Day3)

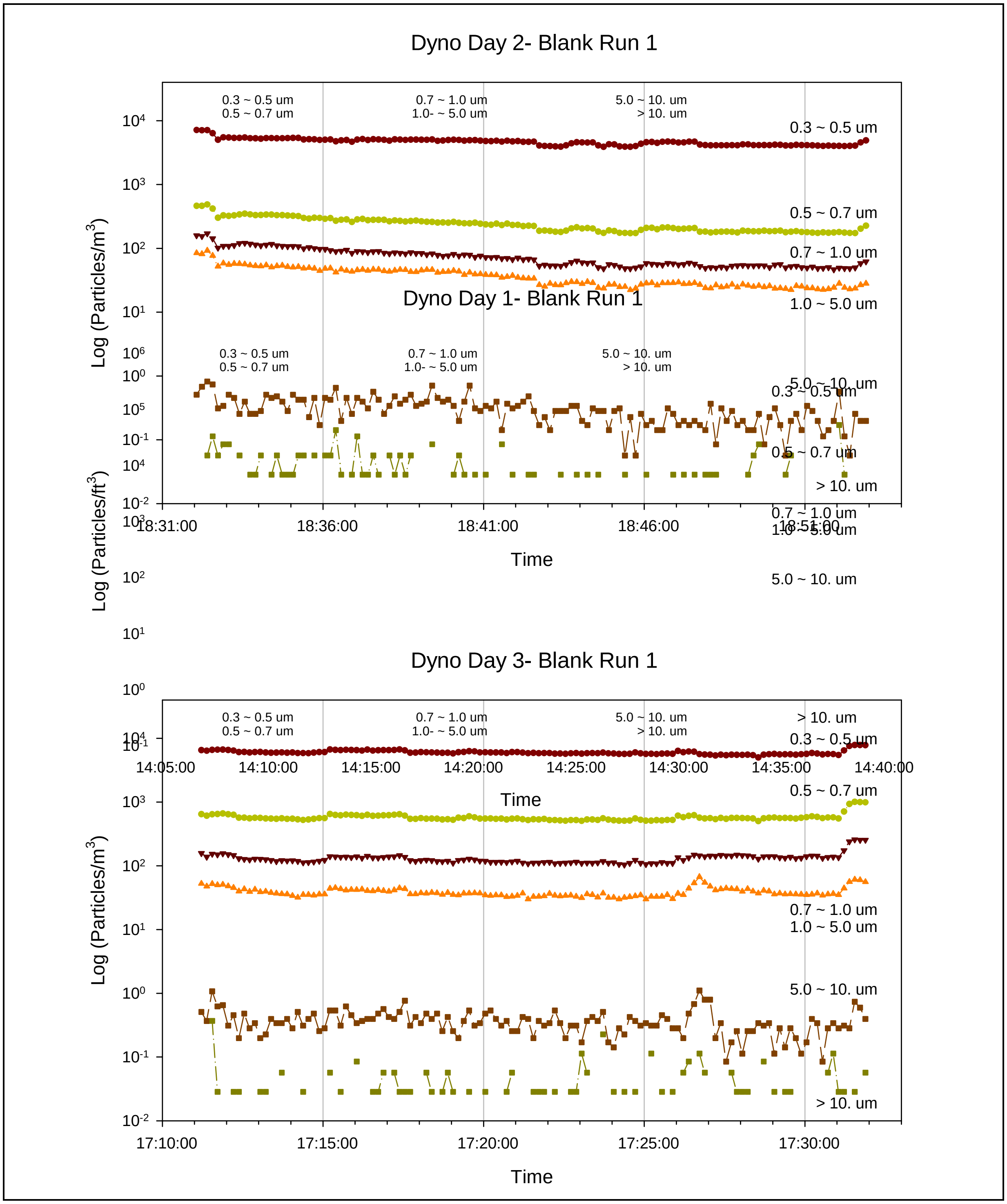




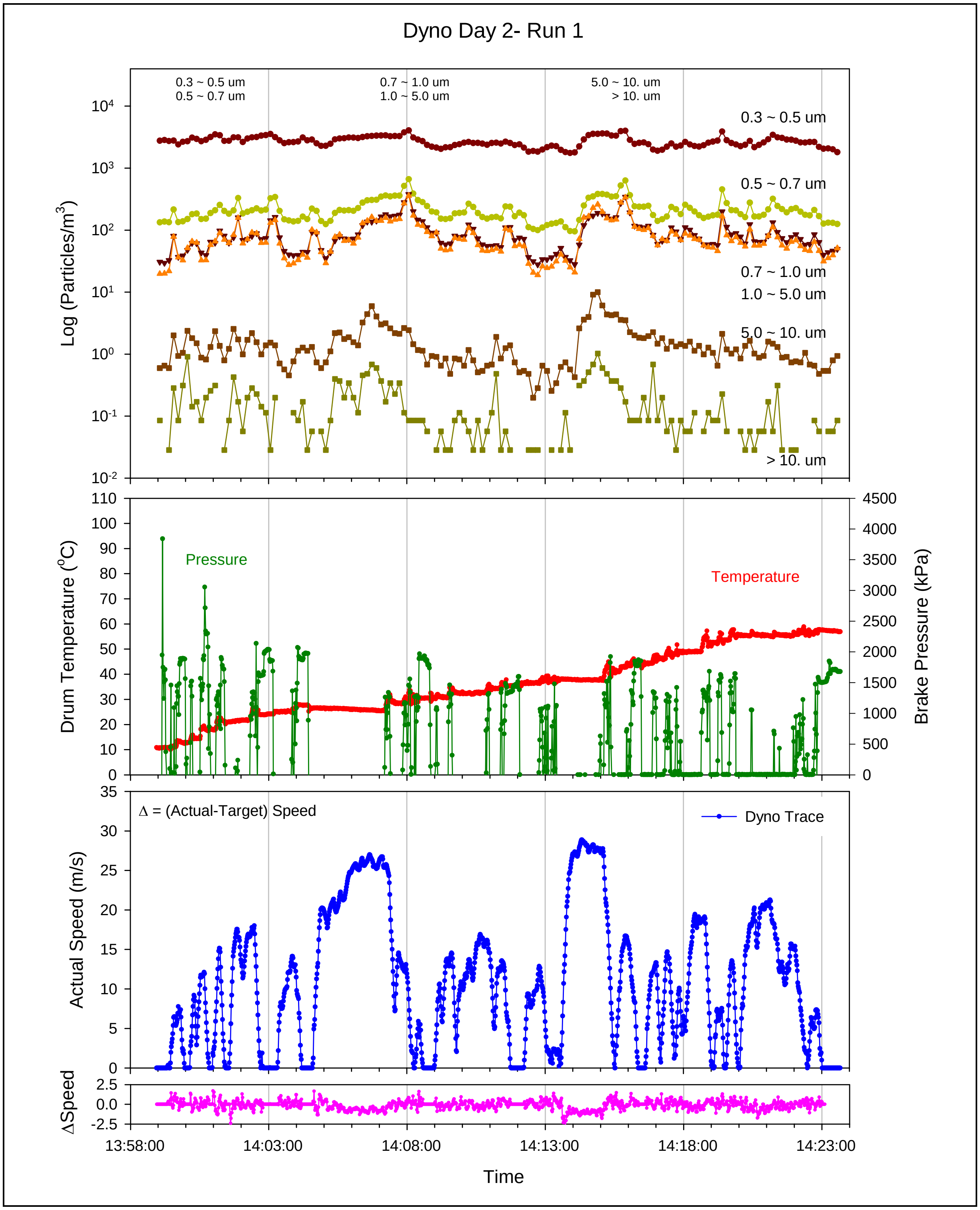
Dyno Day 1- Run 1
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
16:33:00
16:38:00
16:43:00
16:48:00
16:53:00
16:58:00
Time



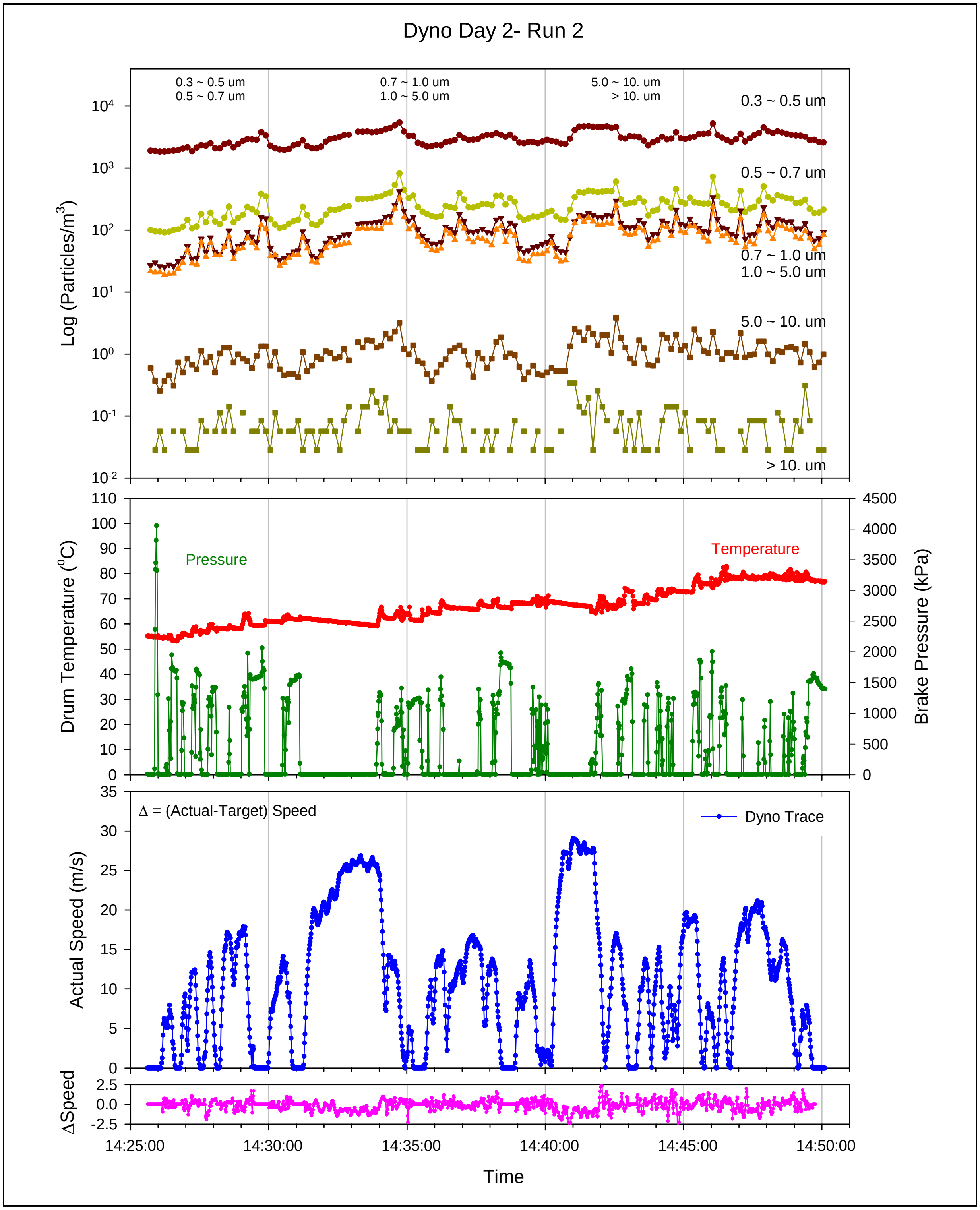
Dyno Day 1- Run 2
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m^3)
Temperature
Pressure
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
16:59:00
17:04:00
17:09:00
17:14:00
17:19:00
17:24:00
Time

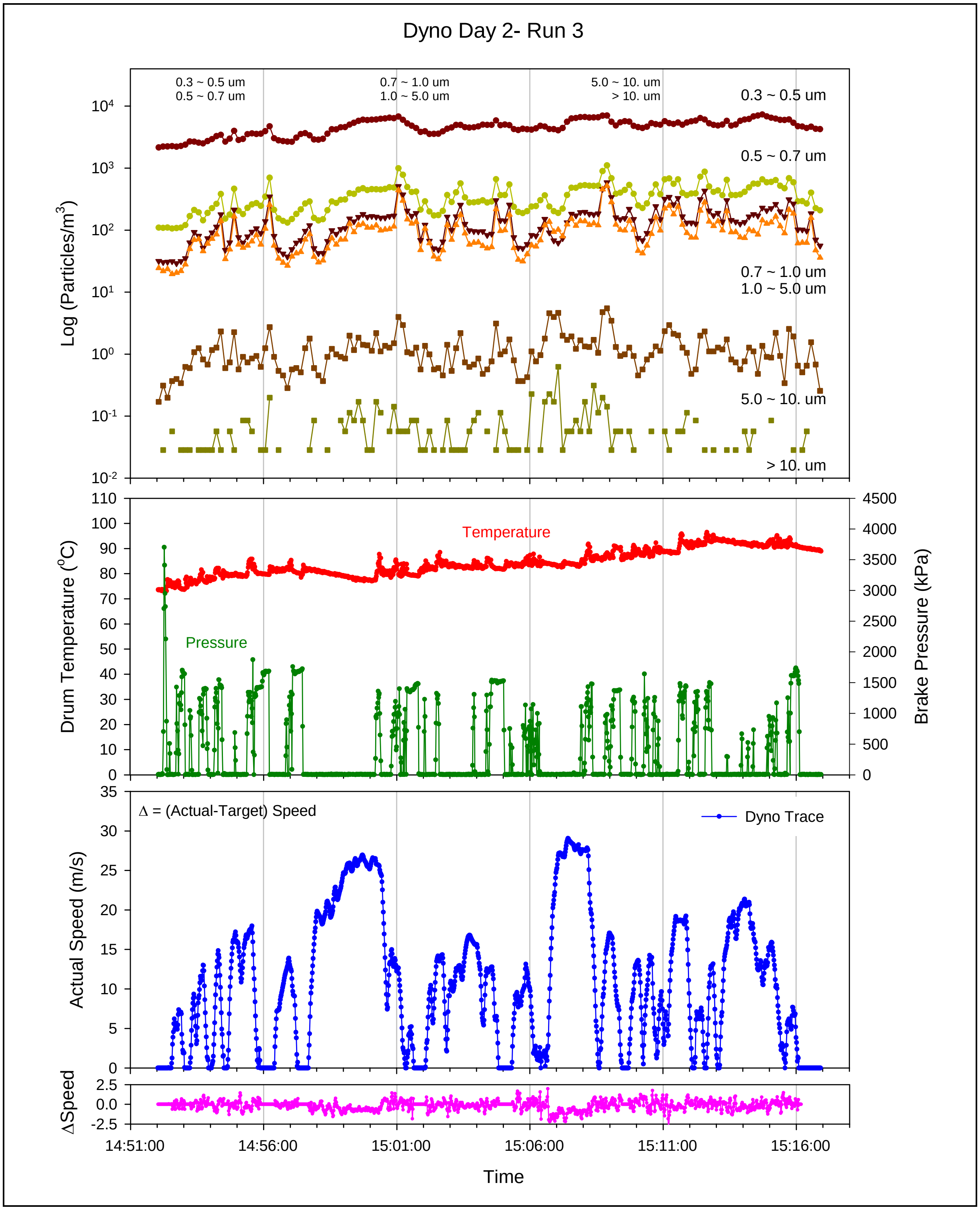


Dyno Day 2- Blank Run 1
Dyno Day 1- Blank Run 1
Dyno Day 3- Blank Run 1
Log (Particles/m3)
Log (Particles/ft3)
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0- ~ 5.0 um
5.0 ~ 10. um
> 10. um
1.0 ~ 5.0 um
18:31:00
18:36:00
18:41:00
18:46:00
18:51:00
14:05:00
14:10:00
14:15:00
14:20:00
14:25:00
14:30:00
14:35:00
14:40:00
17:10:00
17:15:00
17:20:00
17:25:00
17:30:00
Time

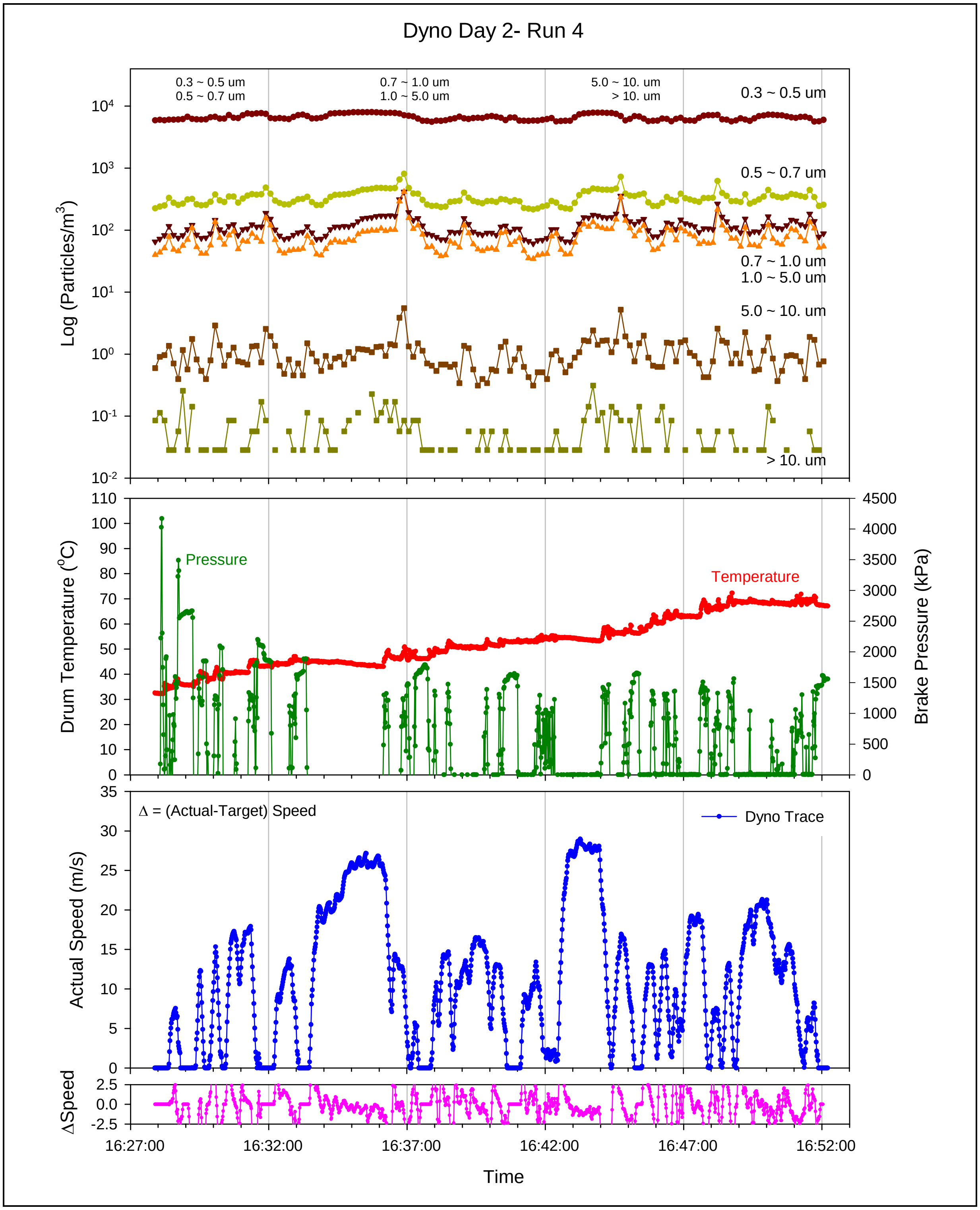


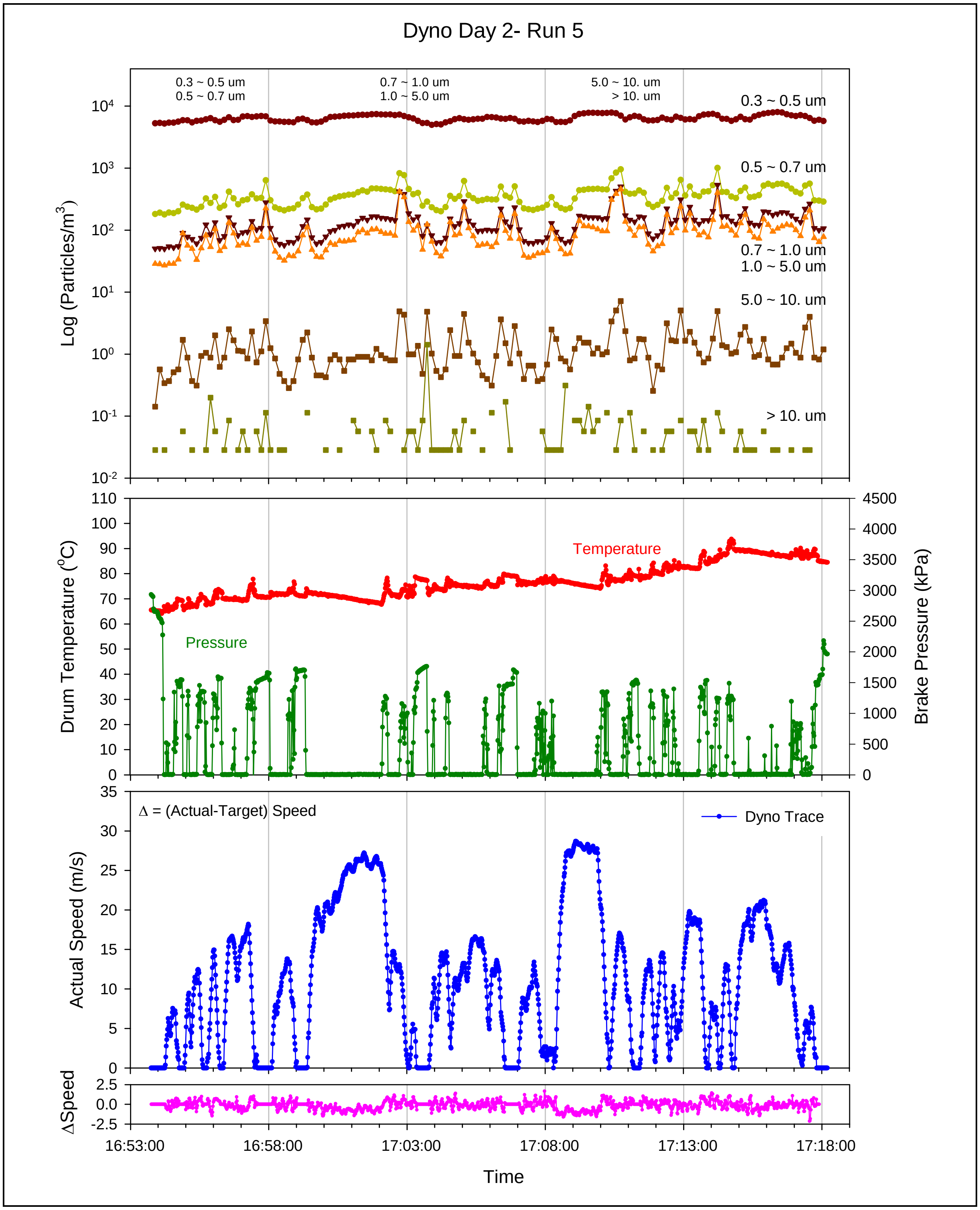
Dyno Day 2- Run 1
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
13:58:00
14:03:00
14:08:00
14:13:00
14:18:00
14:23:00
Time

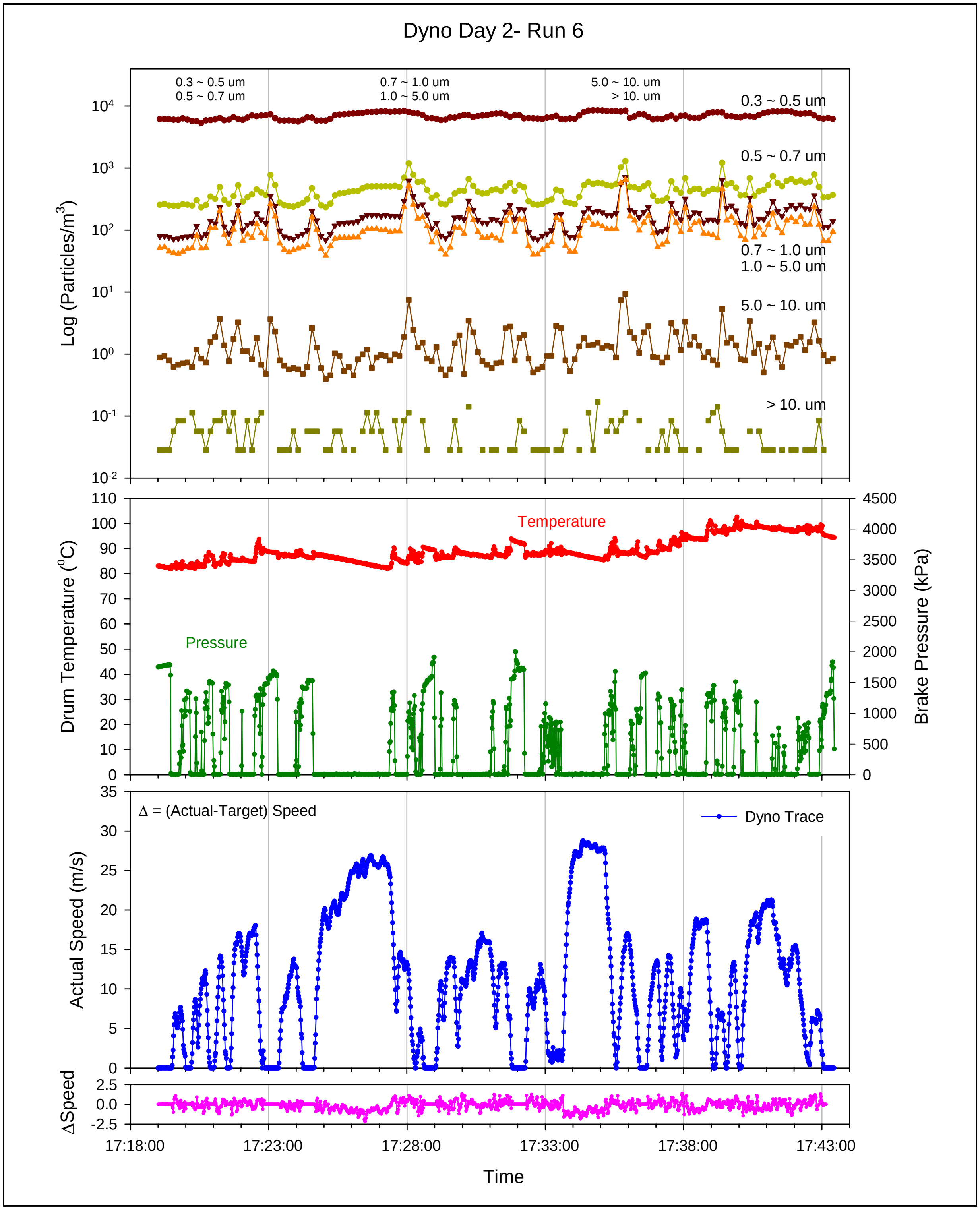

Dyno Day 2- Run 2
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m³)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
14:25:00
14:30:00
14:35:00
14:40:00
14:45:00
14:50:00
Time

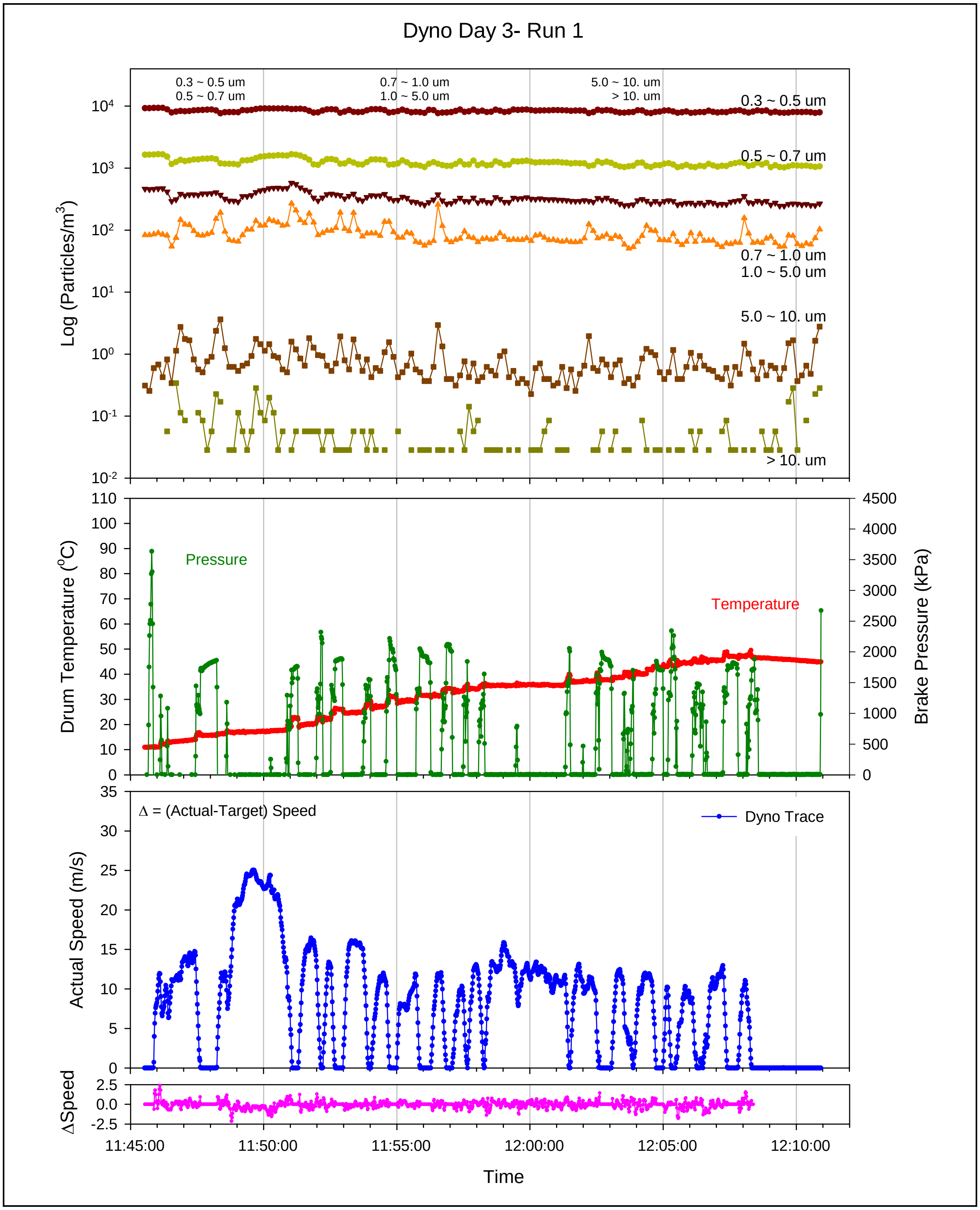


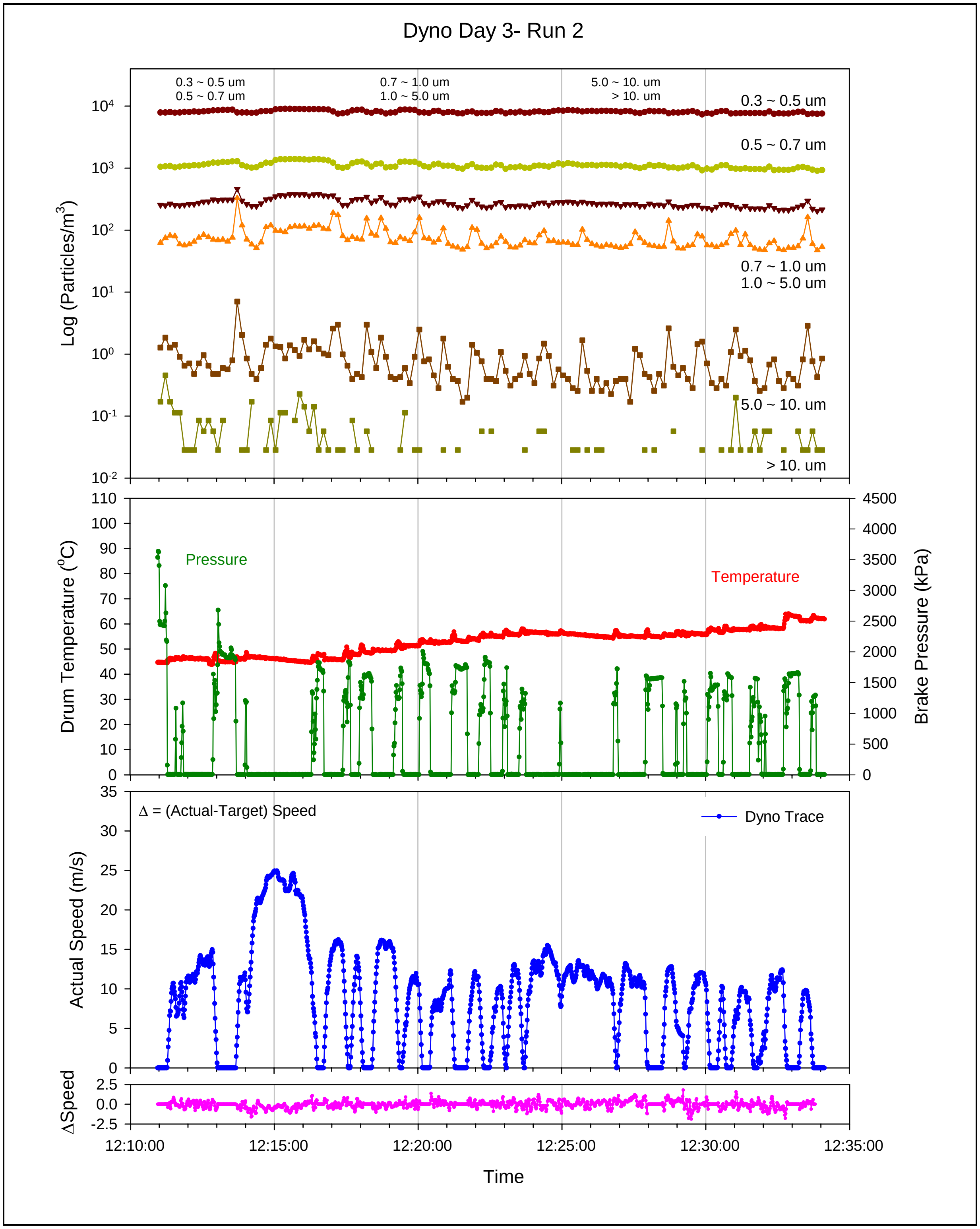
Dyno Day 2- Run 3
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m³)
Temperature
Pressure
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
14:51:00
14:56:00
15:01:00
15:06:00
15:11:00
15:16:00
Time


Dyno Day 2- Run 4
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
16:27:00
16:32:00
16:37:00
16:42:00
16:47:00
16:52:00
Time

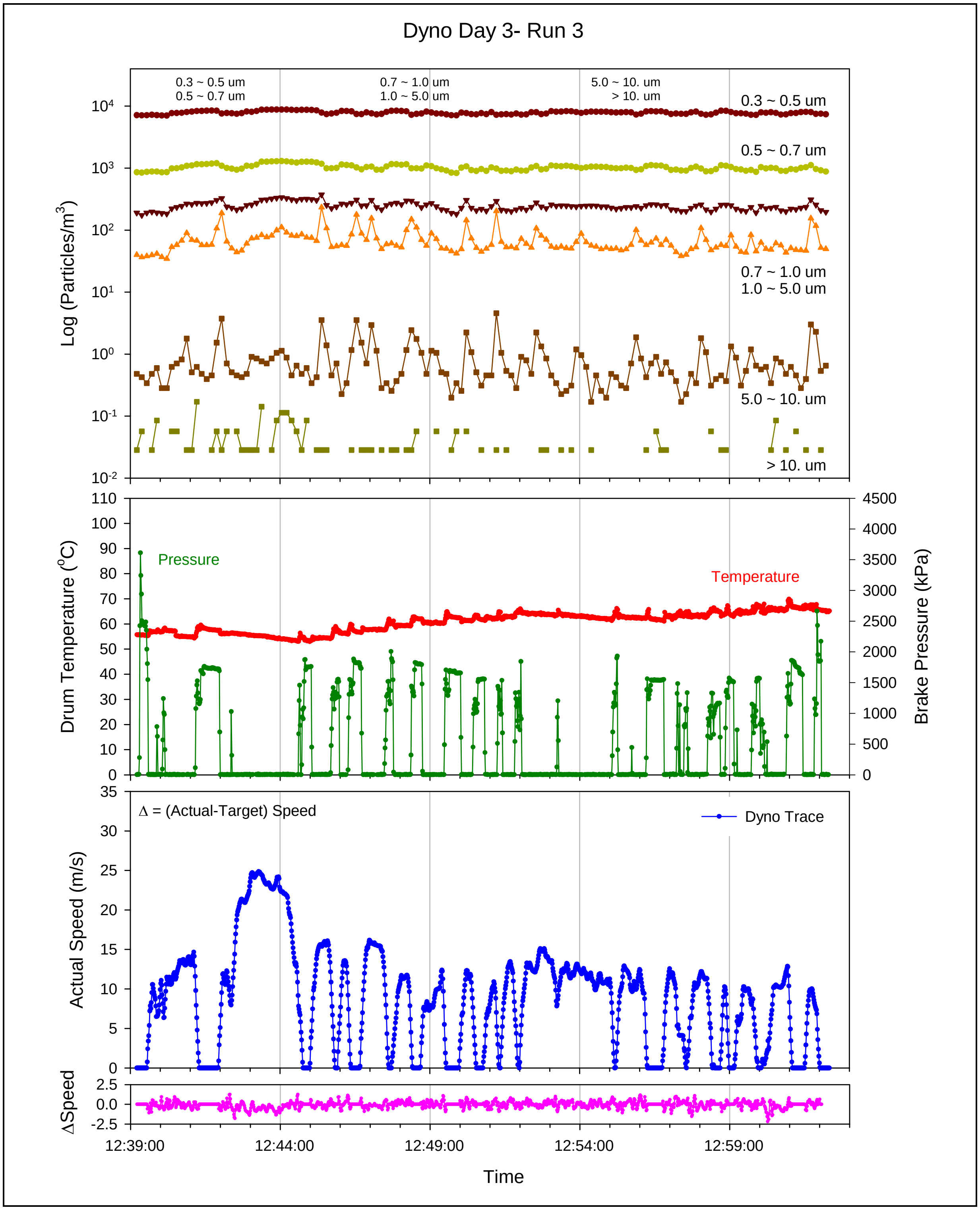

Dyno Day 2- Run 5
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m^3)
Temperature
Pressure
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
16:53:00
16:58:00
17:03:00
17:08:00
17:13:00
17:18:00
Time

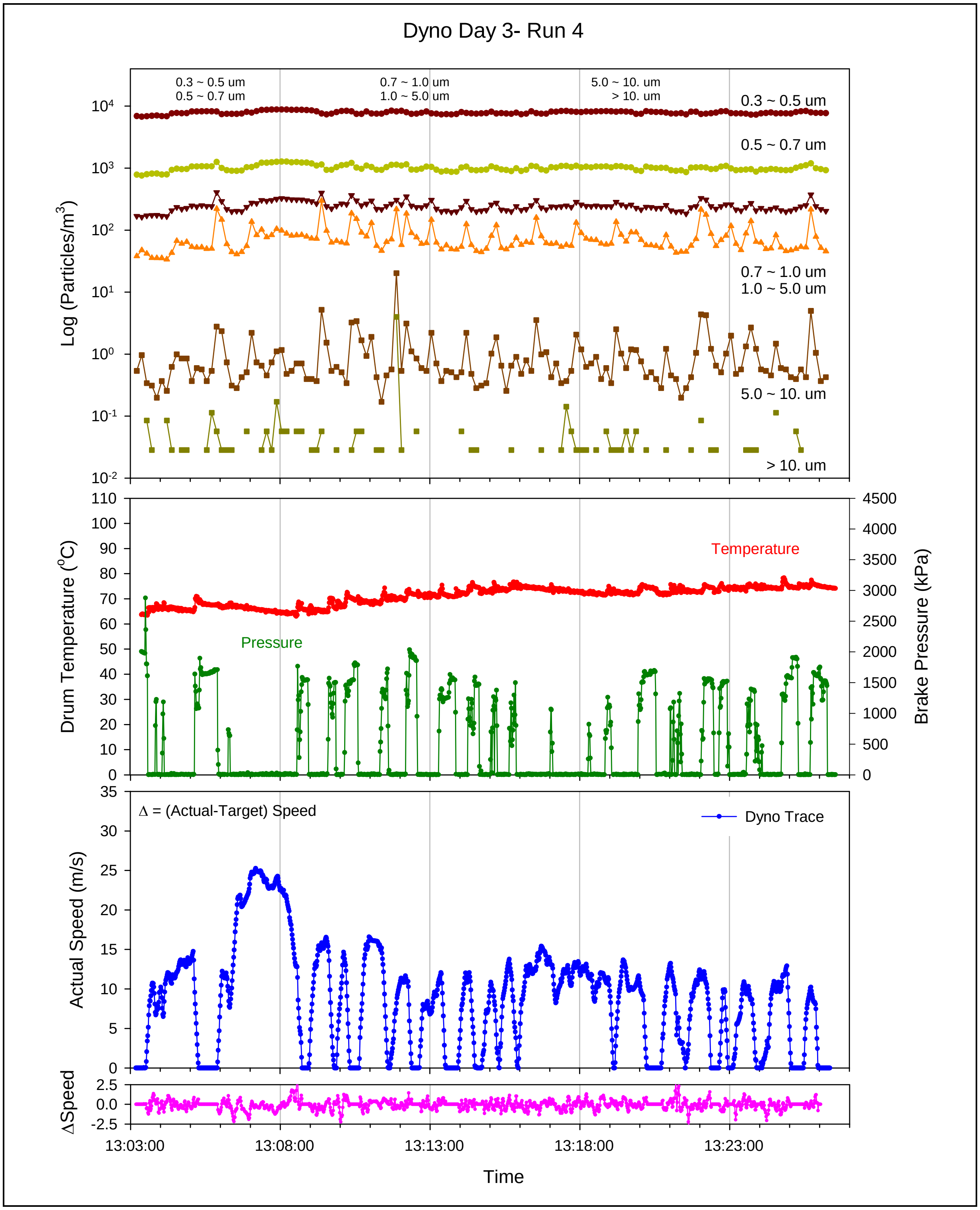

Dyno Day 2- Run 6
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Temperature
Pressure
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
17:18:00
17:23:00
17:28:00
17:33:00
17:38:00
17:43:00
Time


Dyno Day 3- Run 1
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
11:45:00
11:50:00
11:55:00
12:00:00
12:05:00
12:10:00
Time

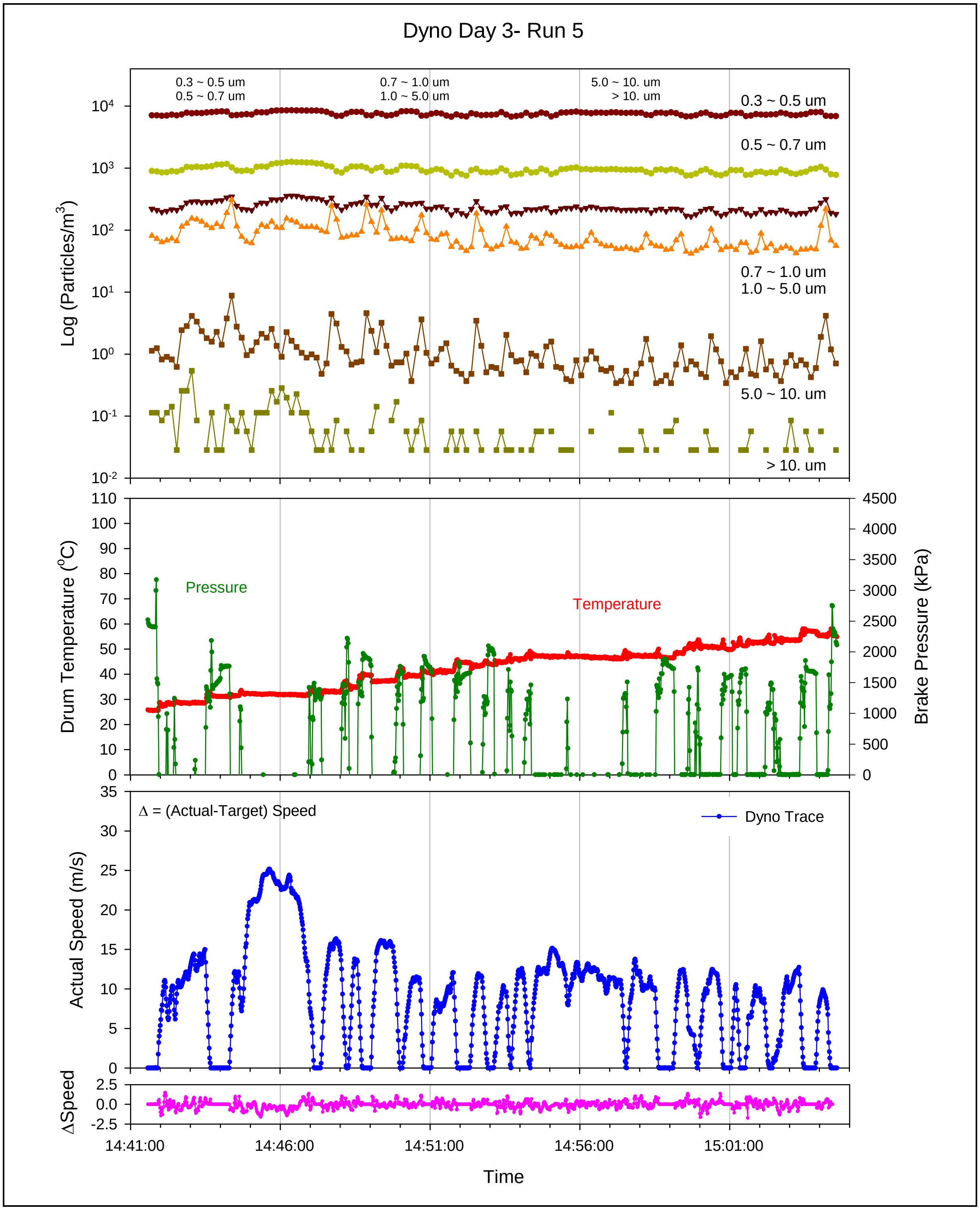


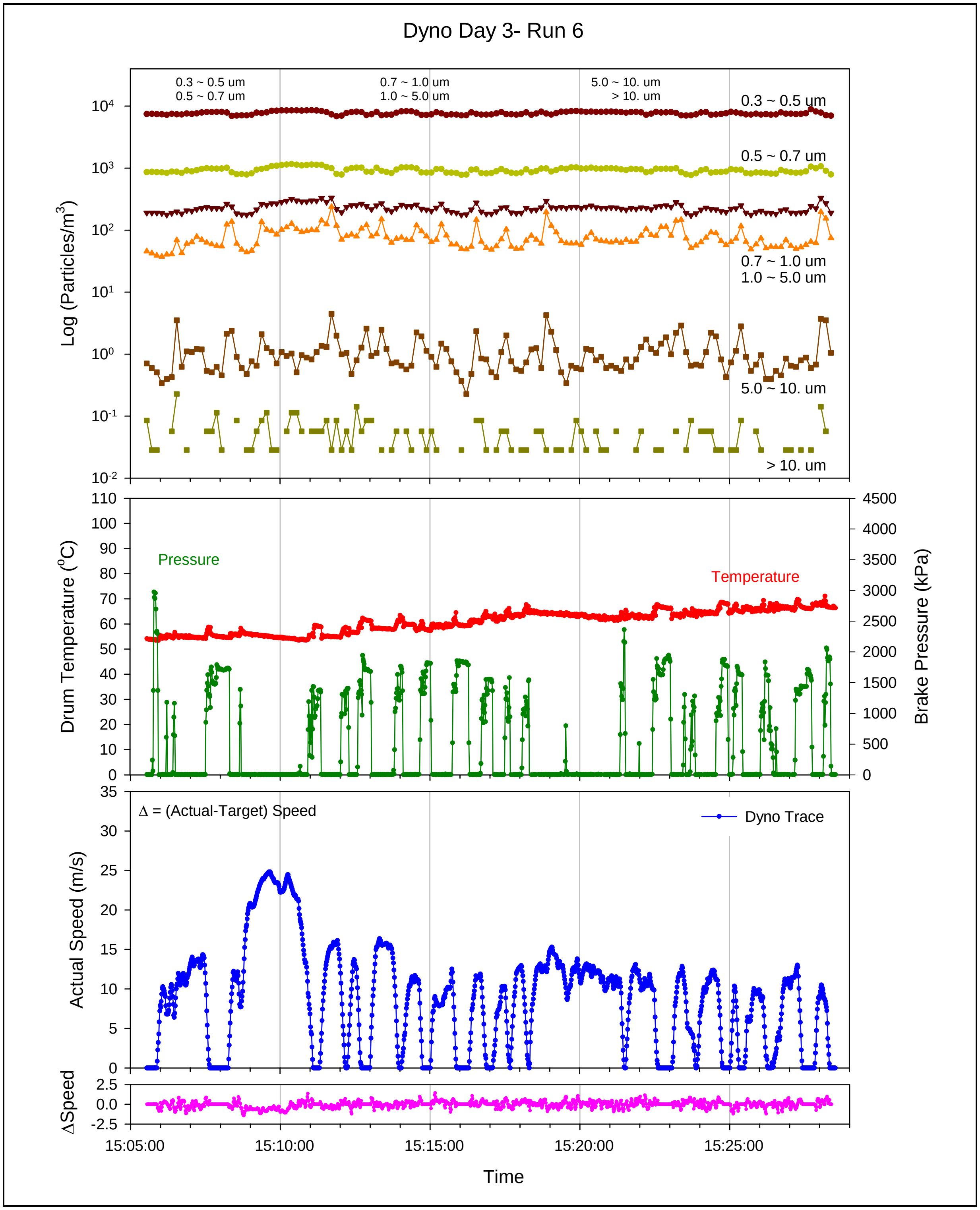
Dyno Day 3- Run 2
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
12:10:00
12:15:00
12:20:00
12:25:00
12:30:00
12:35:00
Time


Dyno Day 3- Run 3
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
12:39:00
12:44:00
12:49:00
12:54:00
12:59:00
Time

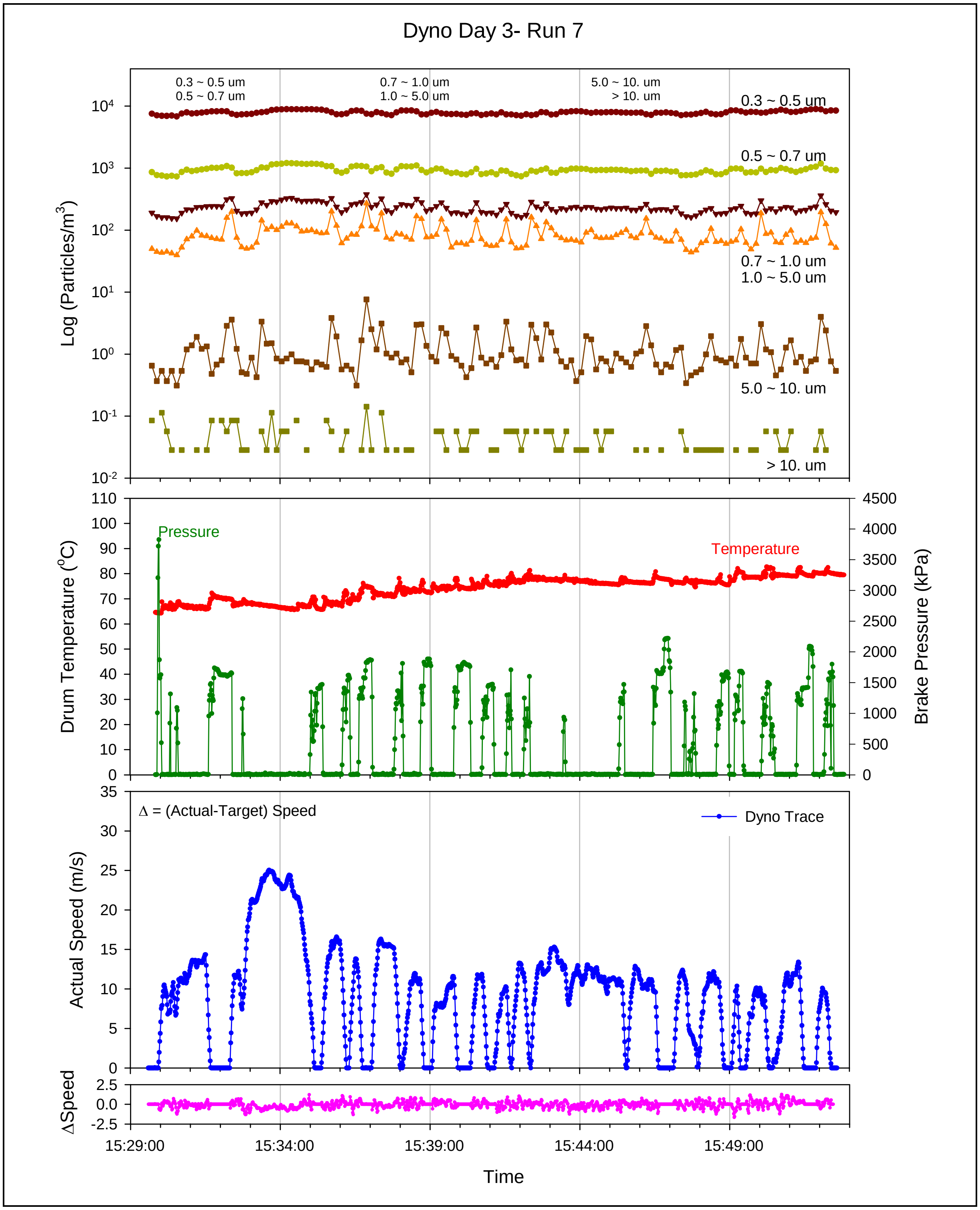


Dyno Day 3- Run 4
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Temperature
Pressure
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
13:03:00
13:08:00
13:13:00
13:18:00
13:23:00
Time

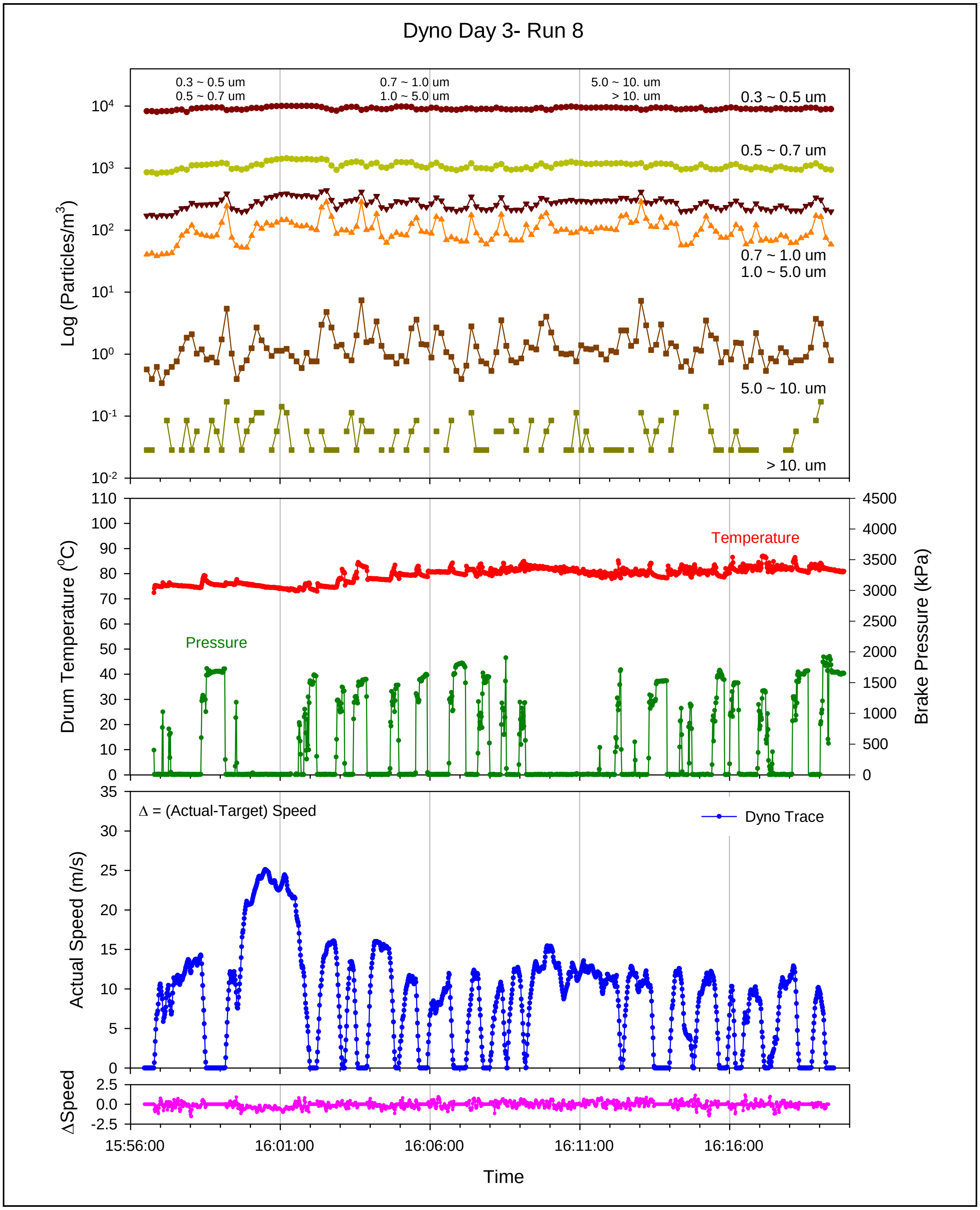

Dyno Day 3- Run 5
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m³)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
14:41:00
14:46:00
14:51:00
14:56:00
15:01:00
Time



Dyno Day 3- Run 6
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m$^3$)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
15:05:00
15:10:00
15:15:00
15:20:00
15:25:00
Time



Dyno Day 3- Run 7
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Pressure
Temperature
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
15:29:00
15:34:00
15:39:00
15:44:00
15:49:00
Time



Dyno Day 3- Run 8
0.3 ~ 0.5 um
0.5 ~ 0.7 um
0.7 ~ 1.0 um
1.0 ~ 5.0 um
5.0 ~ 10. um
> 10. um
Log (Particles/m3)
Temperature
Pressure
Drum Temperature (°C)
Brake Pressure (kPa)
Δ = (Actual-Target) Speed
Dyno Trace
Actual Speed (m/s)
ΔSpeed
15:56:00
16:01:00
16:06:00
16:11:00
16:16:00
Time

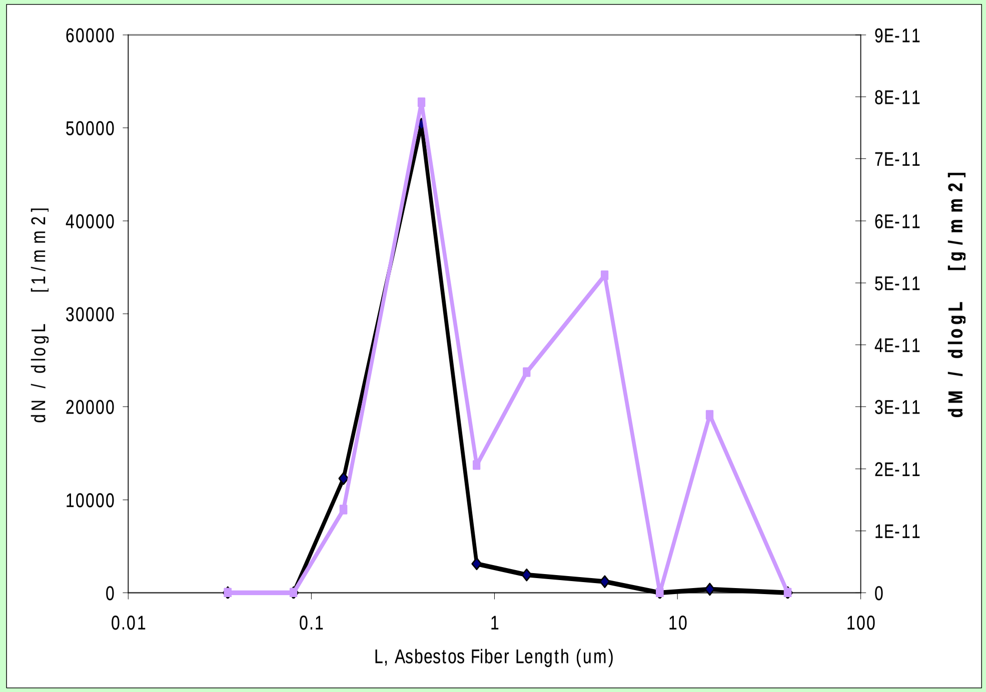
## Appendix I: TEM Asbestos Fiber Counts for Dust and Air Samples Collected during Brake Emission Testing

**Post-Dyno, Drum Dust CARB Cycle**

| | | |
|---|---|---|
| dust sample ID | E0409026-006 | |
| analyst | JW | |
| date | 3/22/2001 | |
| R.Rear Brake Emission | **1985 Chvy G20** | |
| dust mass | 0.0055 | g |
| funnel inner diameter | 16.25 | mm |
| filtered area | 207.3942025 | mm2 |
| original water volume | 50 | mL |
| filtered subsample volume | 1 | mL |
| Sensitivity (0.01 -0.6um) | 0.000754303 | % |
| Sensitivity (0.6 - 60um) | 0.000312932 | % |

| | | |
|---|---|---|
| **Chrysotile fibers counted** | **32** |
| other fib (not MgSi or < Lmin) | 9 |
| fib with CHRY SAED | 27 |

| | | | mag1 58000 Lmin(um) 0.01 | | mag2 9700 Lmin(um) 0.6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Llow(um) | Lhigh(um) | Lmid(um) | # of CHRY | area (mm2) | # of CHRY | area (mm2) | N (1/mm2) | dN/dlogL (1/mm2) | M (g/mm2) | dM/dlogL (g/mm2) |
| 0.01 | 0.06 | 0.035 | 0 | 0.00054065 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.06 | 0.1 | 0.08 | 0 | 0.00054065 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.1 | 0.2 | 0.15 | 2 | 0.00054065 | 0 | 0 | 3699.285113 | 12288.75915 | 4.034E-12 | 1.3401E-11 |
| 0.2 | 0.6 | 0.4 | 13 | 0.00054065 | 0 | 0 | 24045.35324 | 50396.73458 | 3.776E-11 | 7.91313E-11 |
| 0.6 | 1 | 0.8 | 2 | 0.00054065 | 4 | 0.0081473 | 690.6136966 | 3112.993415 | 4.571E-12 | 2.06022E-11 |
| 1 | 2 | 1.5 | 0 | 0.00054065 | 5 | 0.0081473 | 575.5114138 | 1911.807535 | 1.071E-11 | 3.55651E-11 |
| 2 | 6 | 4 | 1 | 0.00054065 | 4 | 0.0081473 | 575.5114138 | 1206.216257 | 2.443E-11 | 5.11993E-11 |
| 6 | 10 | 8 | 0 | 0.00054065 | 0 | 0.0081473 | 0 | 0 | 0 | 0 |
| 10 | 20 | 15 | 0 | 0.00054065 | 1 | 0.0081473 | 115.1022828 | 382.3615069 | 8.631E-12 | 2.86708E-11 |
| 20 | 60 | 40 | 0 | 0.00054065 | 0 | 0.0081473 | 0 | 0 | 0 | 0 |
| | >60 | | 18 | | 14 | | | | | |

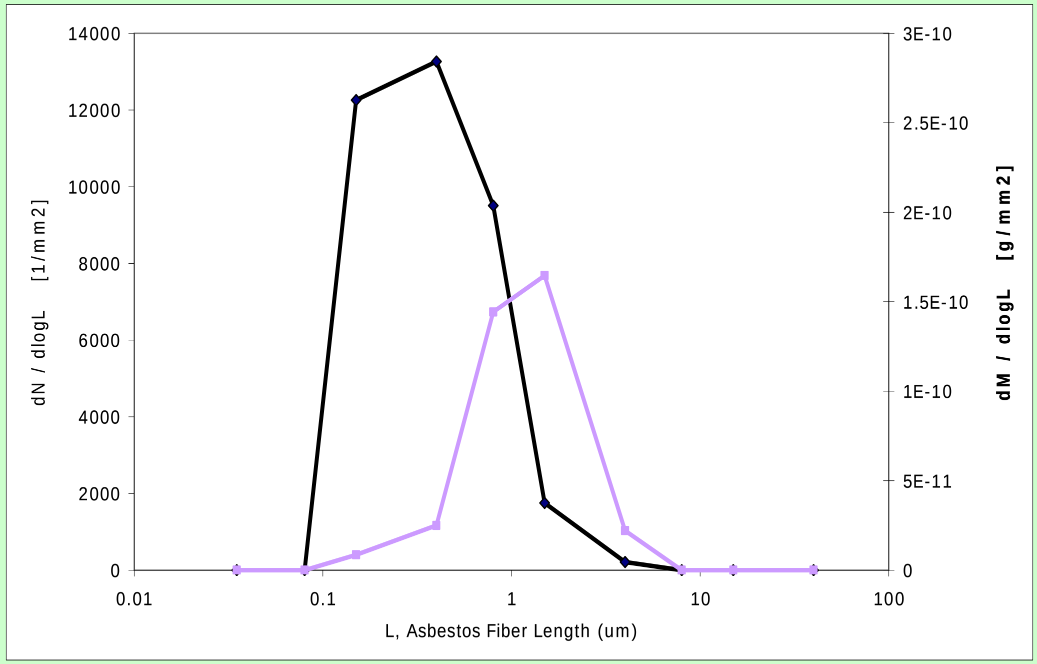


**Field Collected Dust** **Brake Shop**

| | | |
|---|---|---|
| dust sample ID | E0408015-8 | |
| analyst | JW | |
| date | 12/13/2000 | |
| Rear Brake Drum Dust | **1996 Pontiac GM** | |
| dust mass | 0.0056 | g |
| funnel inner diameter | 16.25 | mm |
| filtered area | 207.3942025 | mm2 |
| original water volume | 50 | mL |
| filtered subsample volume | 1 | mL |
| Sensitivity (0.01 -2um) | 0.000211182 | % |
| Sensitivity (2 - 60um) | 5.29888E-05 | % |

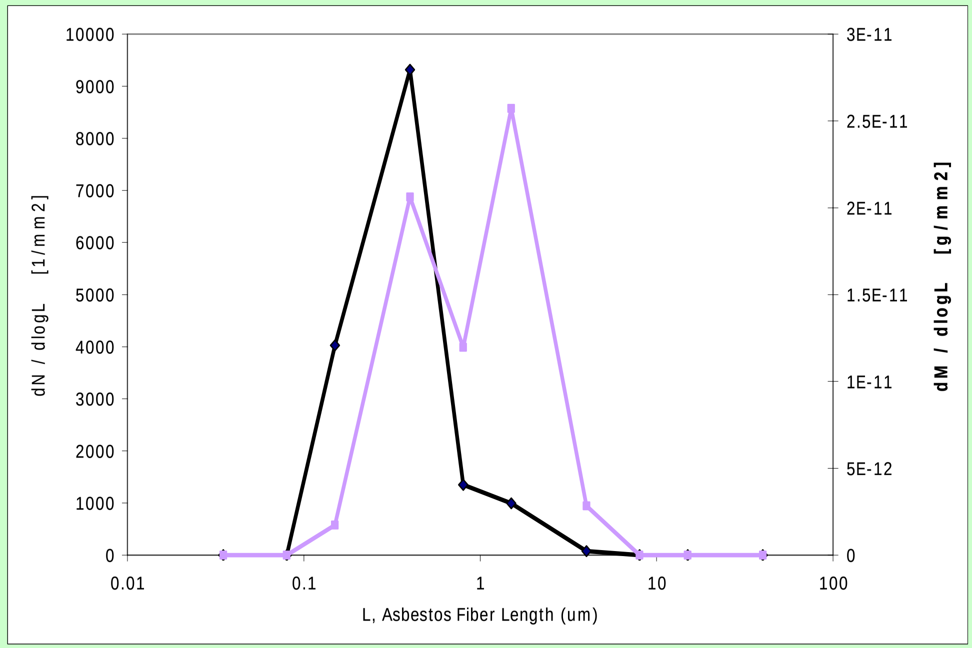
| | |
|---|---|
| **Chrysotile fibers counted** | **29** |
| other fib (not MgSi or < Lmin) | 5 |
| fib with CHRY SAED | 15 |

| | | | mag1 1450x Lmin(um) 2 | | mag2 18500x Lmin(um) 0.01 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Llow(um) | Lhigh(um) | Lmid(um) | # of CHRY | area (mm2) | # of CHRY | area (mm2) | N (1/mm2) | dN/dlogL (1/mm2) | M (g/mm2) | dM/dlogL (g/mm2) |
| 0.01 | 0.06 | 0.035 | 0 | 0 | 0 | 0.0018966 | 0 | 0 | 0 | 0 |
| 0.06 | 0.1 | 0.08 | 0 | 0 | 0 | 0.0018966 | 0 | 0 | 0 | 0 |
| 0.1 | 0.2 | 0.15 | 0 | 0 | 7 | 0.0018966 | 3690.815143 | 12260.62252 | 2.585E-12 | 8.58729E-12 |
| 0.2 | 0.6 | 0.4 | 0 | 0 | 12 | 0.0018966 | 6327.111674 | 13261.01407 | 1.194E-11 | 2.50271E-11 |
| 0.6 | 1 | 0.8 | 0 | 0 | 4 | 0.0018966 | 2109.037225 | 9506.644631 | 3.201E-11 | 1.44277E-10 |
| 1 | 2 | 1.5 | 0 | 0 | 1 | 0.0018966 | 527.2593061 | 1751.517502 | 4.956E-11 | 1.64625E-10 |
| 2 | 6 | 4 | 4 | 0.04849488 | 1 | 0.0018966 | 99.22312264 | 207.9620676 | 1.051E-11 | 2.20273E-11 |
| 6 | 10 | 8 | 0 | 0.04849488 | 0 | 0.0018966 | 0 | 0 | 0 | 0 |
| 10 | 20 | 15 | 0 | 0.04849488 | 0 | 0.0018966 | 0 | 0 | 0 | 0 |
| 20 | 60 | 40 | 0 | 0.04849488 | 0 | 0.0018966 | 0 | 0 | 0 | 0 |
| | >60 | | 4 | | 25 | | | | | |



| **Field Collected Dust** | **Brake Shop** | |
|---|---|---|
| dust sample ID | E0409020-10 | |
| analyst | JW | |
| date | 10/17/2001 | |
| Rear Brake Drum Dust | **1998 Pontiac Sunfire** | |
| dust mass | 0.0056 | g |
| funnel inner diameter | 16.25 | mm |
| filtered area | 207.3942025 | mm2 |
| original water volume | 50 | mL |
| filtered subsample volume | 1 | mL |
| Sensitivity (0.01 -0.6um) | 0.0001618 | % |
| Sensitivity (0.6 - 60um) | 9.99212E-05 | % |
| **Chrysotile fibers counted** | **31** | |
| other fib (not MgSi or < Lmin) | 14 | |
| fib with CHRY SAED | 38 | |

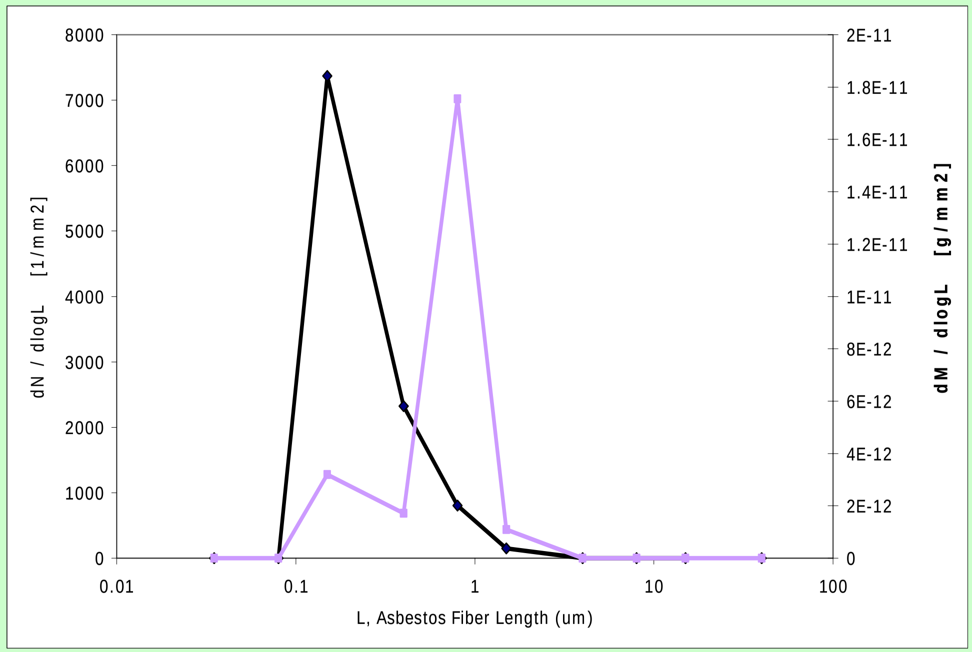
| | | | mag1 9700x Lmin(um) 0.6 | | mag2 58000x Lmin(um) 0.01 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Llow(um) | Lhigh(um) | Lmid(um) | # of CHRY | area (mm2) | # of CHRY | area (mm2) | N (1/mm2) | dN/dlogL (1/mm2) | M (g/mm2) | dM/dlogL (g/mm2) |
| 0.01 | 0.06 | 0.035 | 0 | 0 | 0 | 0.0024755 | 0 | 0 | 0 | 0 |
| 0.06 | 0.1 | 0.08 | 0 | 0 | 0 | 0.0024755 | 0 | 0 | 0 | 0 |
| 0.1 | 0.2 | 0.15 | 0 | 0 | 3 | 0.0024755 | 1211.899887 | 4025.844284 | 5.194E-13 | 1.72544E-12 |
| 0.2 | 0.6 | 0.4 | 0 | 0 | 11 | 0.0024755 | 4443.63292 | 9313.424788 | 9.838E-12 | 2.06196E-11 |
| 0.6 | 1 | 0.8 | 8 | 0.02424744 | 0 | 0.0024755 | 299.3687959 | 1349.427465 | 2.654E-12 | 1.19613E-11 |
| 1 | 2 | 1.5 | 6 | 0.02424744 | 2 | 0.0024755 | 299.3687959 | 994.4816137 | 7.742E-12 | 2.57187E-11 |
| 2 | 6 | 4 | 1 | 0.02424744 | 0 | 0.0024755 | 37.42109948 | 78.43100493 | 1.354E-12 | 2.83732E-12 |
| 6 | 10 | 8 | 0 | 0.02424744 | 0 | 0.0024755 | 0 | 0 | 0 | 0 |
| 10 | 20 | 15 | 0 | 0.02424744 | 0 | 0.0024755 | 0 | 0 | 0 | 0 |
| 20 | 60 | 40 | 0 | 0.02424744 | 0 | 0.0024755 | 0 | 0 | 0 | 0 |
| | >60 | | 15 | | 16 | | | | | |



## Field Collected Dust — Brake Shop

| | | |
|---|---|---|
| dust sample ID | E0409015-4 | |
| analyst | JW | |
| date | 3/27/2001 | |
| Rear Brake Shoe | **1995 VW Jetta** | |
| dust mass | 0.0056 | g |
| funnel inner diameter | 16.25 | mm |
| filtered area | 207.3942025 | mm2 |
| original water volume | 50 | mL |
| filtered subsample volume | 1 | mL |
| Sensitivity (0.01 -0.6um) | 0.000444379 | % |
| Sensitivity (0.6 - 60um) | 0.000119015 | % |
| **Chrysotile fibers counted** | **8** | |
| other fib (not MgSi or < Lmin) | 1 | |
| fib with CHRY SAED | 9 | |

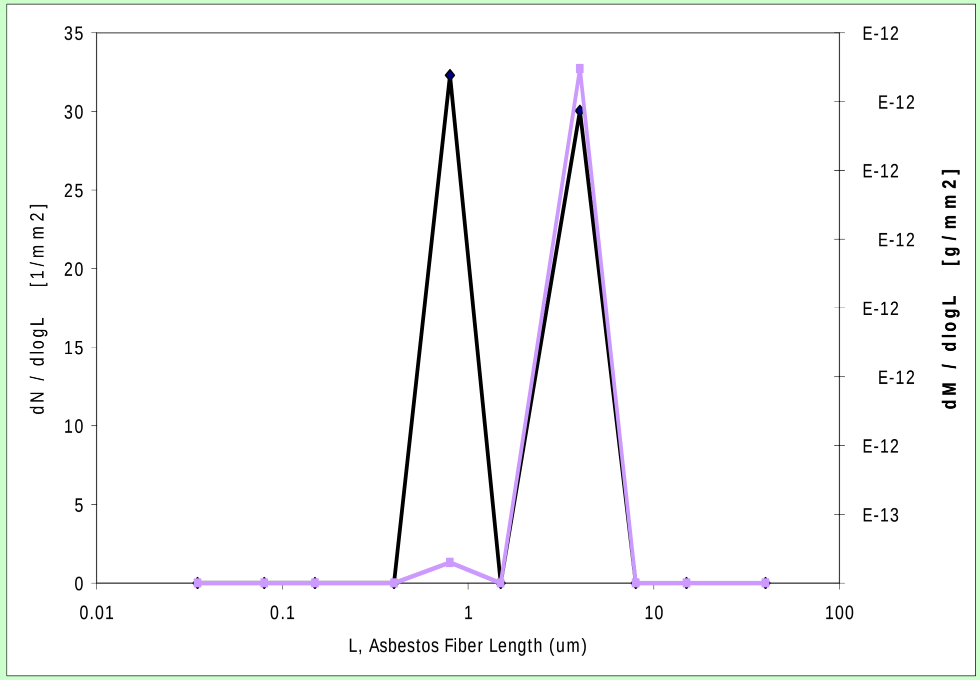
| | | | mag1 9700x Lmin(um) 0.6 | | mag2 58000x Lmin(um) 0.01 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Llow(um) | Lhigh(um) | Lmid(um) | # of CHRY | area (mm2) | # of CHRY | area (mm2) | N (1/mm2) | dN/dlogL (1/mm2) | M (g/mm2) | dM/dlogL (g/mm2) |
| 0.01 | 0.06 | 0.035 | 0 | 0 | 0 | 0.0009013 | 0 | 0 | 0 | 0 |
| 0.06 | 0.1 | 0.08 | 0 | 0 | 0 | 0.0009013 | 0 | 0 | 0 | 0 |
| 0.1 | 0.2 | 0.15 | 0 | 0 | 2 | 0.0009013 | 2218.967736 | 7371.251265 | 9.599E-13 | 3.18878E-12 |
| 0.2 | 0.6 | 0.4 | 0 | 0 | 1 | 0.0009013 | 1109.483868 | 2325.370872 | 8.177E-13 | 1.71384E-12 |
| 0.6 | 1 | 0.8 | 2 | 0.0215343 | 2 | 0.0009013 | 178.2879189 | 803.6462646 | 3.893E-12 | 1.75477E-11 |
| 1 | 2 | 1.5 | 1 | 0.0215343 | 0 | 0.0009013 | 44.57197974 | 148.0649117 | 3.278E-13 | 1.08889E-12 |
| 2 | 6 | 4 | 0 | 0.0215343 | 0 | 0.0009013 | 0 | 0 | 0 | 0 |
| 6 | 10 | 8 | 0 | 0.0215343 | 0 | 0.0009013 | 0 | 0 | 0 | 0 |
| 10 | 20 | 15 | 0 | 0.0215343 | 0 | 0.0009013 | 0 | 0 | 0 | 0 |
| 20 | 60 | 40 | 0 | 0.0215343 | 0 | 0.0009013 | 0 | 0 | 0 | 0 |
| | >60 | | 3 | | 5 | | | | | |



**Dyno Run E3, PM2.5-10 CARB Cycle**

| | | |
|---|---|---|
| air sample ID | CYG25_W1_E3 | |
| analyst | JW | |
| date | 2/7/2001 | |
| R.Rear Brake Emission | **1985 Chvy G20** | |
| funnel inner diameter | 15.52 | mm |
| filtered area | 189.179 | mm2 |
| Air Volume (V) | 580.53 | L |
| Sensitivity (0.01 -0.4um) | 0.2008 | 1/cc |
| Sensitivity (0.4 - 60um) | 0.0023 | 1/cc |
| **Chrysotile fibers counted** | **3** | |
| other fib (not MgSi or < Lmin) | 0 | |
| fib with CHRY SAED | 3 | |
| Chry fib conc. in air | 0.007004492 | f/cc |

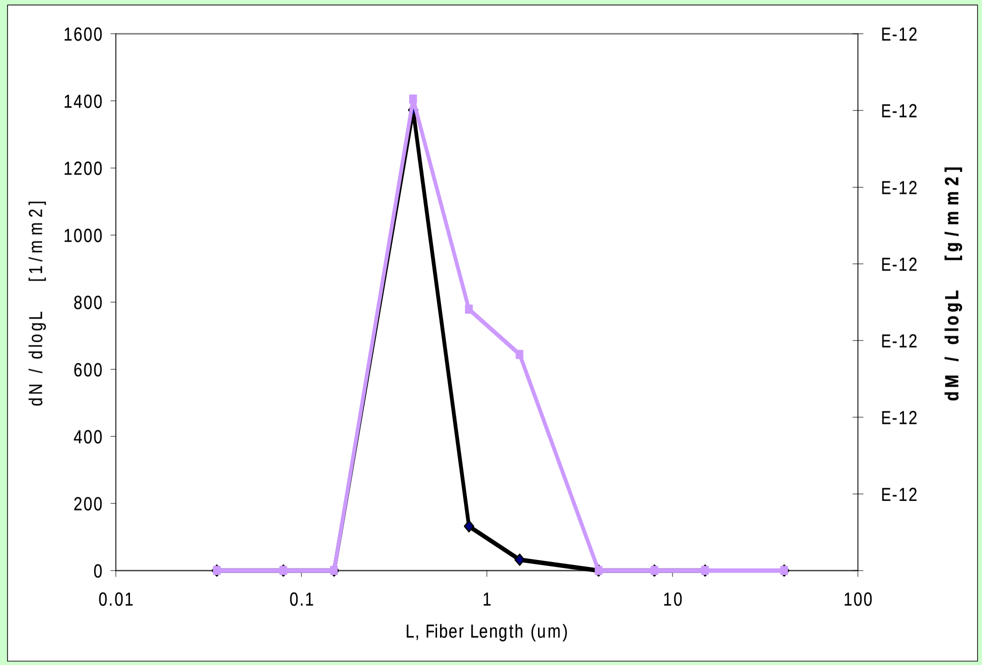
| | | | mag1 9700x Lmin(um) 0.4 | | mag2 58000 Lmin(um) 0.01 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Llow(um) | Lhigh(um) | Lmid(um) | # of CHRY | area (mm2) | # of CHRY | area (mm2) | N (1/mm2) | dN/dlogL (1/mm2) | M (g/mm2) | dM/dlogL (g/mm2) |
| 0.01 | 0.06 | 0.035 | 0 | 0 | 0 | 0.0016231 | 0 | 0 | 0 | 0 |
| 0.06 | 0.1 | 0.08 | 0 | 0 | 0 | 0.0016231 | 0 | 0 | 0 | 0 |
| 0.1 | 0.2 | 0.15 | 0 | 0 | 0 | 0.0016231 | 0 | 0 | 0 | 0 |
| 0.2 | 0.6 | 0.4 | 0 | 0 | 0 | 0.0016231 | 0 | 0 | 0 | 0 |
| 0.6 | 1 | 0.8 | 1 | 0.13794648 | 0 | 0.0016231 | 7.164884814 | 32.29625962 | 3.336E-14 | 1.50385E-13 |
| 1 | 2 | 1.5 | 0 | 0.13794648 | 0 | 0.0016231 | 0 | 0 | 0 | 0 |
| 2 | 6 | 4 | 2 | 0.13794648 | 0 | 0.0016231 | 14.32976963 | 30.03381108 | 1.784E-12 | 3.73836E-12 |
| 6 | 10 | 8 | 0 | 0.13794648 | 0 | 0.0016231 | 0 | 0 | 0 | 0 |
| 10 | 20 | 15 | 0 | 0.13794648 | 0 | 0.0016231 | 0 | 0 | 0 | 0 |
| 20 | 60 | 40 | 0 | 0.13794648 | 0 | 0.0016231 | 0 | 0 | 0 | 0 |
| | >60 | | 3 | | 0 | | | | | |



**Dyno Run E3, PM2.5** **CARB Cycle**

| | |
|---|---|
| air sample ID | CYS25_4P_E3 |
| analyst | JW |
| date | 2/28/2001 |
| R.Rear Brake Emission | **1985 Chvy G20** |
| filter deposit diameter | 35 mm |
| deposit area (At) | 962.1128 mm2 |
| Air Volume (V) | 580.53 Liters |
| Sensitivity (0.01 -0.6um) | 0.1809 1/cc |
| Sensitivity (0.6 - 60um) | 0.0054 1/cc |
| **Chrysotile fibers counted** | **18** |
| other fib (not MgSi or < Lmin) | 19 |
| fib with CHRY SAED | 0 |
| Chry fib conc. in air | 1.150205507 f/cc |

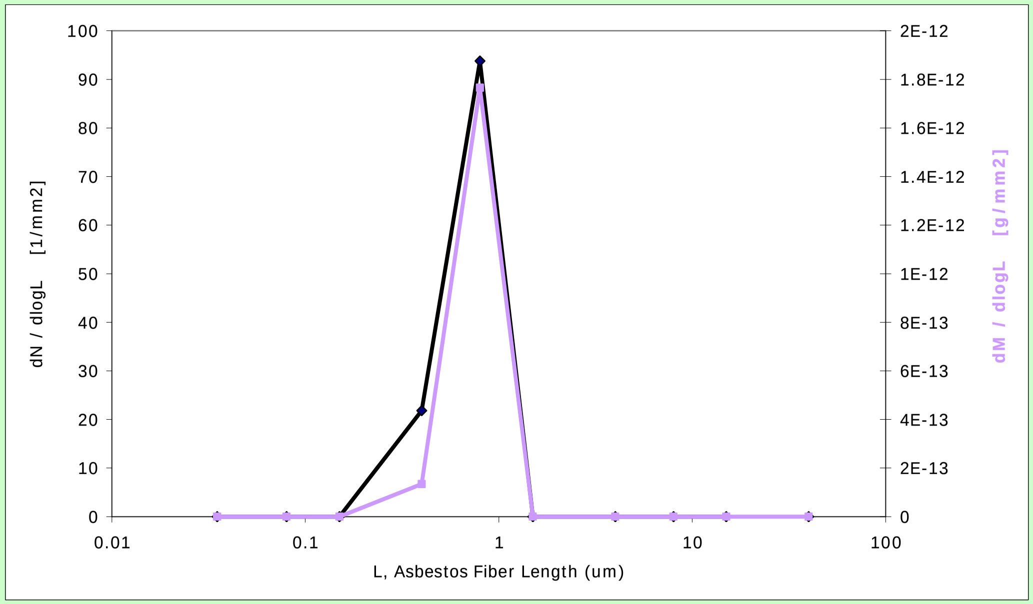
| | | | mag1 9700x Lmin(um) 0.6 | | mag2 58000x Lmin(um) 0.01 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Llow(um) | Lhigh(um) | Lmid(um) | # of CHRY | area (mm2) | # of CHRY | area (mm2) | N (1/mm2) | dN/dlogL (1/mm2) | M (g/mm2) | dM/dlogL (g/mm2) |
| 0.01 | 0.06 | 0.035 | 0 | 0 | 0 | 0.0091604 | 0 | 0 | 0 | 0 |
| 0.06 | 0.1 | 0.08 | 0 | 0 | 0 | 0.0091604 | 0 | 0 | 0 | 0 |
| 0.1 | 0.2 | 0.15 | 0 | 0 | 0 | 0.0091604 | 0 | 0 | 0 | 0 |
| 0.2 | 0.6 | 0.4 | 0 | 0 | 6 | 0.0091604 | 654.9905146 | 1372.796764 | 2.933E-12 | 6.14626E-12 |
| 0.6 | 1 | 0.8 | 7 | 0.29824092 | 2 | 0.0091604 | 29.27768458 | 131.9713752 | 7.56E-13 | 3.40766E-12 |
| 1 | 2 | 1.5 | 3 | 0.29824092 | 0 | 0.0091604 | 9.759228194 | 32.41945432 | 8.485E-13 | 2.81872E-12 |
| 2 | 6 | 4 | 0 | 0.29824092 | 0 | 0.0091604 | 0 | 0 | 0 | 0 |
| 6 | 10 | 8 | 0 | 0.29824092 | 0 | 0.0091604 | 0 | 0 | 0 | 0 |
| 10 | 20 | 15 | 0 | 0.29824092 | 0 | 0.0091604 | 0 | 0 | 0 | 0 |
| 20 | 60 | 40 | 0 | 0.29824092 | 0 | 0.0091604 | 0 | 0 | 0 | 0 |
| | >60 | | 10 | | 8 | | | | | |



**Dyno Run E9, PM2.5-10 Federal Cycle**

| | |
|---|---|
| air sample ID | CYG25_W1_E9 |
| analyst | JW |
| date | 9/6/2001 |
| R.Rear Brake Emission | **1985 Chvy G20** |
| funnel inner diameter | 15.52 mm |
| filtered area | 189.179 mm2 |
| Air Volume (V) | 1120.58 L |
| Sensitivity (0.01 -0.4um) | 0.0406 1/cc |
| Sensitivity (0.4 - 60um) | 0.0018 1/cc |
| **Chrysotile fibers counted** | **3** |
| other fib (not MgSi or < Lmin) | 0 |
| fib with CHRY SAED | 3 |
| Chry fib conc. in air | 0.005268889 f/cc |

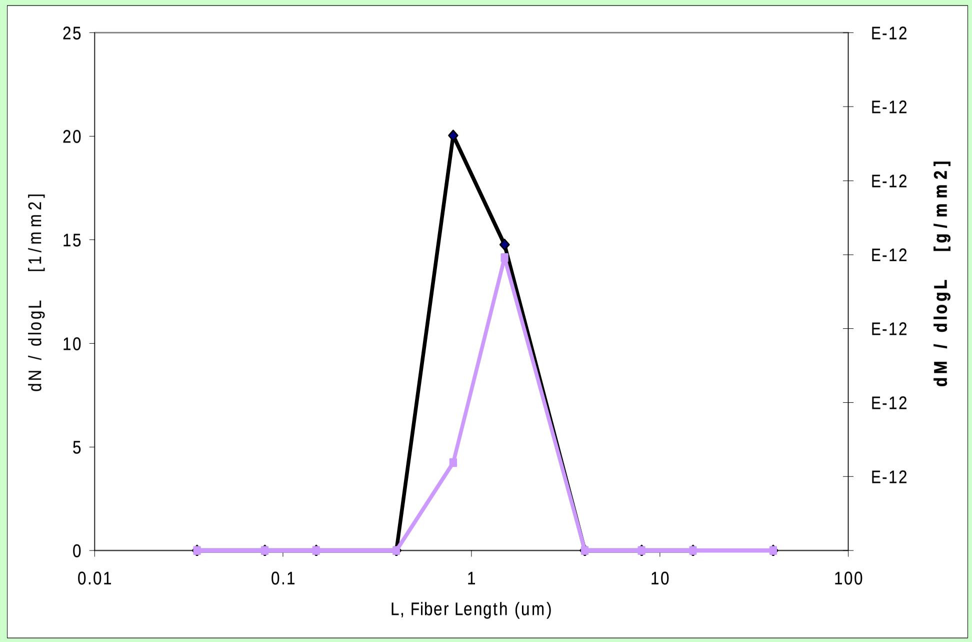
| | | | mag1<br>9700x<br>Lmin(um)<br>0.4 | | mag2<br>58000<br>Lmin(um)<br>0.01 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Llow(um) | Lhigh(um) | Lmid(um) | # of CHRY | area (mm2) | # of CHRY | area (mm2) | N (1/mm2) | dN/dlogL (1/mm2) | M (g/mm2) | dM/dlogL (g/mm2) |
| 0.01 | 0.06 | 0.035 | 0 | 0 | 0 | 0.0041599 | 0 | 0 | 0 | 0 |
| 0.06 | 0.1 | 0.08 | 0 | 0 | 0 | 0.0041599 | 0 | 0 | 0 | 0 |
| 0.1 | 0.2 | 0.15 | 0 | 0 | 0 | 0.0041599 | 0 | 0 | 0 | 0 |
| 0.2 | 0.6 | 0.4 | 1 | 0.09196432 | 0 | 0.0041599 | 10.4032086 | 21.80411897 | 6.401E-14 | 1.3415E-13 |
| 0.6 | 1 | 0.8 | 2 | 0.09196432 | 0 | 0.0041599 | 20.8064172 | 93.78649749 | 3.917E-13 | 1.76562E-12 |
| 1 | 2 | 1.5 | 0 | 0.09196432 | 0 | 0.0041599 | 0 | 0 | 0 | 0 |
| 2 | 6 | 4 | 0 | 0.09196432 | 0 | 0.0041599 | 0 | 0 | 0 | 0 |
| 6 | 10 | 8 | 0 | 0.09196432 | 0 | 0.0041599 | 0 | 0 | 0 | 0 |
| 10 | 20 | 15 | 0 | 0.09196432 | 0 | 0.0041599 | 0 | 0 | 0 | 0 |
| 20 | 60 | 40 | 0 | 0.09196432 | 0 | 0.0041599 | 0 | 0 | 0 | 0 |
| | >60 | | 3 | | 0 | | | | | |



**Dyno Run E9, PM2.5** — **Federal Cycle**

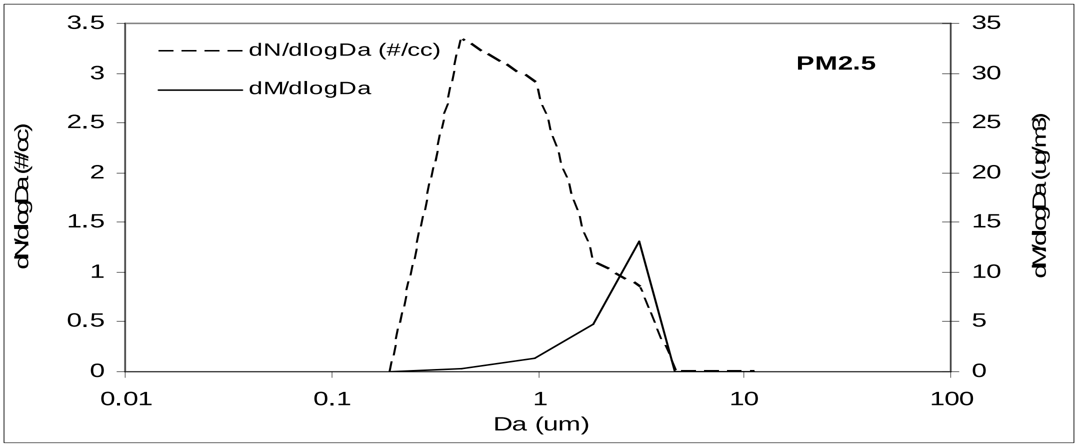
| | |
|---|---|
| air sample ID | CYS25_2P_E9 |
| analyst | JW |
| date | 8/8/2001 |
| R.Rear Drum Dust | **1985 Chvy G20** |
| filter deposit diameter | 35 mm |
| deposit area (At) | 962.1128 mm2 |
| Air Volume (V) | 1120.58 Liters |
| Sensitivity (0.01 -0.6um) | 0.2111 1/cc |
| Sensitivity (0.6 - 60um) | 0.0038 1/cc |
| **Chrysotile fibers counted** | **2** |
| other fib (not MgSi or < Lmin) | 4 |
| fib with CHRY SAED | 1 |
| Chry fib conc. in air | 0.007632334 f/cc |

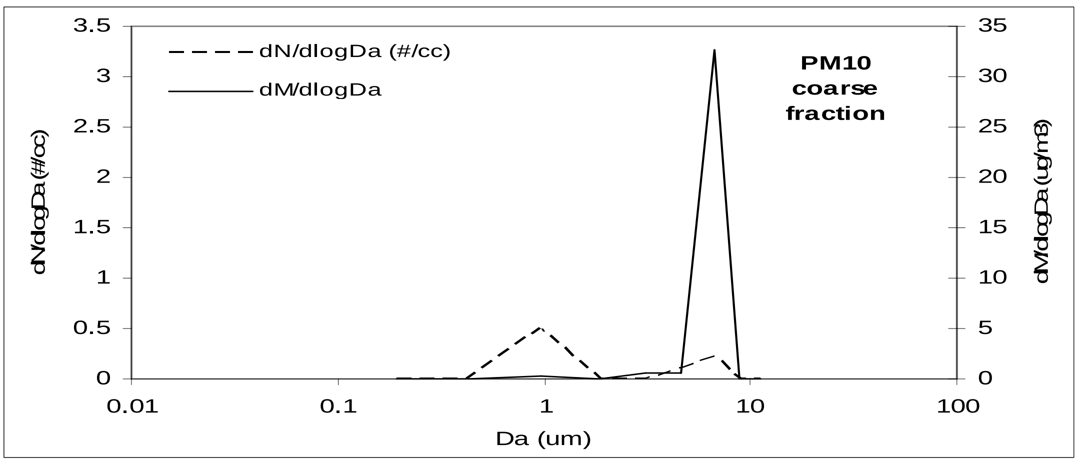
| | | | mag1 9700x Lmin(um) 0.6 | | mag2 58000x Lmin(um) 0.01 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Llow(um) | Lhigh(um) | Lmid(um) | # of CHRY | area (mm2) | # of CHRY | area (mm2) | N (1/mm2) | dN/dlogL (1/mm2) | M (g/mm2) | dM/dlogL (g/mm2) |
| 0.01 | 0.06 | 0.035 | 0 | 0 | 0 | 0.0040669 | 0 | 0 | 0 | 0 |
| 0.06 | 0.1 | 0.08 | 0 | 0 | 0 | 0.0040669 | 0 | 0 | 0 | 0 |
| 0.1 | 0.2 | 0.15 | 0 | 0 | 0 | 0.0040669 | 0 | 0 | 0 | 0 |
| 0.2 | 0.6 | 0.4 | 0 | 0 | 0 | 0.0040669 | 0 | 0 | 0 | 0 |
| 0.6 | 1 | 0.8 | 1 | 0.2209192 | 0 | 0.0040669 | 4.444718634 | 20.03490505 | 2.635E-13 | 1.18771E-12 |
| 1 | 2 | 1.5 | 0 | 0.2209192 | 1 | 0.0040669 | 4.444718634 | 14.7650357 | 1.191E-12 | 3.95801E-12 |
| 2 | 6 | 4 | 0 | 0.2209192 | 0 | 0.0040669 | 0 | 0 | 0 | 0 |
| 6 | 10 | 8 | 0 | 0.2209192 | 0 | 0.0040669 | 0 | 0 | 0 | 0 |
| 10 | 20 | 15 | 0 | 0.2209192 | 0 | 0.0040669 | 0 | 0 | 0 | 0 |
| 20 | 60 | 40 | 0 | 0.2209192 | 0 | 0.0040669 | 0 | 0 | 0 | 0 |
| | >60 | | 1 | | 1 | | | | | |

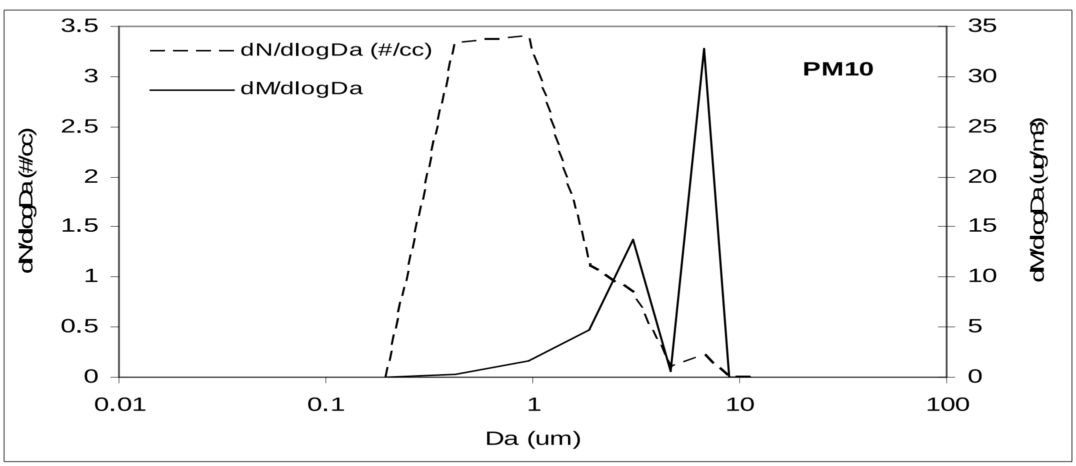


## Appendix J: Aerodynamic Particle Size Mass Distributions by CCSEM for Test Vehicle Brake Emission Air Samples

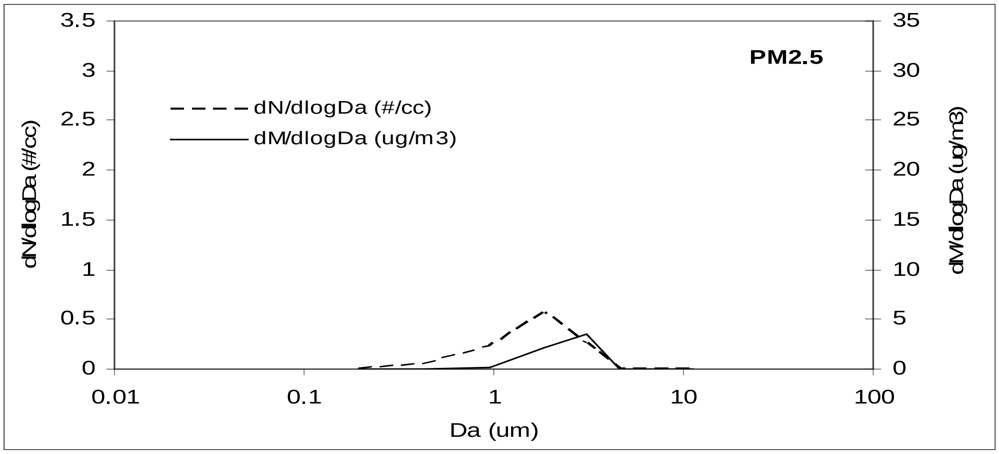
### CCSEM Results – E3 Fine and Coarse Distributions

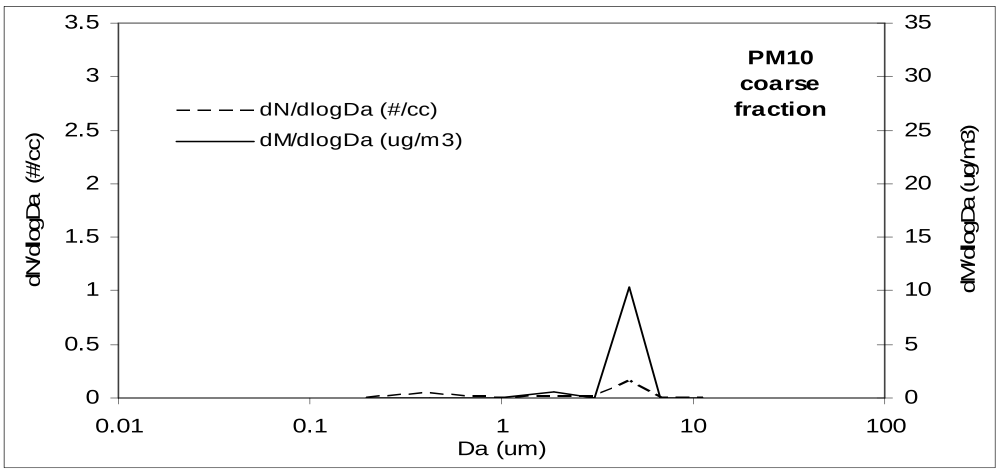


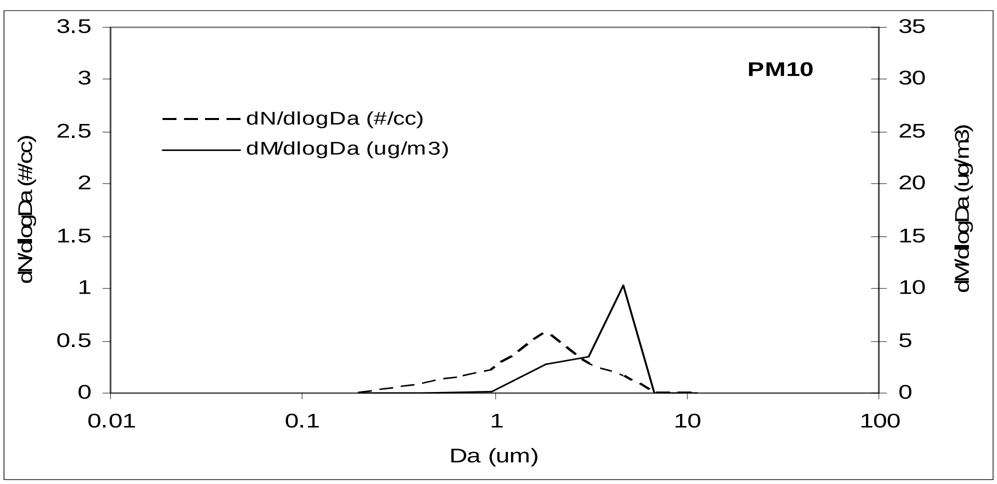



## CCSEM Results – E9 Fine and Coarse Distributions



## Appendix K. Preliminary Direct Evidence for the Conversion of Chrysotile Asbestos Fibers to a different Mineral Form by TEM SAED.

### SEM/EDS Evidence for Heat Transformation of Chrysotile in BFM

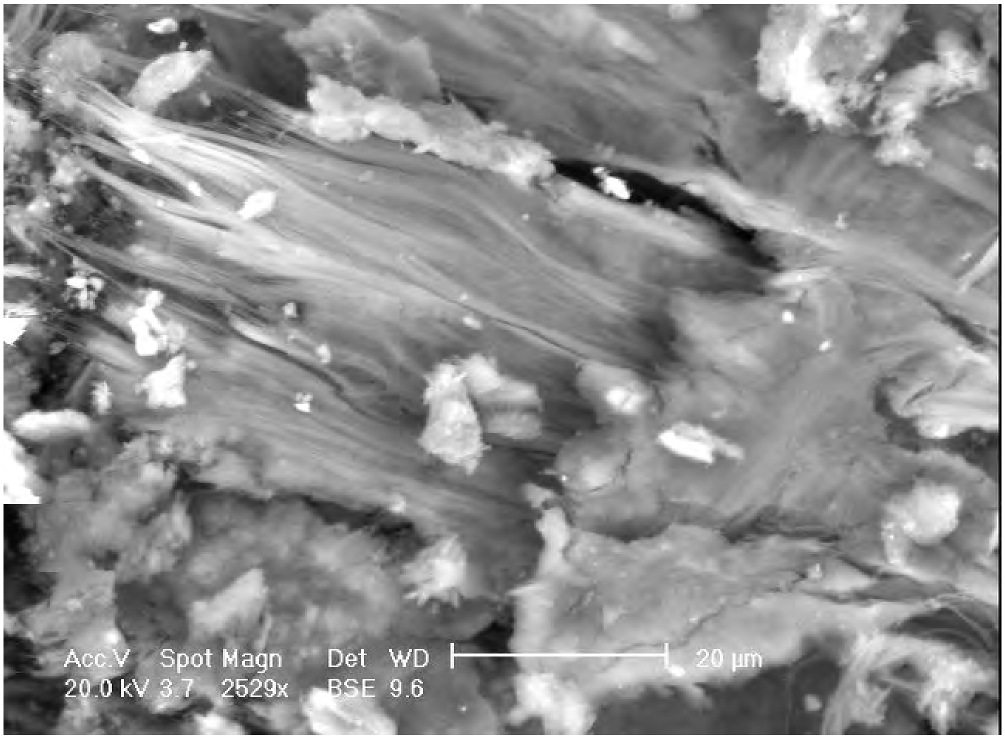
SEM/EDS was performed on brake shoe and brake dust samples to investigate the transformation of chrysotile asbestos at the braking surface.

Brake shoe samples were collected from two regions of the shoe: within the bulk of the shoe (Figure A) and at the surface (Figure B). Samples from within the bulk of the shoe consisted of 60% chrysotile asbestos bundles. These bundles were composed of magnesium and silicon, and were fibrous with rare smooth regions. Many of the smooth regions in Figure A are actually veils of fine, single fibrils when viewed with the higher-resolution, secondary electron detector at high magnification. However, some of these regions maintained their smooth appearance even when viewed at high resolution. These smooth regions appear to be ‘melted’ asbestos fibers, or more accurately, asbestos which has been transformed into non-fibrous, crystalline forsterite or an amorphous transitional state. The remainder of the non-surface bulk brake shoe material was composed of 15% iron oxides, 10% calcium oxides, 10% clay flakes (mostly aluminum and silicon), and 5% organic carbon.

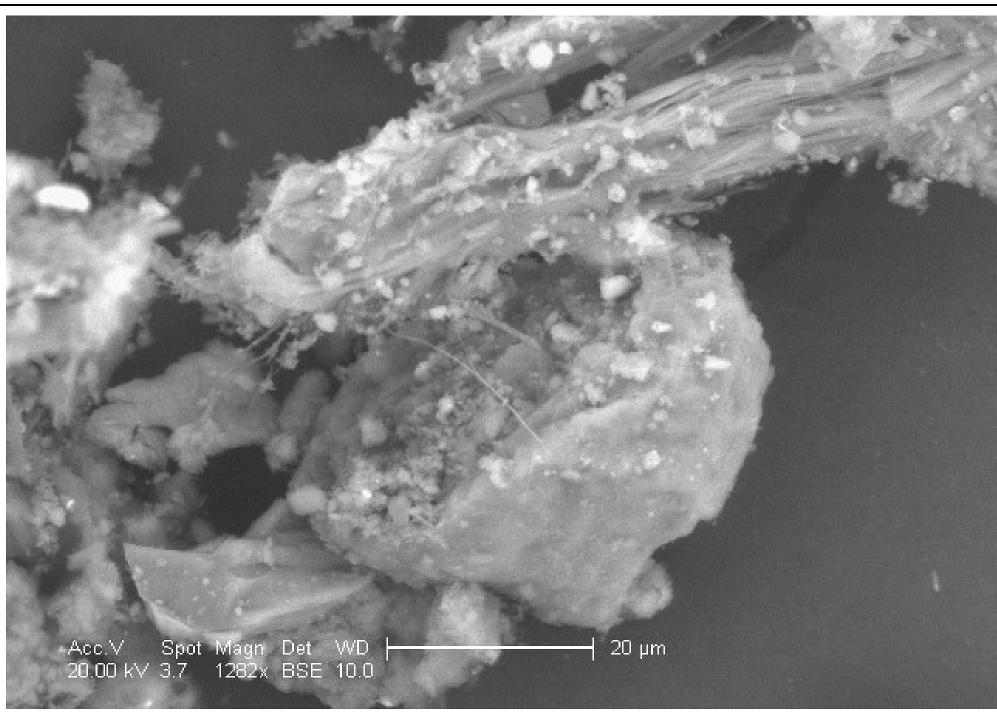
Samples from the shoe surface (Figure B) were different from those within the bulk of the shoe in that they exhibited a substantial amount of large, smooth, flattened flakes and round grains. The flakes and grains had no traces of fibrous morphology even at high magnifications, and were composed of magnesium, silicon, iron, and calcium. This composition implies that the flakes and grains are the product of chrysotile reacting with the iron and calcium oxides, induced by high temperatures and mechanical stress at the brake shoe-rotor interface. The composition at the shoe surface was typically 45% flakes/grains and 40% asbestos bundles.

Dust emissions collected from inside the brakes (Figure C) were almost entirely composed of these flakes and grains (> 80%). Only a small amount of fibrous chrysotile was found in the dust (<1%). The implication is that nearly all of asbestos emitted from the brake shoe was transformed by high temperatures into non-fibrous particles.

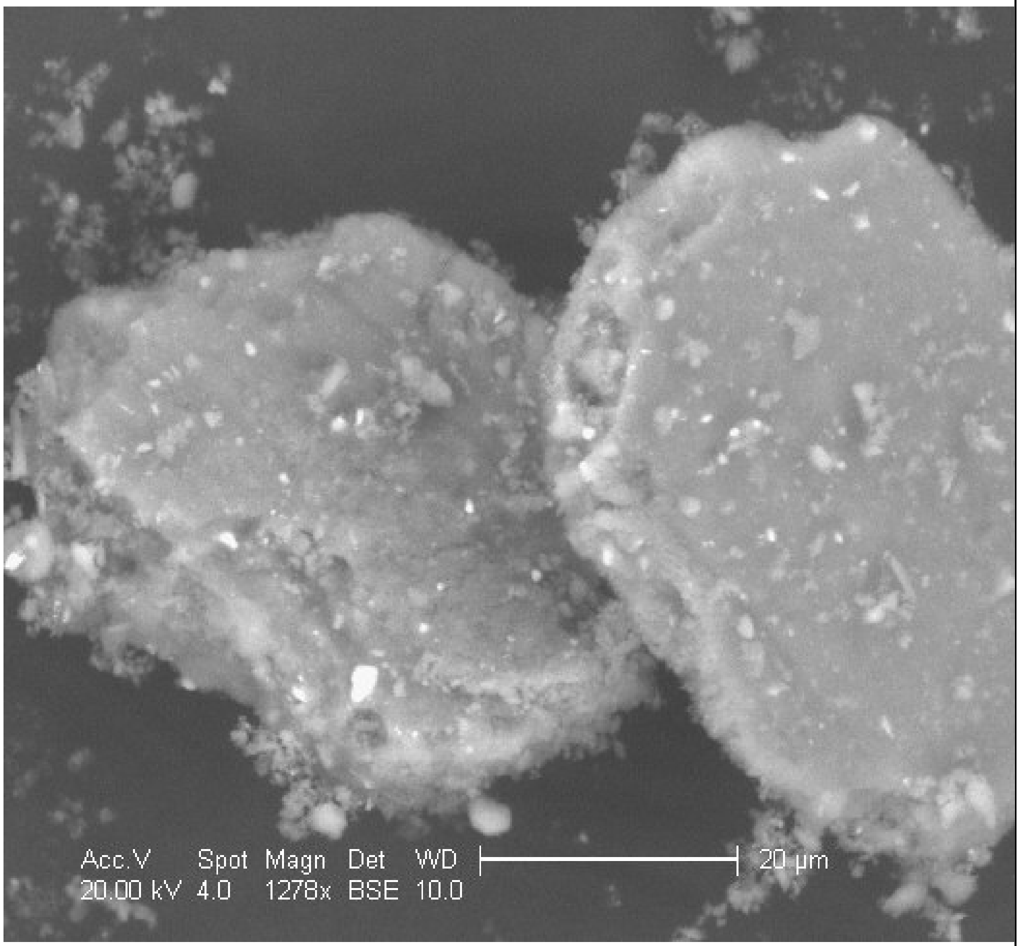
In summary, the brake shoe surface appears to be a transitional region between the mostly fibrous asbestos bulk of the brake shoes and the mostly non-fibrous brake emissions.




(A) Sample from within the bulk of a brake shoe showing mostly fibrous asbestos bundles.




(B) Shoe surface sample showing fibrous asbestos bundle and large, non-fibrous particles composed of magnesium, silicon, iron, and calcium.



(C) Brake dust emission sample showing mostly non-fibrous particles composed of magnesium, silicon, iron, and calcium.

**TEM/SAED Evidence for Heat Transformation of Chrysotile in BFM**
The TEM analyses of brake shoe surface material revealed magnesium silicate particles that had both fibrous and non-fibrous regions, suggesting a transition between chrysotile asbestos to a non-fibrous crystalline form. This transition is consistent with the theory that much of the asbestos in the brake was converted to non-fibrous forms at the shoe surface.

The particle shown in Figure 1 shows a fibrous morphology at the upper left, a plate-like morphology at the bottom, and a mixture of these morphologies elsewhere. The EDS revealed that the entirety of this particle, regardless of morphology, exhibited strong magnesium and silicon peaks and small amounts of iron, consistent with the composition of chrysotile. These EDS spectra were distinct from the EDS spectra of the other, minor (<5%), magnesium-silicate constituent of these brakes, which exhibits small magnesium peaks, as well as aluminum and potassium peaks.

Selected area electron diffraction (SAED) was performed at the four locations shown in Figure 1. Figure 2 shows the SAED pattern obtained from aiming the beam at location #1, which clearly exhibits chrysotile morphology. The SAED pattern, as well, shows the streaked layer lines characteristic of chrysotile.

Figure 3 shows the SAED pattern obtained from location #2, where the same fiber is partially encapsulated by a non-fibrous, possibly non-crystalline section of the particle. The chrysotile SAED pattern is weaker, and no other spots are visible. This is consistent with the initial, amorphous state of chrysotile when it is heated to the point where its structure begins to collapse.

Figure 4 shows the SAED pattern obtained from the middle of the particle at location #3. The complex spot pattern exhibits a mixture of radial symmetry, ordered spot patterns, and other, non-ordered spots. This pattern suggests a superposition of randomly-oriented chrysotile fibers and multiple crystalline structures, which is consistent with the morphology of location #3.

Figure 5 shows the SAED pattern obtained from the smooth, non-fibrous region at location #4. This pattern shows an ordered crystalline structure. Although definitive zone-axis patterns were not obtained, the crystalline structure and magnesium-silicate composition are both consistent with forsterite, the end product of the reaction of chrysotile with heat.

Together, these figures suggest that this particle was a short bundle of chrysotile asbestos that has been partially converted to a non-fibrous crystal. Both the morphology and SAED patterns from the middle of the particle suggest a transition between those of the fibrous upper left region and flake-like bottom of the particle.

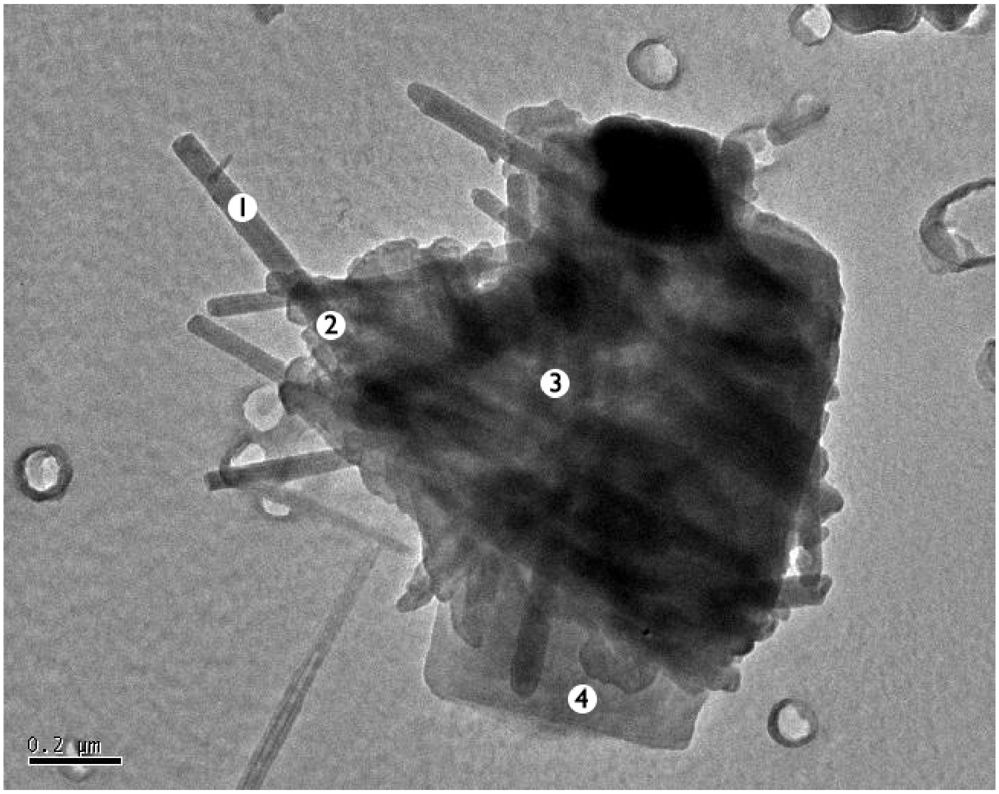


Figure 1. TEM micrograph of particle from brake shoe surface showing locations where SAED patterns were obtained.

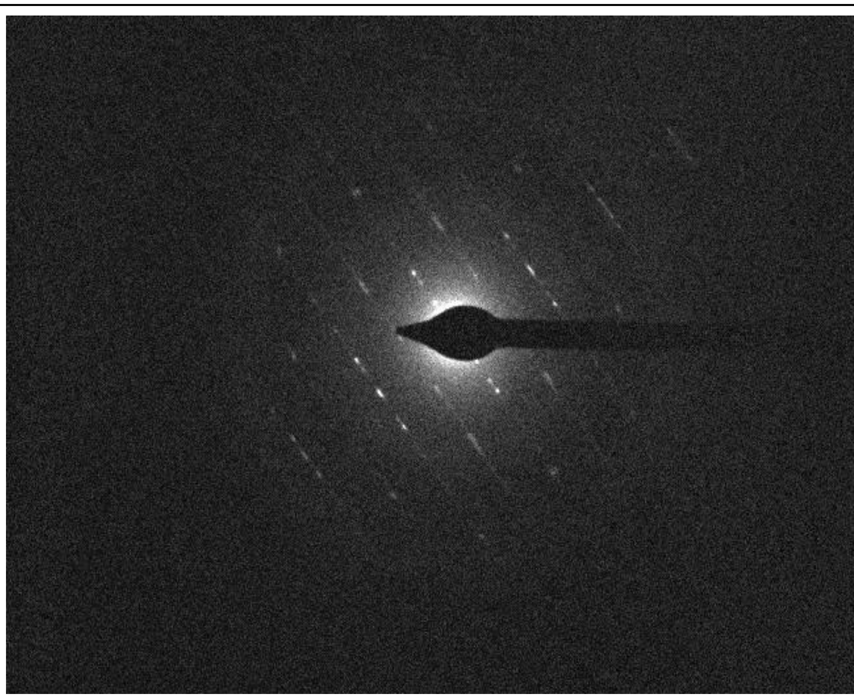


Figure 2. SAED pattern from location #1 on Figure 1.

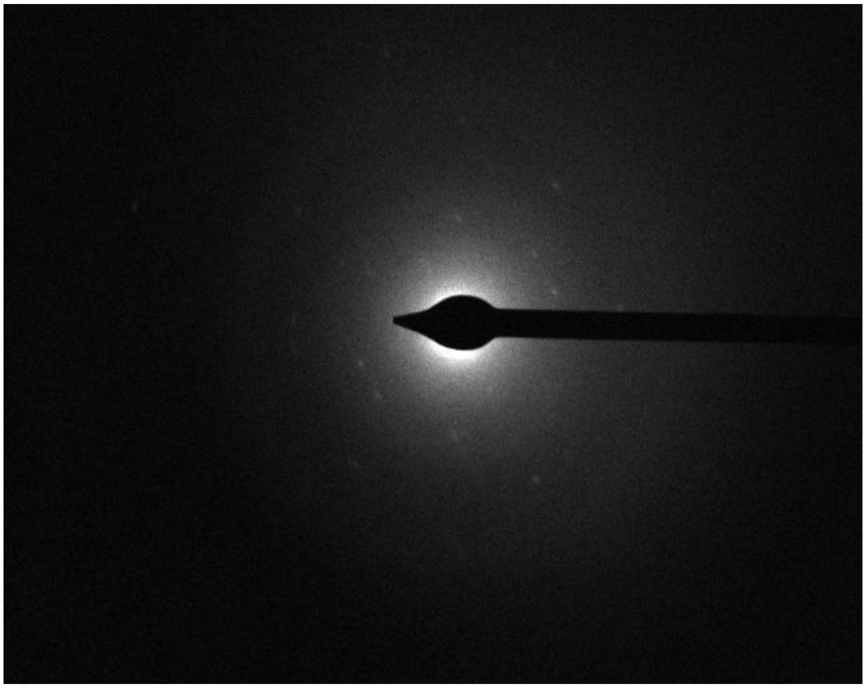


Figure 3. SAED pattern from location #2 on Figure 1.

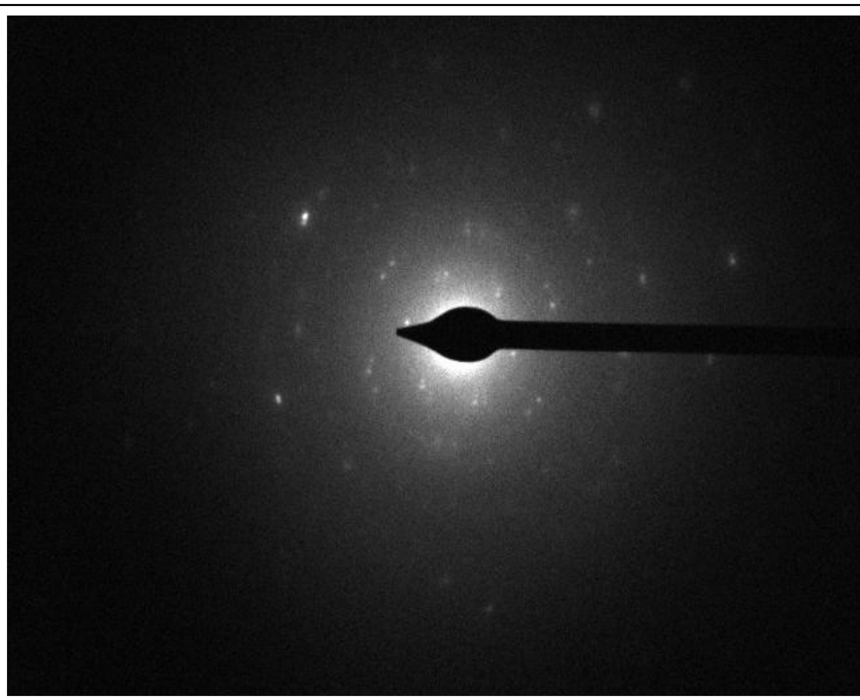


Figure 4. SAED pattern from location #3 on Figure 1

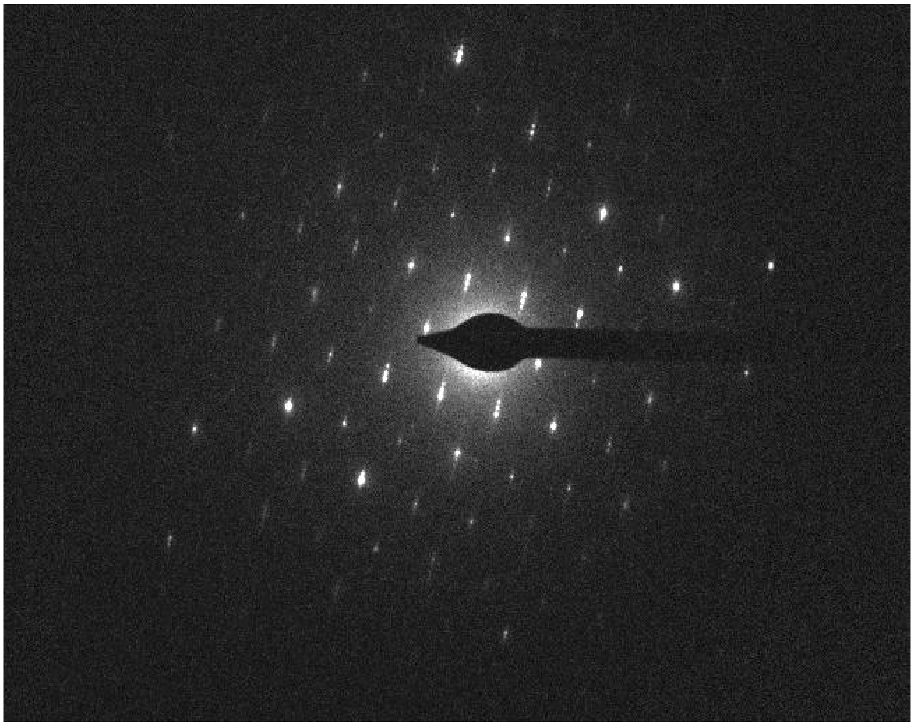


Figure 5. SAED pattern from location #4 on Figure 1