

Other Test Method – 34: Method to Quantify Road Dust Particulate Matter Emissions (PM₁₀ and/or PM_{2.5}) from Vehicular Travel on Paved and Unpaved Roads

This test method is designed to quantify road dust particulate matter (PM) emissions from vehicles traveling on paved and unpaved roads. The method relies on the measurement of the increase in PM concentrations over ambient background levels at one or more locations that are directly influenced by road dust that is emitted from the interaction of vehicle tires with the road surface. This method can be applied to any paved road or unpaved (dirt or gravel) road that is 100 meters or greater in length.

This method was submitted by the Center for the Study of Open Source Emissions (CSOSE) and Desert Research Institute (DRI) to EPA's Office of Air Quality, Planning and Standards – Air Quality Assessment Division – Measurement Technology Group (MTG) for inclusion into the Other Test Method (OTM) category on EPA's Emission Monitoring Center (EMC) website at:

<http://www.epa.gov/ttn/emc/tmethods.html#CatC/>.

The posting of a test method on the OTM portion of the EMC is neither an endorsement by EPA regarding the validity of the test method nor a regulatory approval of the test method. The purpose of the OTM portion of the EMC is to promote discussion of developing emission measurement methodologies and to provide regulatory agencies, the regulated community, and the public at large with potentially helpful tools.

Other Test Methods are test methods which have not yet been subject to the Federal rulemaking process. Each of these methods, as well as the available technical documentation supporting them, have been reviewed by the EMC staff and have been found to be potentially useful to the emission measurement community. The types of technical information reviewed include field and laboratory validation studies; results of collaborative testing; articles from peer-reviewed journals; peer-review comments; and quality assurance (QA) and quality control (QC) procedures in the method itself. A table summarizing the available technical information for each method can be found at the link below. The EPA strongly encourages the submission of additional supporting field and laboratory data as well as comments in regard to these methods.

These methods may be considered for use in Federally enforceable State and local programs (e.g., Title V permits, State Implementation Plans (SIP)) provided they are subject to an EPA Regional SIP approval process or permit veto opportunity and public notice with the opportunity for comment. The methods may also be considered to be candidates to be alternative methods to meet Federal requirements under 40 CFR Parts 60, 61, and 63. However, they must be approved as alternatives

under 60.8, 61.13, or 63.7(f) before a source may use them for this purpose. Consideration of a method's applicability for a particular purpose should be based on the stated applicability as well as the supporting technical information outlined in the table. The methods are available for application without EPA oversight for other non-EPA program uses including state permitting programs and scientific and engineering applications.

As many of these methods are submitted by parties outside the Agency, the EPA staff may not necessarily be the technical experts on these methods. Therefore, technical support from EPA for these methods is limited, but the table contains contact information for the developers so that you may contact them directly. Also, be aware that these methods are subject to change based on the review of additional validation studies or on public comment as a part of adoption as a Federal test method, the Title V permitting process, or inclusion in a SIP.

Method History

Final - 1/15/2014

EPA advises all potential users to review the method and all appendices carefully before application of this method.

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1.0 Scope and Application

1.1. Introduction

This test method is designed to quantify road dust particulate matter (PM) emissions from vehicles traveling on paved and unpaved roads. The method relies on the measurement of the increase in PM concentrations over ambient background levels at one or more locations that are directly influenced by road dust that is emitted from the interaction of vehicle tires with the road surface. Experimental evidence has shown that these elevated PM concentrations can be directly related to the amount of road dust PM emitted per unit distance traveled by the test vehicle^{1,2,3} and that the mass of the test vehicle can be used as a scaling parameter^{4,5} to quantify the PM emissions from other vehicles traveling on the same road.

1.2. Applicability

This method can be applied to any paved road or unpaved (dirt or gravel) road that is 100 meters or greater in length. Depending on the type of PM measurement instrumentation used, PM emissions can be quantified as particulate matter less than 2.5 microns ($PM_{2.5}$), particulate matter less than 10 microns (PM_{10}), and/or coarse particles ($PM_{10-2.5}$). Coarse particle concentrations can be calculated by the difference between PM_{10} and $PM_{2.5}$. In principal, this method can be applied to any measurable particle size fraction. However, the ability to faithfully measure the concentration of the particles of interest, directly impacts the quality of the measurement. Accordingly, application of the method to specific size fractions of interest other than $PM_{2.5}$, PM_{10} , and $PM_{10-2.5}$ requires that the concentration of the size fraction be reliably measured at one or more locations that are directly influenced by road dust that is emitted from the interaction of vehicle tires with the road surface. The user must demonstrate the quality of particulate measurement in the size fraction of interest, when applying the method to particles larger than 10 microns in aerodynamic diameter, such as those that are included in the Total Suspended Particulate (TSP).

1.3. Data Quality Objectives

Specific data quality objectives are suggested for measurement precision and quality of calibration to an external standard. In addition to the inherent measurement uncertainty associated with the instrumentation and design of the specific mobile monitoring system, road dust PM emissions can be highly variable from the same roadway section. Such variability arises from differences in individual test vehicle operator driving practices (e.g., a tendency to drive preferentially on the left side of a travel lane), spatial and temporal variation in road dust emission potential across the lane of travel due to variations in surface moisture (especially for unpaved roads) and road surface roughness, and additionally, spatial and temporal variation in road dust emission potential along the direction of travel.

2. Summary of Method

2.1. Principle

When wheeled vehicles such as cars, trucks, and buses travel on a road, the vehicle tires interact with the road surface through frictional and aerodynamic forces. These interactions result in the emission of PM from the road surface through processes of mechanical and aerodynamic suspension and, to a lesser degree, abrasion of the roadway materials. On unpaved or dirt roads, vehicle tires interact directly with loose, erodible soil aggregates and particles. On paved roads, loose suspendable particles or erodible aggregates can exist on the roadway surface and may have originated from a number of sources. Sources of road dust on paved roads include soil material of geologic origin that may have been transported onto the road by wind or mechanical means, dust from brake and tire wear, and dust from the erosion of the roadway aggregate or cement.

When vehicle tires suspend road dust PM, either through mechanical or aerodynamic means, the PM plume behind each tire disperses with distance from the tire and in the wake of the vehicle. This test method is based on the principle that a test vehicle that quantifies only the increase in concentration of PM above ambient background at a known travel speed and a fixed distance from the vehicle tires can provide repeatable measurements and be reliably calibrated (scaled) to an external standard for measurement of road dust PM emissions. The incremental increase in PM concentration due to road dust emission is quantified by subtracting the background PM concentration from the PM concentration at a location that is directly influenced by the road dust plume. The background concentration can be measured at a location that is not influenced by the test vehicle's own road dust plume (e.g., hood of the test vehicle).

The four principal assumptions that are invoked in the application of this test method are: 1) that for a given test vehicle, under ambient meteorological conditions that fall within prescribed guidelines, the degree of dispersion (dilution) that occurs with distance from the vehicle tires is controlled primarily by the speed of the vehicle; 2) that within certain limits of distance from the vehicle tires, other factors such as the activity of other vehicles on the road, the magnitude of the road dust PM emissions, and the mechanism of road dust PM emission have a negligible effect on the degree of plume dispersion; 3) that the road dust emissions are a result solely of the interaction of the vehicle tires with the road surface and that aerodynamic entrainment of dust from the turbulence created by the vehicle's body is negligible; and 4) that the differences in terms of emissions of road dust between the test vehicle used and other vehicles on the road arising from differences in vehicle weight, aerodynamics, and tire characteristics are either small or can be accounted for through known or presumed mathematical relationships.

2.2. History of the Methodology

Kuhns et al.¹ and Fitz et al.⁶ concurrently developed two similar mobile monitoring systems for road dust emissions starting in 1999. Fitz et al.⁶ used estimates of the profile of the dust plume in the wake of a moving vehicle to relate the PM concentration measured at a specific location in the

wake of a vehicle to road dust PM emissions. Kuhns et al.¹ related PM concentrations measured directly behind the front tires of a test vehicle to emission factors inferred from the silt loading method prescribed in the US EPA AP-42 Guidance document (4th edition)⁷. A critical early finding of Kuhns et al.¹ was that for the same road, the concentrations of PM behind the front tires increased exponentially with test vehicle speed (later revised to the 3rd power of speed by Etyemezian et al.²). This underscored the need to consider the travel speed of the test vehicle both during measurements and as part of the calibration of the test vehicle to an independent measurement method.

These initial efforts led to the fundamental relationship:

$$EF_{ps} = MSC_{i,v,ps} \times K_i(v) \quad (1)$$

where EF_{ps} is the emission factor of PM road dust in grams of PM per vehicle kilometer traveled, $MSC_{i,v,ps}$ is the concentration of PM as measured by a specific mobile measurement system i operating at speed v , and K_i is a function of the mobile measurement system travel speed and is specific to mobile measurement system i . The subscript ps refers to a specific particle size range (e.g., PM₁₀, PM_{2.5}).

2.3. Overview of Methodology Implementation

2.3.1. Measurement of PM Concentrations by a Mobile System

This method requires that mobile measurement systems be capable of resolving PM concentrations with high time resolution. Typically, this level of time resolved measurement is only available from instruments that exploit the optical properties of aerosol particles to estimate mass concentrations. The DustTrak nephelometer, manufactured by TSI, Inc has been used extensively with the test method described here because it allows for PM concentrations to be inferred from the light scattering properties of aerosols. The DustTrak is equipped with nominal size selective inlets for PM₁₀, PM_{2.5}, and other size fractions. The older version, Model 8520 (http://www.tsi.com/uploadedFiles/Site_Root/Products/Literature/Spec_Sheets/2980077_DustTrak_8520.pdf), that has been and is still used frequently requires that the instrument be calibrated to a mass based device (e.g., filter with size selective inlet) because the relationship between light scattering and mass concentration is dependent on a number of parameters specific to the aerosol being measured. A newer version, Model 8530 (<http://www.tsi.com/DUSTTRAK-II-Aerosol-Monitor-8530/>), includes an inline filter that can be used to provide an aerosol mass for calibrating the instrument. Although a comparison of specific models is not provided here, we note that there are alternative PM measuring devices that meet the requirement of high time resolution and may be suitable for use with mobile monitoring systems.

Typically, owing to logistical and safety reasons, instruments to measure PM concentrations, whether nephelometers or some other device, are not placed at the location where it is desirable to measure the PM concentration. Rather, a sample inlet line is used to channel sample air from the desired location to a more convenient location for placing PM measurement devices such as the

inside of the test vehicle. One or more PM measurement devices obtain subsamples from this sample inlet line. The decision of whether or not to use a sample inlet line and the specific configuration depend greatly on where it is desirable to sample the PM concentration.

2.3.2. Measurement of Vehicle Location and Speed

Mobile monitoring systems offer a tool for measuring road dust emissions over many miles of roadway, allowing for a large number of measurements over a roadway network compared to what is achievable using other methods (e.g., inference from silt loading). However, in order to use the information gathered from mobile measurement systems optimally, measurements of PM concentration resulting from road dust emission should be directly tied to a location on the roadway network. Moreover, the travel speed of the test vehicle must be known so that the appropriate value of $K_i(v)$ is applied in Equation 1. Commonplace global positioning system (GPS) receivers are capable of providing both of these parameters with high time resolution and should be used in conjunction with mobile monitoring systems.

2.3.3. Calibration of Mobile Monitoring System

Mobile monitoring systems require calibration against an external standard so that the coefficients $K_i(v)$ in Equation 1 can be quantified. Calibration is the time to relate PM concentration measurements obtained with (likely) an optically based measurement method on board the mobile monitoring test vehicle to PM horizontal flux measurements that are obtained using mass based instruments for PM measurement. The latter essentially provides a first principles estimate of the emissions of PM from the test vehicle. There may be other means to infer a calibration for a mobile monitor. For example, it may be possible to use silt loading as a transfer standard to relate the signal from a mobile monitor to emission factors that were directly measured during a prior study⁷. However, since the ultimate calibration standard - even when silt loading is used as an intermediate transfer standard - is a measurement of PM horizontal flux, the calibration procedure described below focuses on that technique.

Note that if not related to an external standard for emission, then mobile monitoring can still serve as a means for relative comparison of road dust emission potential. For example, if speed is held constant, then the ratio of emission potential from two different roadway sections, treatments, or sampling times can be computed because at a given speed, the calibration factor is constant for a given vehicle. This can be quite useful for quantifying the relative effectiveness of applying surface treatments or comparing different roadway types within the same facility with the intent of identifying which roads are the largest contributors to road dust emissions from that facility. However, if mobile monitoring techniques are to be used to obtain estimates of absolute emissions (i.e., in units of grams of PM per activity), then a calibration against an external standard is needed. Once a calibration for the test vehicle is established, additional correction factors to account for differences between the characteristics of the test vehicle and the mix of vehicles that would travel a road segment of interest are also needed for accurate estimate of absolute emissions. These are discussed in a later section.

Calibration should be conducted under conditions that are as similar as possible to the conditions that are expected to be encountered during actual mobile system measurements. In particular, the range of travel speed expected to be encountered during actual measurements with the mobile systems should be reflected by the calibration protocol.

The calibration procedure relies on measuring the horizontal flux of material in a direction perpendicular to a test road used for calibration purposes (Based on EPA OTM 32)⁸; it has been used in several recent studies^{2,3,4,5,12}. The flux of PM is measured upwind of the road and downwind of the road while simultaneously operating the mobile monitoring system on the same road. In practice, this technique, which is sometimes referred to as a plume profiling or upwind/downwind measurement can be performed in several different ways. The basic principle is that the concentration of PM is measured at several heights above the ground upwind of the calibration test road and downwind of the test road used for calibration of the mobile monitoring system. Wind speed and direction are also simultaneously measured at several different heights above the ground. Through the numerical integration of the PM flux at several different heights, it is possible to quantify the rate at which PM has been added into the atmosphere by the travel of a vehicle along the test road. The assumption invoked in the use of this method is that the test road is essentially a homogeneous source of road dust emissions so that small variations in wind direction do not significantly affect what is measured by the plume profiling instrumentation. In practice, this requires that the test road be of constant grade (preferably level) and reasonably homogeneous in appearance on the scale of a few square meters of area.

It is noteworthy that the above technique for mobile monitoring system calibration requires that the emissions of PM road dust from a given test vehicle be much greater in magnitude than emissions of PM from the tailpipe of the test vehicle. This consideration is especially important when the test road has very low road dust emission potential. Since what is sought is the relationship between the concentration of particles that is measured by the mobile monitor at a given travel speed and the horizontal flux of particles as measured by the plume profiling method, the calibration procedure can be performed on an unpaved road, provided that the road dust emissions are homogeneous over the length of the road section used. This condition can be tested by operating the mobile monitor on the candidate test road section several times to identify spatial variations in the along-road direction. Use of an unpaved road greatly improves the signal strength of the dust plume generated by the mobile monitoring test vehicle over the signal strength from a comparatively clean, paved road.

2.3.4. Quantifying Road Dust PM Emissions

Measurement with the mobile monitoring systems is fairly automated. Once all instruments are operating properly, the measurement procedure amounts to driving a route within the network of roads that is of interest. Several hundred miles of roadway network can be traversed in a single day of measurement. It is important to ensure that the goal of the measurement effort is well represented by the route selected. If the goal is to obtain emission factors for a range of road types

and regions within a roadway network, then it is important that those road types and regions are represented in the measurement route.

Once measurement data are collected, a series of validity criteria are applied. Several criteria are applied to screen out measurements when the mobile monitoring system was traveling too slowly, accelerating or decelerating outside of a prescribed range, performing a turn, or under the influence of the exhaust or road dust plume of another vehicle. Depending on the purpose of the measurements, other example criteria that could be used to screen out or combine measurements include proximity to an intersection, proximity to a known source of road debris material such as a construction site, and season or month when testing was performed. While not a required part of the described test method, the utility of Geographic Information System (GIS) software for mapping the measurement route, selecting specific subsets of data, and examining spatial trends cannot be overstated.

Finally, the calibration procedure (discussed in the prior section) must be used to translate the raw signal from the mobile monitoring system to a mass based emission factor using Equation 1.

3. Definitions

3.1. Background concentration

Refers to the measurement of PM at a location that is not influenced by the tires of the test vehicle. The background concentration is used to identify periods of time when there may be external influences on the PM concentration measured behind the tires such as in the wake of an exhaust plume of a large vehicle (e.g., diesel truck). On roads with low road dust emissions and correspondingly low PM concentrations behind the tires of the test vehicle, measured concentrations may have to be corrected for the background concentration.

3.2. External calibration

Refers to the measurement of road dust PM emissions by means that are substantially independent of the mobile monitoring system. The purpose of an external standard is to relate the PM concentration measured with an optical based instrument on the test vehicle to an emission factor that is measured using a first principles approach and mass-based instruments for PM measurement.

3.3. GPS

Refers to a global positioning system receiver.

3.4. Mobile Measurement System

This refers to a vehicle-based platform for measurement of road dust emissions. There are a number of different configurations of mobile measurement systems, but a common characteristic

among them is that the concentration of PM in the wake of the tires of the test vehicle is measured and related to road dust emissions.

3.5. Optical instrument for PM measurement

Refers to an instrument that uses the light scattering and/or absorption properties of particles to infer PM concentration. Nephelometers and optical particle counters may be equipped with a nominal size cut device so that measurements are limited to a specific particle size (e.g., PM₁₀). Nephelometers measure only optical properties of a large number of particles. Such a measurement can be related to traditional mass based particle concentrations if the latter is measured concurrently.

3.6. Operator

The person who drives the test vehicle for the purpose of collecting measurements.

3.7. Road Dust

Refers to particulate matter (PM) that is suspended into the atmosphere through the interaction of a moving vehicle and the road surface. Road dust as measured by a mobile monitor through the means described here is further restricted to PM that is less than 10 microns (PM₁₀), less than 2.5 microns (PM_{2.5}), and coarse particles (PM_{10-2.5}) that is suspended into the atmosphere as a consequence of the interaction of vehicle tires with the road surface..

3.8. Test Vehicle

Refers to the vehicle with a specific mobile measurement system being used to conduct measurements of road dust emissions.

4. Interferences

4.1. Sources of PM from Other Vehicles, Activities, or Modes of Road Dust Emission

The mobile monitoring system concept relies on the working assumption that in the wake of the test vehicle tires the measured concentration of PM is dominated by road dust that has been emitted through the contact of the vehicle tires with the roadway surface. This assumption can be violated under certain conditions. For example, under certain conditions, exhaust from other vehicles (e.g., diesel truck) may result in much higher concentrations of PM than can be caused by road dust emissions. Background concentrations of PM are monitored at a location on the test vehicle that is not in the wake of the test vehicle tires. The purpose of monitoring this background concentration is to identify periods when the background concentration is elevated due to sources of PM other than the road dust emitted by the test vehicle.

In certain roadway configurations, the emission of road dust may be dominated by a process other than the interaction of vehicle tires with the road. For example, PM dust emissions on a paved road with an unpaved shoulder may be dominated by the interaction of vehicle wakes with the material on the unpaved shoulder⁹. In this case, mobile monitoring techniques would not be able to adequately examine this mode of road dust emission.

4.2. Rain and Puddles

Instrumentation used to measure PM such as nephelometers provide spurious data in the presence of mist and spray resulting from the test vehicle traveling on wet surfaces. Therefore, using mobile monitoring systems while roads are wet or in the process of drying after a precipitation event is likely to result in highly erroneous estimates. Under certain conditions, driving through a puddle can result in the need to perform extensive maintenance and service of PM measurement instruments.

5. Safety

5.1. Roadway Traffic

The primary safety concern for operating mobile monitoring systems is related to driving safety. When driving the test vehicle for an extended period of time, it is natural for the operator to forget that to other motorists and pedestrians, the test vehicle is essentially just another vehicle on the road. In addition, for measurements with specific goals (e.g., measure road dust emissions from fast lane of a four-lane road), there is a natural temptation on the driver's part to avoid disrupting a measurement (e.g., by not moving to the slow lane to allow another car to pass). Test vehicle operators should be trained to always place a higher priority on motor vehicle and roadway safety than the quality of road dust emissions measurement obtained with a mobile monitoring system.

5.2. Speed Bumps, Road Debris, and Other Hazards

A specific test vehicle may have undergone some modifications to enable mobile measurement of road dust emissions. These may include the installation of a sampling line behind a tire, the deployment of equipment on a trailer, or the placement of equipment on a platform mounted on the front or rear of the test vehicle. It is important to remember that when designing vehicle clearances, the manufacturer generally does not account for these types of modifications. For example, a sampling line behind a tire may not clear a speed bump or a large piece of road debris, resulting in a potentially hazardous situation. As another example, a piece of equipment mounted on a trailer may come loose during operation and fall off and cause a potential hazard to other vehicles. It is important that the operator be aware of the conditions that can result in a safety hazard for the specific configuration of the test vehicle being used.

6. Equipment and Supplies

6.1. *PM Concentration Measurement*

6.1.1. **Sample Lines and PM Inlets**

In most embodiments of mobile monitoring systems, a sample inlet line of some type is required to measure the PM concentration in the wake of the test vehicle tires. An example of a sample inlet line that is used to measure PM directly behind the front tire of a test vehicle is shown in Figure 1. In the aerodynamic wake of the vehicle tire, the air is relatively stagnant regardless of the test vehicle travel speed. Therefore, particle sampling losses and size biases are small or negligible since the difference between the air speed at the point of sample collection and the air speed through the sample collection device (sample inlet line) is also small. For the example test vehicle shown, the sample inlet line goes through the van's underside into the van, where the PM concentration is measured with a nephelometer-style instrument. A flow-controlled pump is used to maintain the air flow rate through the sample inlet line at a constant value. Since road dust emissions can be variable across a lane of travel, one sample inlet line is used behind the left front tire and one is used behind the right front tire. PM concentrations from each sampling line are measured separately.

In a different configuration (as shown in Figure 2), the sample inlet line for measuring PM concentration is located on a trailer behind the test vehicle. The center of the trailer is subject to PM emissions from both the left and right tires of the test vehicle in equal proportion, presumably. While the test vehicle does create its own aerodynamic wake bubble, a region characterized by fluid (air in the present case) stagnation and significantly slower fluid motion as compared to the travel speed of the vehicle, the air speed at the location of the PM sample inlet line does vary with vehicle travel speed⁶.

Regardless of where the inlet line is located, several relationships must be obeyed in order to minimize particle losses between the inlet where road dust particles are sampled and the instruments where characteristics and concentrations of road dust particles are measured. Figure 3 provides a schematic of a typical sample collection train used in mobile monitoring configurations. Sample air is introduced into the train at the right side, directed into a mixing volume and subsequently directed through a manifold, where a portion of the sample air is presented to measurement instruments - nephelometers in the present case - while another portion is extracted through a flow meter and pump. The following constraints should be used when designing such a system:

1. The difference between the speed of the sample air in the vicinity of the inlet ($V_{\text{near-inlet}}$) and the speed of the air through the inlet must be small¹⁰:

$$-2.5 \text{ m/s} < V_{\text{in}} - V_{\text{near-inlet}} < 1.7 \text{ m/s} \quad (2)$$

Differences outside of this range would result in over- or under-representation of 10 micron particles by greater than 5% as compared to their true concentration in sample air. Note that V_{in} is a design parameter given by:

$$V_{\text{in}} = Q_{\text{in}} / (\pi D_{\text{in}}^2 / 4) \quad (3)$$

whereas $V_{\text{near-inlet}}$ is obtained by direct measurement of air speed in the sampling region of interest. $V_{\text{near-inlet}}$ may be characterized by use of pitot tubes (as shown in Figure 3, pitot tube: Dwyer Instruments Inc., Series 160; pressure transducer: All Sensors Corporation MBAR-D-4V), cup anemometers, or sonic anemometers as appropriate. As a rule, the nominal dimension of the device used to characterize the air speed should be less than one tenth of the lesser of: Distance between the device and the next closest upstream object or the nominal dimension of the upstream object. For example, the nominal dimension of a pitot tube is the larger of its diameter or its length whereas the nominal dimension of a cup anemometer is the diameter of the cup circle. The nominal dimension of a vehicle tire is the width of the tire. If measuring in the wake of a large object, such as the vehicle itself, then the nominal dimension is the lesser of the width or height of the vehicle. When choosing an instrument for the characterization of near-inlet air speed, the entire range of vehicle speeds and the corresponding measurement requirements should be considered. For example, if a pitot tube is being used, then the pressure transducer(s) used in conjunction with the pitot tube should be selected so that the minimum and maximum near-inlet air speeds that can be expected to occur can be measured with a precision of 1 m/s or less.

2. If the half-angle of enlargement between where the sample line enters the mixing volume/plenum and the maximum diameter of the plenum (ϕ in Figure 3) is less than or equal to 4° , then there is no minimum length requirement for the plenum (L_{plen} in Figure 3). For half angles larger than this threshold value, turbulent eddies will form as a result of the expansion. Consequently it is necessary to ensure that the flow within the chamber is thoroughly mixed prior to sub-sampling at the next stage, the inlet line manifold. A plenum length equal to 6 diameters is sufficient to ensure thorough mixing (i.e., $L_{\text{plen}} = 6D$). Note that if the plenum is much longer than necessary to achieve good mixing, additional, unnecessary PM depositional losses to the plenum walls can be expected.

3. Flow through the sample inlet lines into the measurement instruments must also be designed so that:

$$-2.5 \text{ m/s} < V_i - V_{\text{plenum}} < 1.7 \text{ m/s} \quad (4)$$

where V_i is the air velocity at the inlet to instrument i , which can be calculated from the flow-rate of instrument i , Q_i and the diameter of the inlet line at the manifold for instrument i , D_i as:

$$V_i = Q_i / (\pi D_i^2 / 4) \quad (5)$$

The equation that relates all of these flow-rates is:

$$Q_{\text{in}} = \sum_{i=1}^n Q_i + Q_{\text{pump}} \quad (6)$$

where n is the number of active sample lines being used by instruments in the inlet line manifold and Q_{pump} is the flow-rate through the perforations in the manifold. The air flowing through these perforations goes through a mass flow meter, followed by a filtration device to remove particles (to protect downstream pump), that is followed by a vacuum pump.

4. The locations of inlet lines can vary from one mobile monitoring system to another. Similarly, the locations of the plenum, sample manifold, and particle characterization instruments can also vary. Consequently, the routing of sample air from inlet to instrument can require passage through several curves in the sample lines. It is advisable that the maximum combined losses associated with bends in the sample line be less than 30% for all particle sizes. The reader is referred elsewhere¹⁰ for guidance on calculating such losses.
5. Optionally, an inline size selective inlet (SSI), such as a cyclone, may be used to remove particles of a certain size from the sample stream (e.g., particles larger than 2.5 micrometers in aerodynamic diameter). If so, then the flow-rate through the inlet Q_{in} must equal the design flow-rate of the SSI, $Q_{\text{SSI, Design}}$ within the tolerances specified by the SSI manufacturer. Note that some optical based instruments (e.g., TSI 8530) are equipped with their own SSI at the inlet of the instrument itself so that it is not necessary to pass all of the sample inlet air through an SSI. It is important to note that subjecting all of the sample to an SSI can result in the plenum being under substantial vacuum since there is a pressure drop across most SSIs that use inertial separation methods to achieve size segregation. Unless it can be demonstrated that such pressure drops do not affect the performance of downstream instrumentation, such as nephelometers and other samplers if applicable, it is advisable to ensure that the pressure inside the plenum and atmospheric pressure do not differ by more than 2 kiloPascals (kPa), (0.6 inches of Hg, or 8" H₂O).

6. The pressure within the sample plenum (P_{plenum}) must be kept within 2 kPa (or equivalently, 0.6 inches of Hg, or 8" H₂O) of the atmospheric pressure in order to ensure that the instruments that are sampling from the are able to draw their aliquot of sample air. Since those instruments are often operating with their own pumps and flow controllers, excessive differences in pressure between the plenum and ambient conditions could result in erroneous readings. A pressure tap within the plenum, at least 10 cm (4 in) from any inlet or outlet as shown in Figure 3 can be used in conjunction with a readout pressure gauge (e.g., Dwyer, Magnehelic 2300-6000-PA) or digital pressure gauge (e.g., Dwyer, Digihelic, DHII-008-NIST) to ensure that P_{plenum} is within the required range of atmospheric pressure.
7. Exhaust from the make-up air pump and from any power generators used on board the mobile monitoring system, if applicable should be directed so as not to influence the air near the sample inlet. In practice, it is best to route the pump and generator exhaust so that it is emitted safely downstream (more than 1 meter) of the sample inlet location.

6.1.2. Size-Selective Inlets for PM measurement

There are two options for achieving size segregation when sampling for PM with the current method. The first option, which has been widely used to date, is to employ a size-selective inlet in conjunction with the specific instrument that is being used to characterize PM concentration. Several manufacturers of near real-time PM measurement devices supply a selection of size selective inlets that are designed to provide a pre-determined size cut at the operating flow rate of the instrument. For example, the nephelometer manufactured by TSI (DustTrak, 8530) is shipped from the manufacturer with four size selective inlets with cut sizes corresponding to aerodynamic diameters of 1, 2.5, 4, and 10 micrometers. Typically, these manufacturer-supplied, instrument-specific SSI have not been shown to be compatible with stringent EPA sampling requirements for National Ambient Air Quality Standard (NAAQS) compliance. This is acceptable provided that the nominal cut size is within 5% of either 10 micrometers or 2.5 micrometers, depending on the size fraction being measured and that the size cut characteristics, especially the particle penetration/cutoff in the vicinity of the nominal cut size, have been documented (See e.g., http://www.tsi.com/uploadedFiles/Site_Root/Products/Literature/Application_Notes/EXPMN-003_DustTrakII_Impactor.pdf for model 8530 impactor cutoff efficiency).

The second option for achieving the desired size cut SSI is to subject the entire sample air flow within the sample inlet to an SSI (i.e., use an SSI upstream of the sample plenum/mixing chamber – location 5 in Figure 3). For PM_{2.5}, a cyclone is a useful way to achieve the desired size cut. A cyclone is compact enough to use in the immediate vicinity of the vehicle tires, can provide size-cut characteristics that are consistent with strict EPA guidelines for PM_{2.5}, and is able to achieve this with pressure drops that are reasonable in view of the requirements set forth in section 6.1.1. Cyclones with cut sizes that are sharp enough to meet EPA Federal Reference Method criteria are commercially available (e.g., PM_{2.5} Very Sharp Cut Cyclone, BGI Incorporated, Waltham, MA) in a number of configurations, with pressure drops on the order of 2" of water at the design flow-rate.

SSI for PM₁₀ are somewhat more difficult to employ in the immediate vicinity of the vehicle tires because of their tendency to be larger than SSI for PM_{2.5}. If used in the vehicle wake as with the configuration depicted in Figure 2a, a PM₁₀ SSI that is approved for use as part of a Federal Reference Method for PM₁₀ NAAQS compliance may be used. Such PM₁₀ “heads” are widely available commercially.

6.1.3. PM Concentration Measurement

Mobile monitoring systems for road dust emission measurement rely on fast-response instruments for PM concentration measurement. A test vehicle can cover a long segment of road in a matter of seconds. For example, when traveling at a speed of 45 miles per hour, a test vehicle is creating road dust emissions from 66 feet (20 meters) of roadway length per second of operation. Thus, to optimally use the capabilities of a mobile monitoring system, PM concentrations should be measured with a time resolution on the order of seconds or less.

The TSI DustTrak nephelometer (model 8520, http://www.tsi.com/uploadedFiles/Site_Root/Products/Literature/Spec_Sheets/2980077_DustTrak_8520.pdf) is one commercially available nephelometer that has been used extensively with mobile monitoring systems in the past. However, there are several manufacturers of such instruments and any model that has similar operating characteristics may be used. The DustTrak, shown in Figure 4, has a response time of one second, operates with a flow-rate of 1.7 or 3.0 lpm, can measure PM concentrations over 5 orders of magnitude (ranging from 1 µg/m³ to over 100 mg/m³), and is supplied with several different size selective inlets (including a nominal PM₁₀ inlet and a nominal PM_{2.5} inlet). The manufacturer recently updated the instrument (model 8530, <http://www.tsi.com/DUSTTRAK-II-Aerosol-Monitor-8530/>) with a slightly different form factor and to include more capabilities. A notable new capability is the ability to collect particles sampled through the instrument onto a filter for subsequent gravimetric analysis. It is important to note that all nephelometers use optical properties of particles to infer mass concentrations. There are assumptions about particle size distributions and mineral composition that are inherent to such an inference. For more accurate inference of mass from optical properties, collection of mass-based concentration data (e.g., by filter sampling) should be done concurrently with nephelometer measurements.

The principal means by which PM is being quantified in each sample line (such as the one shown in Figure 3) should be collocated with either an identical device or with a device that measures substantially the same quantity with as good or better precision and bias. For example, if the principal means by which PM is quantified is a DustTrak equipped with a nominal 10 micron inlet, then there should be another DustTrak with a 10 micron sample inlet attached to the same plenum. In this way, the two identical instruments can serve as quality checks on one another (See Section 8.3).

6.2. *Pumps or Blowers*

One or more air pumps or blowers are needed to pull sample air through the sample inlet lines. There are a large number of such devices available on the market and no specific model or type is suggested. Generally, in configurations where substantial pressure drops may be encountered (e.g., if the entire sample air flow is pulled through a filter), a pump will be required. Otherwise, it may be possible to use a blower which uses much less electrical power. The pumps used must meet the requirements of the specific mobile monitoring configuration. The pump must be able to process the maximum design air flow (Q_{pump} in Figure 3) under the pressure conditions imposed by the mass flow meter and HEPA filter downstream of the pump and the vacuum created in the plenum upstream of the pump (note that such vacuum should be relatively low and in any case less than 2 kPa). In the absence of specific knowledge of the range of flows of interest, a rotary vane pump, capable of providing a maximum vacuum of 80 kPa and a maximum flow rate of 160 lpm at about 30 kPa of vacuum (e.g., Gast series 1423) is adequate. Diaphragm and piston pumps should be avoided because of their tendency for vacillating.

6.3. *Pitot Tubes and flow meters*

Typically, the rate of air flow through the sample inlet lines must be maintained at some constant design value or varied to meet the needs of isokinetic sampling protocols. The speed through the sample inlet line can be measured directly or inferred from the flow rate through the inlet line. For direct measurement, pitot tubes provide a measure of the air speed and are useful for providing feedback information to pumps or blowers. No specific model or type is advocated. Rather, the geometry of the sample inlet line for the mobile system and the specific needs (e.g., measurement range, sensitivity, etc) should dictate what type of pitot tube is used. In any case, the pitot tube should not block more than 5% of the cross-sectional area of the sample inlet line. Pressure measurements should be accurate enough so that the overall pitot tube accuracy is 1 m/s (e.g., All Sensors Corporation MBAR-D-4V). For sample inlet lines that are 2 cm (0.02 m) in diameter and less, small body pitot tubes (e.g., Dwyer Instruments Inc., Series 160) should be used.

Alternative methods for flow measurement such as rotameters, mass flow meters, and other devices are acceptable as long as they do not interfere with the measurement of PM concentration. Regardless of the device chosen, it should provide an accuracy in the flow-rate measurement that translates (See Equation 5) to an accuracy in the inlet air speed of less than 1 m/s. It is recommended that a NIST-traceable device or a device that has been calibrated to a NIST-traceable device over the temperature (0 – 45°C) and relative humidity (0 – 95%) range that can be encountered during measurements be used. One option is to locate a mass flow controller (e.g. Alicat Scientific, MCR 100 SLPM) downstream of the HEPA filter as shown in Figure 3 so that the functions of flow measurement and control are fulfilled by a single NIST-traceable device.

6.4. *GPS*

GPS receivers are widely available commercially. The location is a primary output of the GPS receiver and secondary outputs such as speed, acceleration, and heading of the mobile monitoring system are either provided by the receiver (higher end models) or can be calculated as secondary quantities. One practical note is that the GPS should be equipped with some suitable communications protocols (typically RS 232, TCP/IP, or Bluetooth) in order to communicate with the datalogger/computer in real time.

6.5. *Datalogger/Computer*

A laptop computer is a useful datalogger for mobile monitoring system applications because it can also serve as a means to display the measurement information in real-time and to control certain devices such as pumps. The laptop records measurement data from the GPS, DustTrak nephelometers, and flow measurement devices such as pitot tubes. Depending on the specific sample inlet line configuration, the laptop can also use information from the pitot tubes to maintain pump/blower operating levels at the desired levels.

6.6. *External Standard for Calibration*

An external standard method of measuring road dust emissions from a test road is required to calibrate every mobile monitoring system. The overarching requirement for an acceptable standard is that the measurement should be substantively independent of the mobile monitoring system being calibrated. An example of such a standard is given in 2.3.3.

7. Sample Collection

7.1. *Preliminary Determinations*

The design of a measurement route and measurement plan for a test vehicle should be driven by the specific goals of the measurement campaign. Such goals can vary considerably and measurement plans can vary accordingly. For example, if the goal is to obtain a characteristic estimate of road dust emissions from a region within a metropolitan area, then the measurement route should include roads that are representative of the entire region of interest. Such a route would include freeways, arterials, collector roads, and local roads. Although the larger roads tend to be associated with the highest traffic volumes, smaller, less busy roads should also be included, because often, such smaller roads exhibit much higher emissions per unit activity (vehicle miles traveled in the case of road dust). An example measurement route is provided in Figure 5. The sampling route shown is for Clark County, Nevada. Those measurements were conducted in 2005 and were intended to provide an overview of road dust emissions across the Las Vegas Valley on all types of roads, ranging from freeways to local roads¹¹. Each road type was represented in each of the four quadrants of the Las Vegas valley.

As another example, if the goal is to estimate the increase in road dust emissions caused by a certain activity (e.g., road construction) on an arterial road, then the measurement route should include multiple arterial roads that exhibit the activity as well as multiple arterial roads that do not.

The timing of measurements should also be considered when developing a measurement plan. There are significant seasonal differences in road dust emission rates, especially at locations where traction control material (such as sand) is applied to the roads during winter months. Therefore, at such locations, mobile measurements (or any measurement of road dust emissions) that are obtained in the spring, when significant traction control materials may still be present on roads, would likely overestimate road dust emissions on an annual basis. It may be necessary to conduct road dust emission measurements at several different times over the course of a year or several years to accurately estimate an annual average^{3,12}.

7.2. *Pre-test Preparation*

A sample check list for pre-test preparation has been provided as an attachment to this document. In addition to filling out a similar checklist prior to the beginning of a measurement effort, several activities must be completed well in advance of the measurement effort. These include periodic calibration of flow and PM measurement instruments, cleaning of sample lines, and other activities that require a comparatively long lead time to complete.

7.2.1. **PM Monitors**

Calibrate PM monitors according to manufacturer's specifications. If DustTrak nephelometers are in use, ensure that each unit has been factory recalibrated and serviced within the previous twelve (12) months as specified by the manufacturer. If filter-based monitors for PM are used in conjunction with nephelometer style instruments (e.g., as with the TSI model 8530) all filters should be properly labeled and pre-weighed prior to use.

7.2.2. **Mobile Monitoring System Calibration**

Mobile monitoring systems for road dust measurement can vary in their specific configuration. PM concentration measurements obtained by each system will respond differently to the same road dust emission rate due to differences in the location of the sample inlet with respect to the vehicle tires. Furthermore, PM monitoring devices will respond differently for measurements conducted on the same road but at different test vehicle travel speeds. It is essential that each test vehicle configuration be calibrated to an external standard for road dust emissions measurement. Calibration of the test vehicle should be completed under conditions that are similar to what the test vehicle will encounter during monitoring.

Since test vehicle speed can affect the measured PM concentration, it is especially important that the test vehicle be operated at multiple discreet speeds that span the expected speed range to be encountered during actual measurements. At a minimum, it is recommended that ten separate measurements of PM emission (e.g., by plume profiling) and mobile measurement be completed at

each discreet speed to provide enough replicate measurements for reasonable assessment of the uncertainty of the plume profiling measurement. In practice, this means that valid data (for both test vehicle and plume profiling technique) should be collected for ten passes of the test vehicle in front of the plume profiling instrumentation. Ultimately, the number of test passes during the calibration process should be determined by the desired confidence limits for values of K_i in Equation 1 for different speeds. The standard error, defined as the standard deviation divided by the square-root of the number of samples (n) is an appropriate metric to determine the confidence with which a mean value of a particular parameter is known based on n independent measurements of a parameter. Thus, the uncertainty with which the mean value of K_i is known is inversely proportional to the square root of the number of times K_i is measured.

7.3. *Field Check Prior to Measurement*

7.3.1. **Flows through sample inlet lines**

Visually inspect sample inlet lines to ensure that they are free of debris and flow obstructions. The air flow rate through the sample inlet lines should be checked with an independent calibrated flow measurement device such as a rotameter or mass flow meter. If possible, the air flow rate should be varied over the range expected during actual operation and rechecked. The purpose of this step is to ensure that any pitot tubes used within the sample line are operating properly and that there are no leaks within the sample line.

At a minimum the total air flow through the inlet when all instruments and make-up air pump are operating should be measured with a low pressure drop device such as a rotameter or mass flow meter. In either case, the device should be either NIST traceable or calibrated against a NIST-traceable standard. The measured flow at the inlet should be within the smaller of the measurement uncertainty of the device being used and 3% of the sum of the make-up air flow and the flow through the individual sample instruments (See Equation 6). It is assumed that the make-up air flow and the flow through individual instruments is independently verified with a NIST-traceable device. In configurations where there is substantial, measurable pressure drop in the sampling plenum, such as could occur if an SSI was used upstream of the plenum, the gauge pressure within the plenum should be checked with NIST-traceable pressure gauge (readout or digital) to ensure that it is within the $\pm 5\%$ of its known “no-leak” value. A significantly lower pressure drop may indicate a leak in the system whereas a higher pressure drop may indicate blockage.

7.3.2. **GPS**

GPS receivers can require several minutes to achieve a reliable satellite lock. The time and the geographic coordinates reported by the GPS unit should be checked against known standards prior to the beginning of measurements.

7.3.3. PM Concentrations

PM measuring instruments should be checked and set to the manufacturer's recommended standards.

7.3.4. Connectivity

On systems that use multiple PM monitors to sample air from multiple sample inlet lines, it is important that the monitors are connected and labeled correctly. Check labeling of monitors and trace inlet lines to ensure the proper connectivity between each monitor and the corresponding sample inlet line.

7.3.5. Clean Sample Lines

Sample lines should be clean. Buildup of deposited materials on the inside of sample lines can result in erroneous measurements when the test vehicle is subjected to vibration – such as a bump or from the engine. If PM concentration monitors with fast response are in use, a good test is to knock on the sample inlet lines with a wrench to simulate road vibrations. If the sample inlet lines are clean PM concentrations should not be affected by this action. An alternative to frequent cleaning is to grease the inside of the sample inlet lines with a non-volatile material (e.g. Apiezon grease, bearing grease). The grease serves to arrest particles that deposit within the sample inlet lines and prevent them from becoming resuspended. Note that greasing of sample inlet lines in other particle sampling applications is considered deleterious to the measurement because a bias is introduced by the removal of particles within the sample line. In the present case, the small bias that may be introduced, principally for larger particles, as a result of sample line greasing is preferable to the potential for re-entrainment of previously deposited particles as a result of vibration. If greasing is deployed, grease should only be applied up to the point within the sample line that an SSI is used. Downstream of the SSI, greasing is unnecessary since large clumps of soil and other debris would be effectively removed from the system. Cleaning of sample inlet lines is still required, but may be reduced in frequency by use of grease. Testing the potential for particle resuspension by knocking on the sample lines with a wrench also works with greased sample lines.

7.4. *Computer Clock*

Electronic data files written to the laptop are recorded with a time stamp so that all data collected can be referenced to a specific time and test vehicle location. If the laptop clock is used to supply this common time stamp, the laptop clock should be checked against the GPS and set to local time prior to the beginning of measurements. This should be repeated at the beginning of each day of measurement.

7.5. *Sample Recovery*

Under normal operating conditions, a physical sample will not be collected. The method can be used to collect filter samples of particulate matter. Additionally, filter samples may be collected in

conjunction with other instrumentation. For example, certain nephelometer devices enable the use of inline filters as a means for comparing mass based measurements to optical based measurements. This method does not include prescriptive information on filter sample collection in conjunction with mobile monitoring.

7.6. Chain of Custody

Under normal operating conditions, a physical sample will not be collected.

7.7. Maintenance Log

Field and laboratory personnel will keep a log of all repairs, calibrations, and replacements of PM concentration monitors and flow measurement and control devices. This log will be kept in a field notebook within the test vehicle.

7.8. Electronic Data

The majority of data collected by mobile monitoring systems will be in electronic format. All data files should be downloaded to two independent storage locations to avoid data losses. Each file should be opened and the time stamp of the first data point and the last data point should be compared to the start and end times of the measurement effort. Any discrepancies should be noted in a field notebook. A "Readme" file is often a useful way to ensure that field notes are not overlooked during subsequent data analysis.

8. Quality Control

8.1. Review GPS Data

Plot the geographic coordinates collected with the GPS, preferably using GIS software. Visually identify gaps in the data stream. These gaps are best seen by zooming the view so that individual coordinate locations can be differentiated. Invalid GPS data generally invalidate the corresponding mobile measurement data point because it is difficult to tie the measurement to a specific location on the roadway network.

8.2. Review Sample Air Flow Data

Ensure that the air flow rates through the sample inlet lines were within design criteria discussed in Section 6.1.

8.3. Check PM Concentration Data

PM concentrations measured by the test vehicle should be inspected to remove obviously invalid data and identify possible measurement biases. Guidelines are provided below for PM concentrations measured with a DustTrak (TSI 8520), but ultimately professional judgment must

be applied for each specific setting, PM measurement instrumentation, and test vehicle configurations.

8.3.1. Check DustTrak Measurement Limits

Check all DustTrak data and invalidate data points associated with concentrations outside of the instrument's measurement range. Note that the DustTrak 8520 will report concentrations even if they are higher than the upper 150 mg/m³ limit. Unless the specific instrument being used has been calibrated or checked against an independent measurement device at concentrations higher than the 150 mg/m³ limit, PM concentrations reported above this limit should be invalidated or flagged as suspect.

8.3.2. Check Collocated DustTrak Measurement

Mobile monitoring system configurations should utilize at least two DustTraks to either provide collocated PM measurements or to provide PM concentrations in two size fractions (PM_{2.5} and PM₁₀). For example, two DustTraks equipped with PM₁₀ inlets or one DustTrak with a PM₁₀ inlet and one with a PM_{2.5} inlet may be connected to the same sample line. Inspect the time series for the entire data set for collocated DustTraks. PM concentration changes should be highly correlated between collocated instruments. Scatter plots of subsets of the time series can be helpful in assuring correlation between two collocated units. Note that on a second by second basis, two DustTraks with identical size selective inlets may report significantly different concentrations. This can be due to subtle differences in timing. However, a regression between two units using the same size-selective inlet (PM₁₀ or PM_{2.5}) over a hundred data points or more should yield a slope between 0.8 and 1.2 (Note: The inter-instrument precision is reported to be 10% by manufacturer). This slope should be relatively constant for any two instruments, even if compared over different measurement time periods.

8.3.3. Check PM Concentrations from Each Side of the Vehicle – applicable to systems with bilateral sample inlet lines

Mobile monitoring systems that have separate PM concentration measurement apparatus for the left side and the right side of the vehicle will obtain two different measurements every second, one for the left side and one for the right side. A time series plot of DustTrak concentrations from the left side and right side is helpful for ensuring that, in general, the concentrations increase and decrease at the same time. However, it is important to note that real roads are not homogeneous in terms of road dust loading and it is very likely, that there will be periods with large differences between PM concentrations measured on the left side and the right side of the test vehicle². For example, on roads with limited or no shoulder, much of the road debris accumulates on the right side of the rightmost travel lane and concentrations measured behind the right front tire will be higher than those behind the left front tire when the rightmost lane is sampled.

8.3.4. Check Background Concentrations

PM concentrations intended to reflect the background PM (usually collected in front of the test vehicle) should be examined in a time series. Periods with obvious spikes in background PM concentration that may be associated with interference from other sources of PM on the test road should be invalidated. A spike can be operationally defined as an incident where the background concentration of PM increase by a factor of two or more over average values for a short interval. Note that if the PM concentrations measured in the wake of the vehicle tires at a particular time remain more than a factor of ten higher than the background PM concentration, then such spikes can be ignored because they represent only a small portion of what is being measured in the wake of the vehicle tires. That is, their influence on the overall measurement uncertainty is significantly smaller than the overall uncertainty of the measurement. Note also that background PM concentrations can change over time due to changes in ambient air quality. What is important is that the fluctuations in the background PM concentration are fairly small compared to the PM concentrations measured in the wake of the vehicle tires.

9. Calibration and Standardization

9.1. PM Concentrations

Check all PM measurement devices prior to every field deployment. A good check is to collocate all of the instruments to be used on a test vehicle in a setting where the PM concentrations are homogeneous and compare time series and average concentrations. See Figure 6 for an example of six collocated DustTraks.

10. Data Analysis and Calculations

10.1. Review One-Second Raw Data Records

Perform quality control checks for missing, anomalous, and invalid one second concentration data as discussed in Section 8.3.

10.2. Calculate One-Second Net Raw PM Concentrations

The raw signal from the mobile monitoring method is the PM concentration in the wake of the vehicle tires corrected for the background PM concentration. The raw signal is given by

$$MSC_{ps,t} = C_{wake,ps,t} - C_{back,ps,t} \quad (7)$$

where $MSC_{ps,t}$ is the raw PM concentration in the size fraction denoted by ps (e.g., PM_{10}) from the mobile monitoring system at time t , $C_{wake,ps,t}$ is the PM concentration measured in the wake of the test vehicle tires at time t , and $C_{back,ps,t}$ is the background PM concentration measured upstream of

the vehicle tires (generally towards the front of the vehicle) at time t . Unless there is a reason not to do so (e.g., as part of the objectives of a specific study), for mobile monitoring systems configured to measure the PM concentration in the wake of the tires separately on the left and right sides of the test vehicle, $C_{wake,ps,t}$ should reflect the average of the two measurements.

10.3. Apply Time Delay Correction to Raw Data Records

The time, location, and speed information provided by the GPS reflects the activities of the test vehicle with a resolution of one second or less. In contrast, concentrations of PM measured from sample inlet lines may be delayed compared to the event that is reflected by those concentrations. Sample air requires a finite amount of time to travel from the wake of the vehicle tire(s) through sample inlet lines, and to a PM analyzer. This time delay between when an event occurs at the vehicle tires and when it is registered in the PM concentration time series can be up to several seconds. The raw signal from the test vehicle should be retarded by the appropriate time interval so that the data collected by the GPS are temporally matched with the data collected by the PM concentration monitors. The time delay can be estimated by adding all of the travel times within the different segments of the sample line and the temporal resolution of the measurement instrument. The travel time through any one section of sample line can be estimated by dividing the length of the segment by the air speed through the segment. As depicted in the example of Figure 3, there are three segments of the sample inlet line. The first is the segment that begins at the inlet and ends at the plenum; the second begins at the right edge of the plenum and ends at the instrument inlet lines; the third is the instrument sample line from the manifold to the instrument. The temporal resolution of the sample instrument or its response time are usually specified by the manufacturer. Alternatively, the lag time can be measured directly by operating the mobile monitor sampling system while the test vehicle is stopped. Using a common time standard, light a match and blow it out and immediately place it in the inlet opening noting the exact time. The extinguished match will produce a very sharp rise in PM concentrations. Note the time that the sharp rise is reported by the instruments. The difference in time between when the match was placed in the inlet and when the associated peak was reported by the instrument is the lag time. Although it varies from one configuration to the next, under typical conditions, the lag time is generally less than 5 seconds.

10.4. Apply GPS-based Validity Criteria

Mobile monitoring systems are subject to interferences resulting from specific driving conditions. If the test vehicle speed is too low, crosswinds may affect the quality of the measurement; crosswinds will result in the plume position shifting with respect to the test vehicle body and the location for the sample inlet line (generally fixed with respect to vehicle body) would also be shifted with respect to the normal (non-windy) plume position. During acceleration, deceleration, and turns, PM concentration measurements may not reflect normal driving conditions. Unless the objectives of a measurement campaign include characterizing PM road dust emissions from “Stop and go” traffic, it is best to exclude periods of linear or angular acceleration because it is unclear at this time how such measurements performed by the test vehicle can be related to other vehicles. Guideline

criteria are provided in Table 1. Note that a relationship between test vehicles and other vehicles based on mass and speed has been obtained empirically for constant speed travel on a relatively level road⁵.

10.5. Apply PM Mass/Optical Correction

If a filter-based method for PM collection was operated in parallel with a fast response PM concentration measurement instrument such as a nephelometer, the ratio of the mass-based PM measurement to the average PM concentration according to the fast-response instrument should be applied as a correction to all raw signals calculated with Equation 2.

10.6. Calculate Emission Factors

Using Equation 1, calculate PM emission factors on a one-second basis.

10.7. Calculate Road Segment-Average Emission Factors

Plot the emission factors using GIS software that also shows the roadway network where the measurements were completed. Using the appropriate GIS utility, associate each data point with a roadway segment. Each segment may have multiple measurements associated with it, but each measurement should only be associated with a single roadway segment. Direction of travel, speed, and other parameters can help assign data points to the correct roadway segments. The analyst should determine what geographic parameters should be used to include/exclude specific data points. For example, data points collected within some specified proximity of an intersection may/may not be desirable.

Table 1. Example of criteria applied to ensure valid measurements based on vehicle driving conditions^{2,11,12}.

Parameter	Threshold for validity	Underlying premise
Speed (test vehicle)	Less than 11 miles/hr – paved roads (5 m/s)	Minimize disturbances due to ambient winds. Crosswinds modify the effective orientation of the sampling location with respect to the vehicle tires by shifting the plume shape and center of mass.
Acceleration	Less than 1.3 miles/hr/s (0.7 m/s ²)	Lateral shear during acceleration and transient airflow around sample inlet lines render measurements during times of high acceleration unreliable.
Deceleration	Absolute value less than 1.3 miles/hr/s (0.7 m/s ²)	Applying the brakes releases dust particles and may result in false high road dust readings.

Wheel Angle	Less than 3 degrees with respect to the vehicle body	Turns cause the front wheels to form an angle with the vehicle body. This in turn changes the shape of the tire wake with respect to sample inlet lines. Data associated with sharp turns are not valid.
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Average emission factors can now be calculated for each road segment. A good rule of thumb is that at least 80% of the maximum number of data points attainable at a given travel speed should be valid when calculating a road segment average. For example, at 36 miles per hour the test vehicle would traverse 0.1 miles in 10 seconds. Thus, in order for the average emission factor calculation for that 0.1 mile-long road segment to be considered valid, at least 8 data points from that road segment should be valid if the data collection rate is once per second. A road segment is defined as the shorter of the entire length of the link in the GIS representation of the roadway network or at most 0.1 miles or 0.05 miles on major arterial roads or local minor roads, respectively.

Operationally, a link in the roadway network can be defined as the segment that connects two adjacent intersections. Sometimes, long roads are broken into smaller segments within the representation of the roadway network so that there are multiple links between two adjacent intersections. In any case, the analyst will have to inspect the distribution of the valid data points on the road segment to ensure that they adequately represent conditions over the entire length of the road segment.

The emission factors calculated from test vehicle measurements are applicable at the speed that the test vehicle was operated. An underlying assumption is that the test vehicle travels at the same speed as other roadway traffic. Similarly, the emission factors calculated through Equation 1 apply to the vehicles and conditions used when calibrating the test vehicle to an external PM emission measurement standard. The analyst may have to apply corrections for vehicle weight and speed if calibration conditions deviate significantly from the conditions on a specific road segment. In the absence of specific information to the contrary, simple linear corrections may be used⁵ for small deviations in vehicle weight and speed:

$$EF_{actual} = EF_{test\ vehicle} \times \frac{M_{actual}}{M_{test\ vehicle}} \times \frac{S_{actual}}{S_{test\ vehicle}} \quad (8)$$

where the subscripts refer to the actual average speed and mass of vehicles traveling on a given road segment as compared to the speed and mass of the test vehicle.

10.8. Tabulate Results

Tabulate road segment emission factors in a spreadsheet or database. It is sometimes useful to convey this information using GIS plotting capabilities. An example is provided in Figure 7.

11. Other Useful Results

11.1. Emissions Inventory

Mobile monitoring systems provide a measurement of the emissions factors for PM road dust in terms of emissions of PM per unit activity. Typical units are grams of PM per vehicle mile traveled (g/vmt). Traffic demand models (TDM) are used by transportation planning agencies to model the traffic flow in a jurisdiction of interest. The TDM models use basic principles of traffic flow along with real traffic counts at a finite number of locations within a road network to estimate the flow of traffic on every road segment in the modeled area. Emissions factors of PM obtained with mobile monitoring systems over a finite number of roads can be extrapolated to an entire area that is represented by the TDM. Parameters such as roadway type, posted speed limit, average traffic volume, and location within the modeled area can be used as parameters for refining the extrapolation. The data analyst must determine the best approach for the specific area modeled by the TDM. The outcome is that a PM emissions factor can be assigned to every road segment within the TDM. When combined with modeled traffic volume, total PM emissions in terms of mass per unit time (typical units are tons or metric tons of PM per year) can be calculated. This greatly facilitates the assembly of emissions inventories for road dust PM.

11.2. Influence of Specific Road Conditions

Road dust PM emissions factors measured within a roadway network can be compared by road condition subgroup. For example, PM emissions factors for roads with paved shoulders can be compared to roads that have unpaved shoulders, areas that are frequently serviced by street sweepers can be compared to areas where sweepers are not in use, and areas with comparatively higher levels of construction activities can be compared with areas that are well developed. This information can provide insight into what activities and road conditions affect the potential for PM road dust emissions.

11.3. Effectiveness of Dust Control Techniques

The effectiveness of dust control strategies can be evaluated on a relative basis without the need for calibrating a mobile monitoring method. This can be accomplished, for example, by using the mobile monitor to sample an unpaved road prior to some chemical treatment and then repeating sampling periodically after chemical treatment. The effectiveness of controls can be calculated as the ratio of the average *MSC* (see Equation 1) as measured under the different conditions or different times after treatment to the baseline *MSC* (untreated) of the road.

12. Example Application

This method was used to measure PM₁₀ road dust emissions factors on about 100 miles of roads in Clark County, Nevada in February 2005¹¹. The same measurement route was completed on four

consecutive days. The mobile monitoring system used for this study was the Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER) as described by Etyemezian et al.². The TRAKER was not calibrated at the time of these on-road measurements. A Clark County-specific calibration of the TRAKER was conducted in September, 2006 as part of a much larger effort to characterize mobile systems for PM road dust emissions measurement¹³. This study, described below, was titled the Clark County Phase IV study¹⁴.

Several mobile monitoring systems for road dust PM measurement were operated on a mile-long road segment in Boulder City, Nevada^{13,14}. These included an early version of TRAKER as described by Etyemezian et al.², a second version that was under development and was used on a test basis, and a version of the System for Continuous Aerosol Monitoring of Particulate Emissions from Roads (SCAMPER) as described by Fitz et al.⁶. Details of the Phase IV study are provided in Langston et al.¹³. The portion related to the calibration of the TRAKER is briefly described below.

A tower (10 meters in height) was used for plume profiling. The tower was equipped with DustTrak nephelometers with PM₁₀ inlets at five heights ranging from 0.7 meters to 9.8 meters above ground level (Figure 8). An anemometer was collocated with each DustTrak. The tower was located on the downwind side of the test road. DustTrak concentrations were corrected to a mass basis by procuring the road dust material, resuspending the material in a laboratory chamber, and simultaneously measuring PM₁₀ concentration with a DustTrak and with a filter-based device equipped with a PM₁₀ size-selective inlet (Figure 9). Using corrected DustTrak concentrations, the horizontal flux of PM₁₀ was calculated by numerical integration of the flux through the tower (Figure 10).

A total of 13 sets (each consisting of multiple passes) of simultaneous measurements of PM₁₀ emissions by plume profiling and mobile system measurements were completed. In 9 out of the 13 sets the test vehicle travel speed was kept constant at either 25 mph (2 sets), 35 mph (4 sets), or 45 mph (3 sets). For sets with a common travel speed, the ratio of the average PM₁₀ plume profiling flux to the average mobile monitoring systems concentration signal was examined to determine if the ratio of the measured PM₁₀ emission factor to the raw test vehicle concentration signal ($EF_{10} / MSC_{10, TRAKER, v}$, see Equation 1) exhibited a dependence on test vehicle speed (See Figure 11). At first glance, the data in Figure 11 seem to strongly suggest that the $EF_{10} / MSC_{10, TRAKER, v}$ ratio does depend on speed (supported by an $R^2=0.99$). However, if the magnitudes of the standard error bars in the figure are examined, it becomes clear that the apparently strong regression relationship is just a coincidence and that the data do not allow for identifying a speed dependence. Therefore, it was assumed that K_{TRAKER} in Equation 1 is constant with speed and is equal to 0.54 ± 0.16 [(g/vkt)/(mg/m³)] based on all of the measurement sets available from the collocation of the plume profiling measurement with the mobile system measurement.

This calibration factor was retroactively applied to the 100 miles of roadway in Clark County, Nevada that were repeatedly measured earlier in 2005. Specific road segments of interest were also characterized using the silt loading measurement as described in the USEPA AP-42 5th edition document¹⁵. Figure 12 shows a comparison of emissions factors for several different road segments.

The entire 100-mile route was completed in about 3 to 4 hours of driving. In comparison, each measurement of silt represented in the figure required 3 to 4 hours of planning, setup, and execution.

An interesting outcome of the 2005 measurements on the Clark County roads was that it was possible to determine the repeatability of the TRAKER mobile system measurement¹⁶. Figure 13 shows the coefficient of variation (COV, defined as the standard deviation divided by the average and expressed as a percentage) by test vehicle travel speed. The COV was calculated separately for each segment of road from the averages of the four different days of measurements. For any given day the segment average was computed from all the valid measurements for that segment. There were a total of 645 segments that met the data completeness criteria. An underlying assumption was that the road dust emissions were essentially constant over the four-day period so that the COV represents a measurement uncertainty rather than actual emission factor variability. Figure 13 shows that as vehicle travel speed increases, the average COV decreases and the maximum COV for any road segment approaches 30%.

13.Method Performance

Data quality objectives for the average measurement precision, defined as the coefficient of variation over a large (>100) number of road segments, each at least 500 meters in length, varies from 14% to 26% depending on the speed of travel of the test vehicle (See Figure 13)¹⁶. Note that precision can generally be improved by increasing the number of data points for calculating an average value or equivalently, averaging over longer/multiple road segments. Measurement accuracy is defined with respect to the external standard, which in the present case is the plume profiling method. The standard error of regression between the horizontal flux measurements is an estimate of how well the signal from the mobile monitoring technique can be transformed into horizontal flux. The ratio of twice the standard error of the slope to the value of the slope estimate expressed as a percentage will provide a first order estimate of bias. This ratio varies and is best calculated from the specific calibration correlation between mobile monitor and flux measurement. In the specific case of the Clark County, Nevada study¹⁴, the biases for three different vehicle platforms (two versions of the TRAKER and one version of the SCAMPER) ranged between 22% and 34%. Twice this ratio (i.e., 44% to 68%) provides an estimate for the 95% confidence interval of the bias.

14.Pollution Prevention

Not applicable.

15. Waste Management

Not applicable.

16. Figures

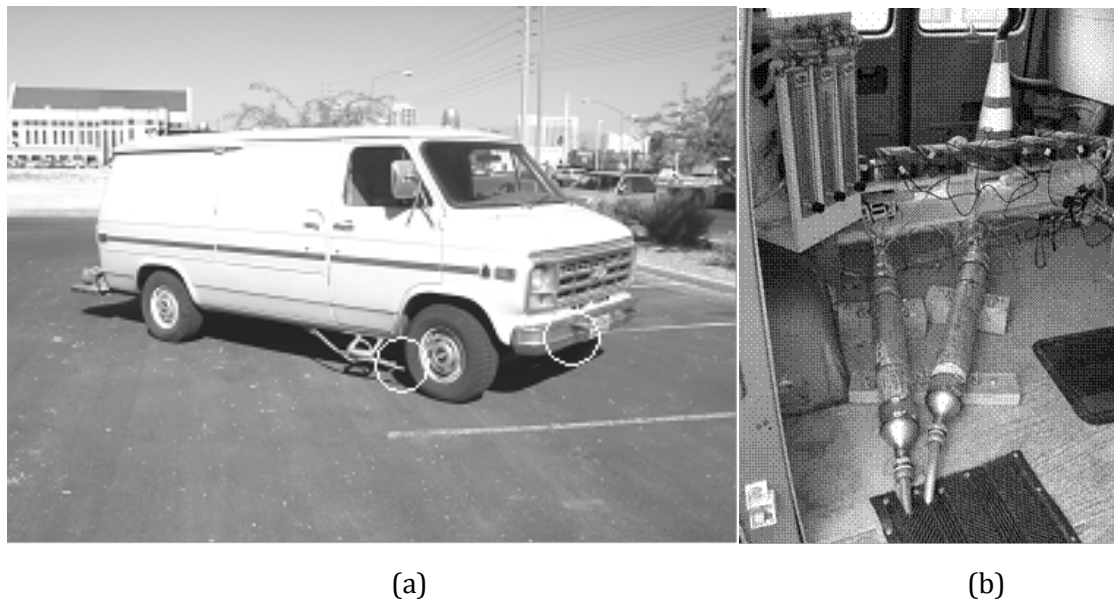
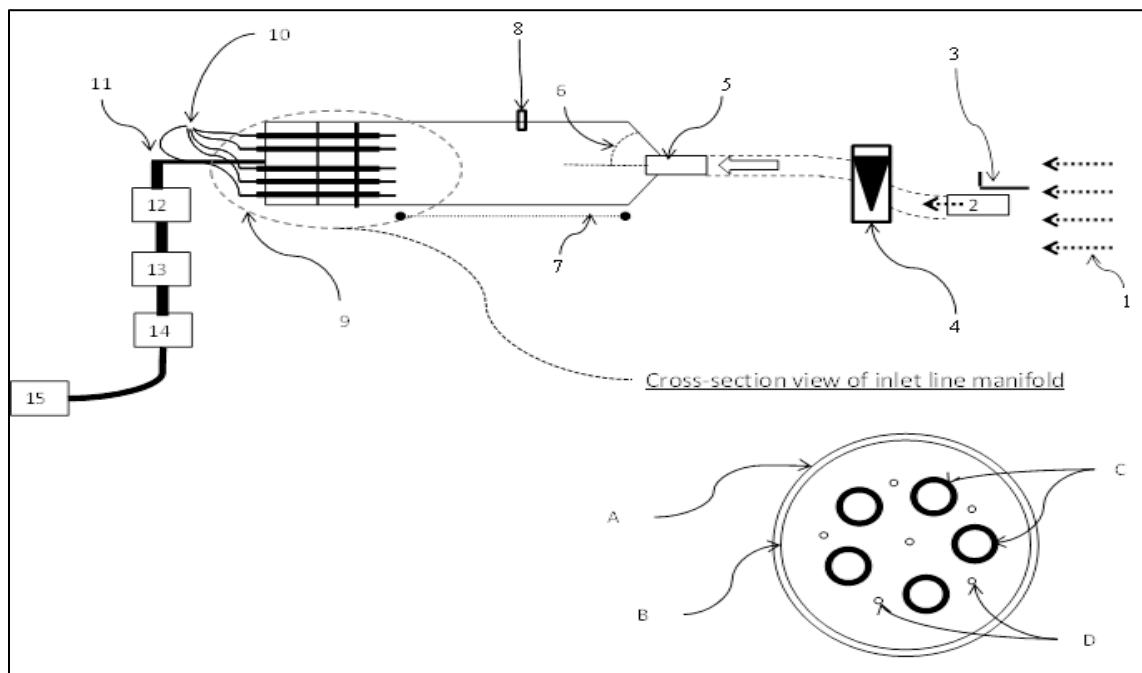


Figure 1. Example of PM sample inlet line that is located behind the front tire of a test vehicle. a. white circles highlight the sample inlet line behind the front passenger side tire to measure PM emitted by the interaction of the tire with the road and the sample inlet line protruding through the front bumper to measure the background concentration of PM; b. Sample Inlet lines enter the van body and the sample air is distributed to nephelometer-style instruments for measuring PM concentrations.



Figure 2. Example of PM sample inlet line that is located on a trailer behind the test vehicle. a. On the front end of the test vehicle, a sample inlet line is used to direct air to a nephelometer-style instrument that measures background PM; b. the sample inlet line located on the trailer behind the test vehicle is centered between the trailer tires. Both background and trailer sample inlet lines are equipped with an isokinetic sampling system.



Code	Description	Related parameter
		Units: m – meters; m/s – meters per second; lpm – liters per minute; kPa – kiloPascals,
1	Air speed near inlet	$V_{near-inlet}$: Air velocity near inlet by pitot tube (m/s)
2	Inlet for sample.	V_{in} : Air velocity inside inlet by pitot tube (m/s) Q_{in} : Air flow rate into sample plenum. (lpm) D_{in} : Inner diameter of inlet line and tube to plenum (m)
3	Pitot tube for measuring air speed near inlet aligned in the direction of inlet, upstream of inlet by 1 – 2 cm, and no more than 1 cm from edge of inlet.	$P_{pitot-inlet}$: Pressure difference measured by pitot tube (kPa) $V_{near-inlet}$: Air velocity near inlet by pitot tube (m/s)
4	Optional inline size selective device	$Q_{SSI, Design}$: Design flowrate (lpm) should be equal to Q_{in} .
5	Supply to plenum from inlet line	D_{in} : Inner diameter of inlet line and tube to plenum (m)
6	Half-angle of expansion between inlet line and sample plenum	ϕ : Half angle of expansion in Degrees
7	Mixing volume and sample plenum	D_{plen} : Inner diameter of sample plenum (m) L_{plen} : Length of sample plenum from beginning of constant diameter portion to first instrument sample port (m)
8	Pressure tap on plenum	P_{plen} : Gauge pressure/vacuum (kPa)
9	Manifold for instrument sample lines and flow-through air to pump: Expanded cross-section view appears below	
10	Sample lines to nephelometers and other instruments as appropriate	$Q_1, Q_2, Q_3, \dots, Q_n$: Flow rates through each of sample lines 1 – n (lpm)
11	Make-up air to flow meter and pump.	Q_{pump} : Flow rate of make-up air (lpm)
12	HEPA Filter for pump protection	Q_{pump} : Flow rate of make-up air (lpm)
13	Mass flow measurement device	Q_{pump} : Flow rate of make-up air (lpm)
14	Make-up air pump	Q_{pump} : Flow rate of make-up air (lpm)
15	Make-up air exhaust	Q_{pump} : Flow rate of make-up air (lpm)
A	Mixing volume/ plenum wall	
B	Seal between plenum and inlet manifold	
C	Instrument sample ports 1-n.	D_1, D_2, \dots, D_n : Diameters of ports 1-n (m) V_1, V_2, \dots, V_n : Air velocity inside ports 1-n (m/s) Q_1, Q_2, \dots, Q_n : Flowrates through ports (1-n) (lpm)
D	Perforations for make-up air to flow meter and pump.	Q_{pump} : Flow rate of make-up air (lpm)

Figure 3. Schematic view of inlet lines.



Figure 4. Photographs of TSI, DustTrak. a. Model 8520; b. Model 8530

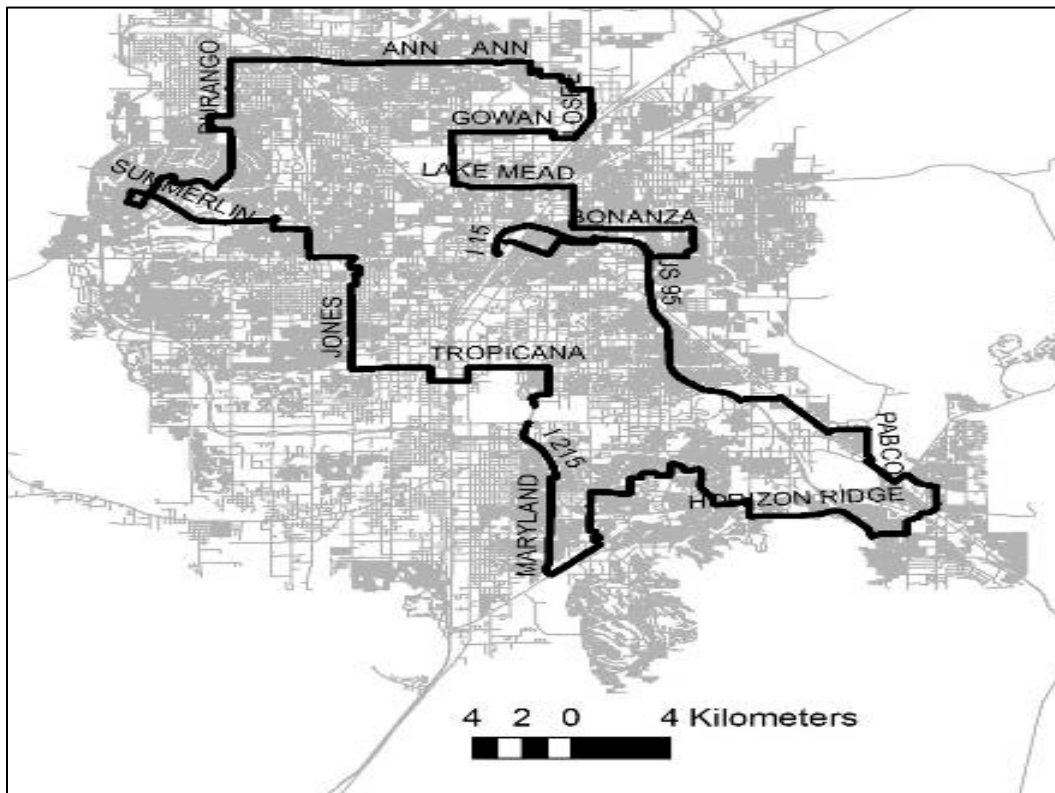


Figure 5. Example mobile system measurement route during Clark County, Nevada Phase II Study.¹¹

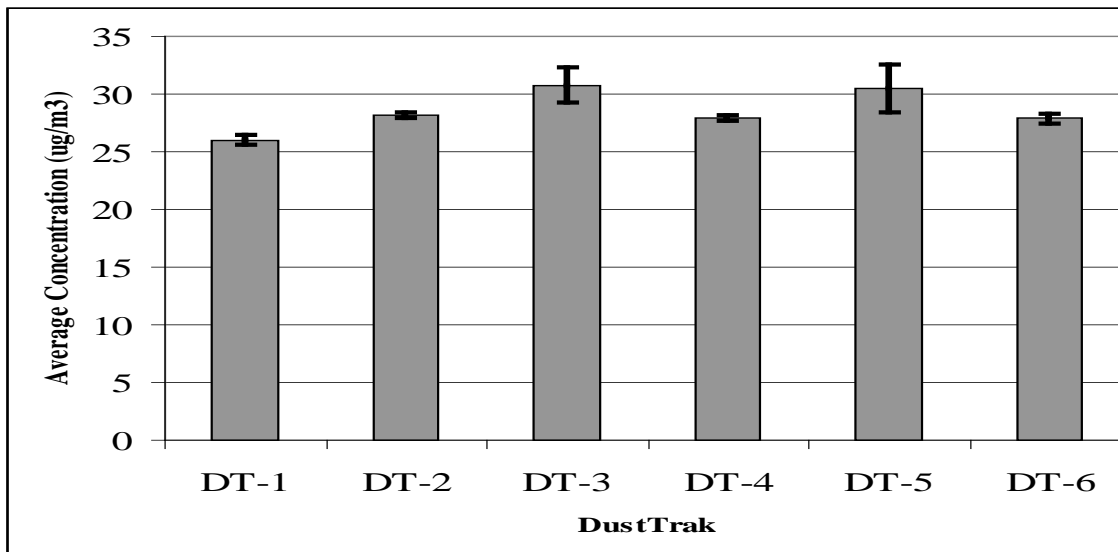


Figure 6. Example of average concentrations from six collocated DustTraks in an outdoor setting in Clark County, Nevada. Averages represent 1,140, one-second data points. Vertical bars represent the standard error. The ratio of the highest-reading unit to the lowest-reading unit is 1.19.

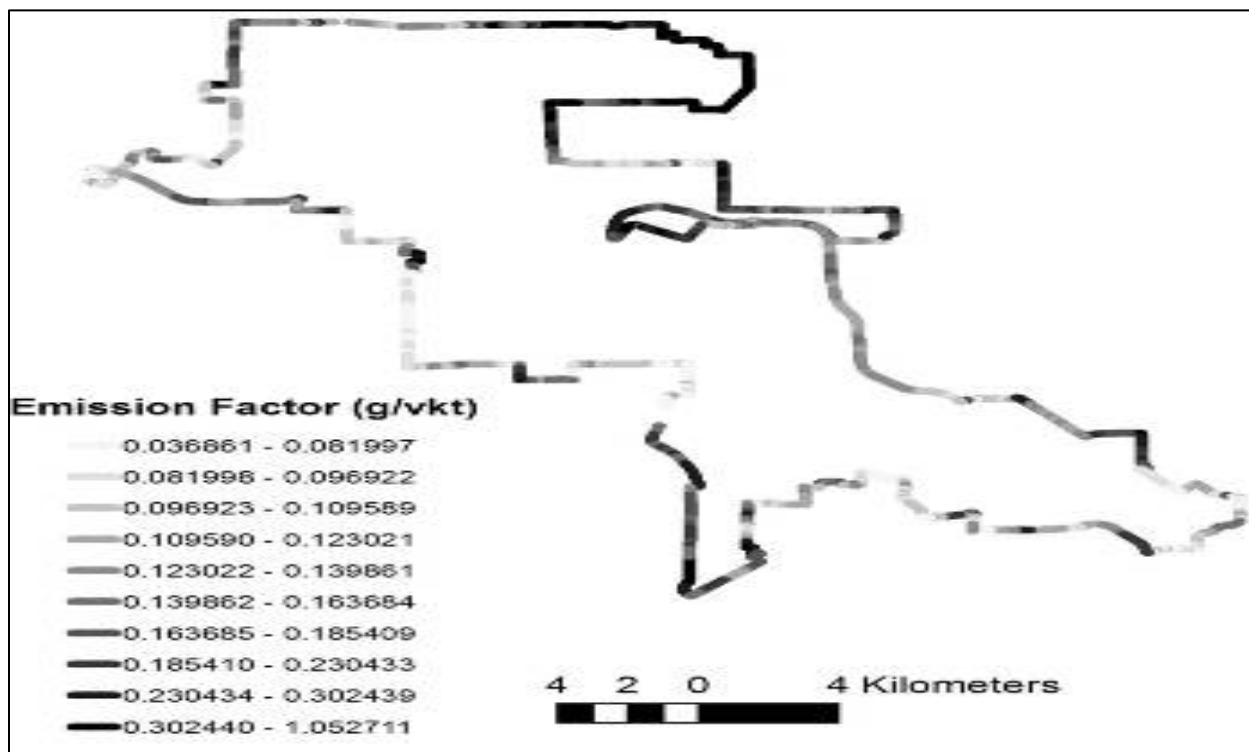


Figure 7. Example of variable shading used to convey emission factor distributions by roadway segments for the same test vehicle route shown in Figure 5.



(a)



(b)

Figures 8. Telescoping trailer-tow tower with instrumentation at 5 heights. Plastic enclosures contain DustTrak nephelometers (a). Weather proof enclosure at base is used for data collection. Tower is 9.8 meters in height when extended (b).

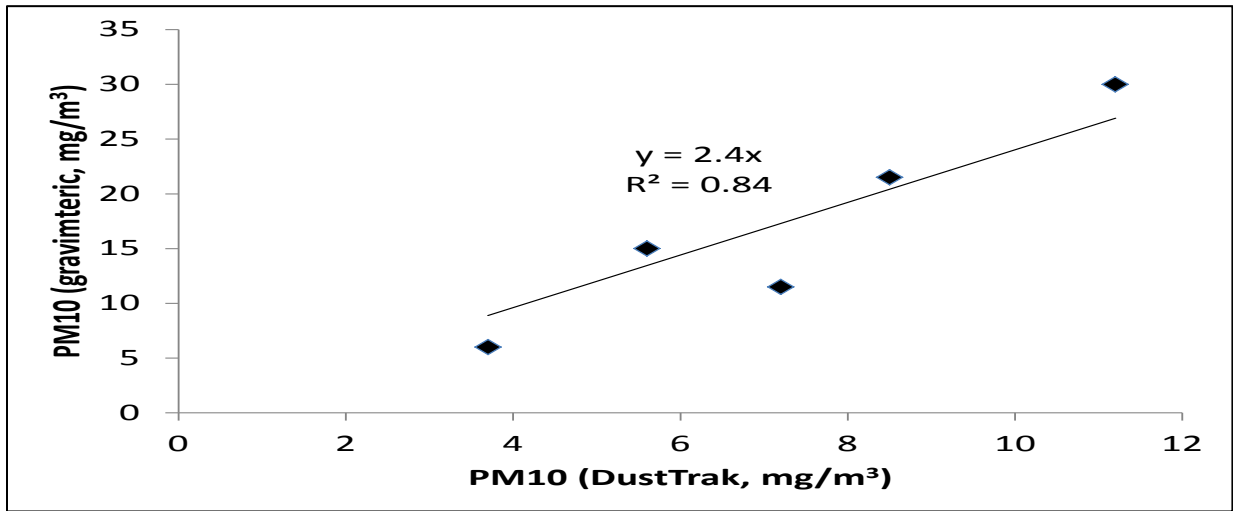


Figure 9. Results of comparing DustTrak-measured PM₁₀ with filter-based PM₁₀. Data are from material that was used to seed the test road during the Phase IV Clark County, Nevada study. The material was resuspended in a special chamber and simultaneously sampled by DustTrak and filter instruments.

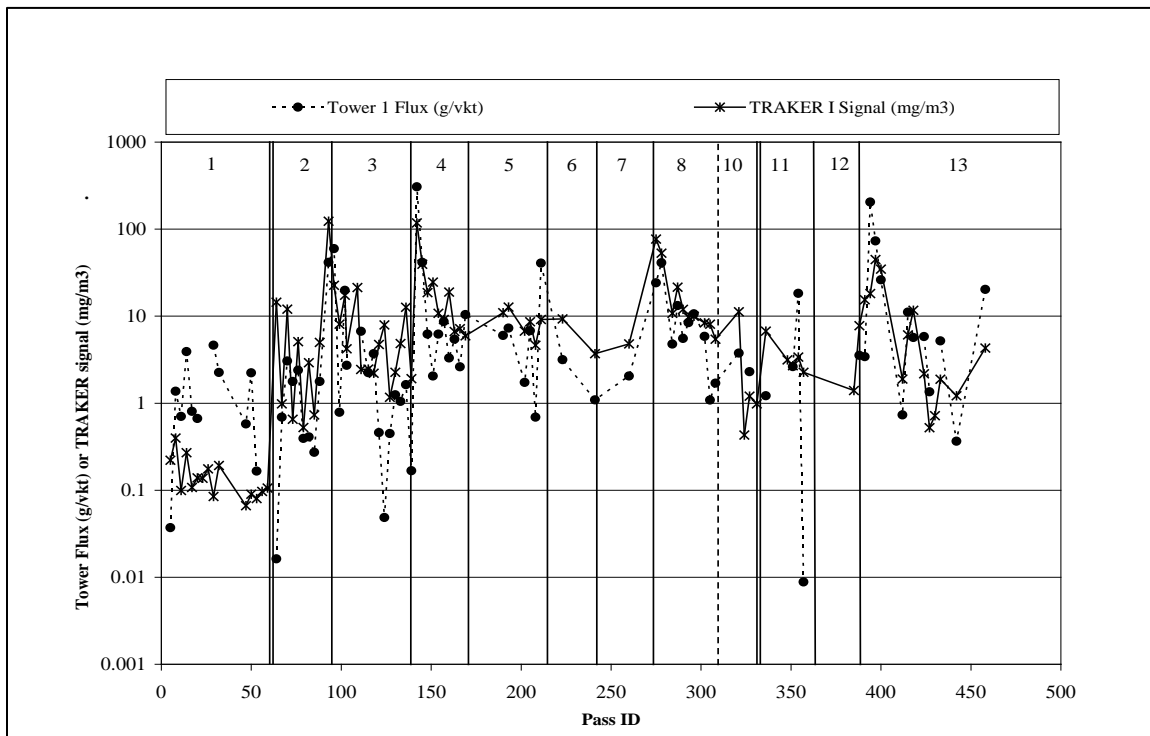


Figure 10. Time series of TRAKER raw signal as calculated in Equation 7 and the horizontal flux of PM₁₀ emissions as measured with a modified plume profiling technique. Data collected during Clark County, Nevada Phase IV Study¹³.

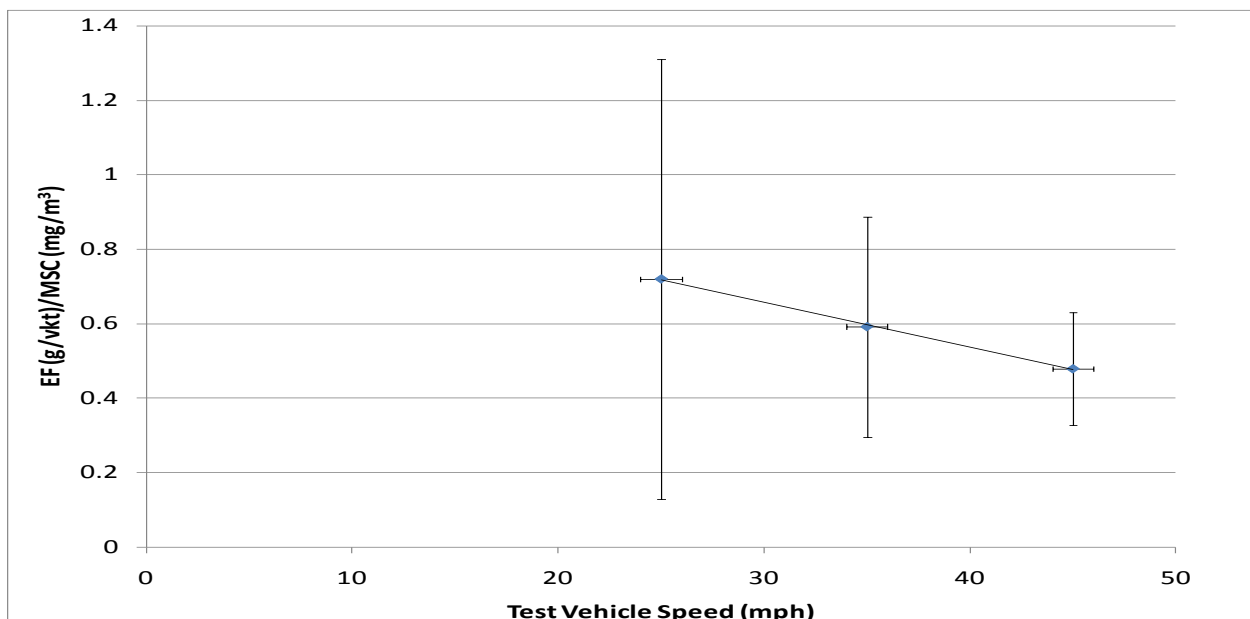


Figure 11. Ratio of externally based PM₁₀ emission factor to TRAKER mobile system PM₁₀ concentration signal. Data points represent averages from multiple sets of measurements (2 sets at 25 mph, 4 sets at 35 mph, and 3 sets at 45 mph). Vertical bars represent propagated standard errors, which provide a measure of how well a value is known.

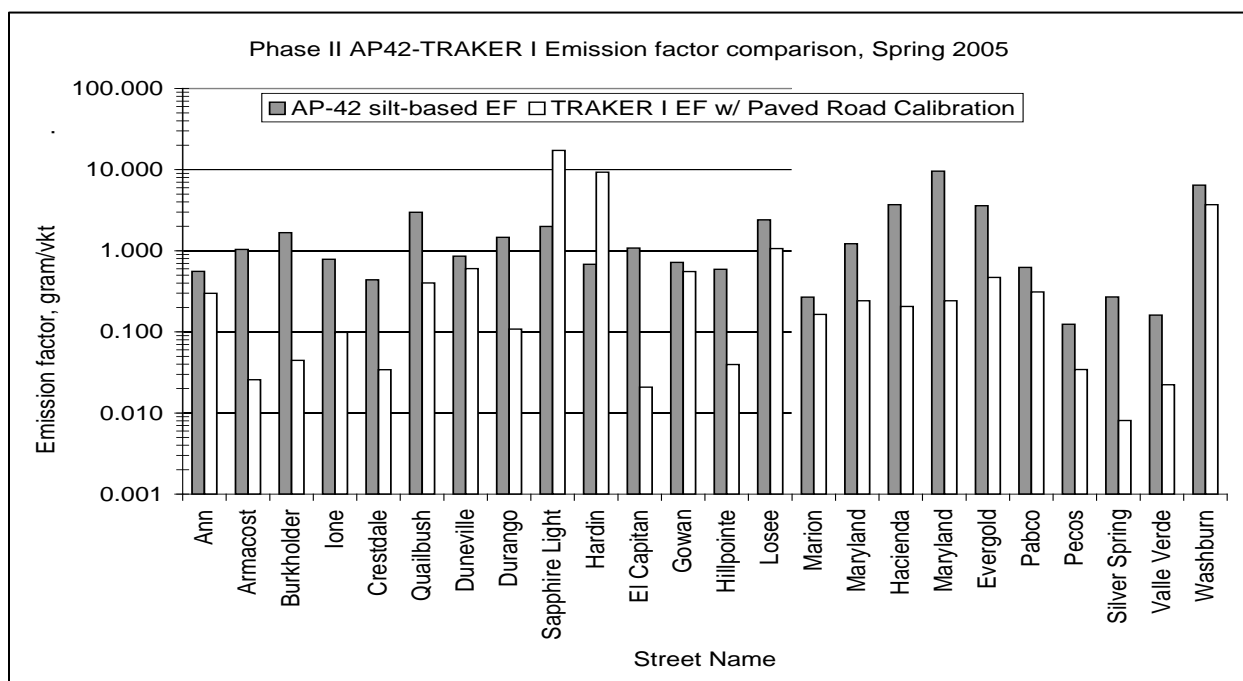


Figure 12. Comparison of PM₁₀ emissions factors measured using a calibrated TRAKER mobile system with emissions factors calculated using silt measurements with a version of the 5th edition AP-42 equations¹⁵. Reference: Langston et al.¹³.

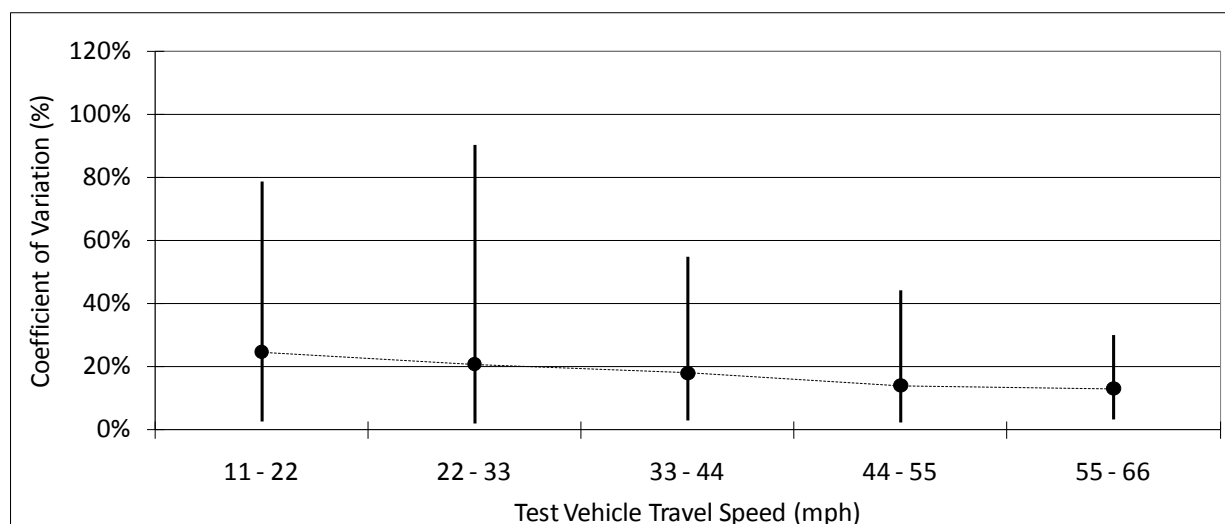


Figure 13. Coefficient of Variation of PM₁₀ road dust emissions factor measured with TRAKER mobile monitoring system segregated by speed range. The coefficient of variation (COV) is the standard deviation divided by the average expressed as a percentage. The data shown are from four measurements conducted on consecutive days in February 2005. COV was calculated for each road segment (total 645 segments). The dot in the figure shows the average COV for all road segments with travel speeds in the range shown. The vertical bars correspond to the maximum and minimum COVs within each speed range shown. Reference: Etyemezian et al.¹⁶.

17. References

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¹⁴ Langston, R., R.S. Merle Jr., V. Etyemezian, H. Kuhns, J. Gillies, D. Zhu, D. Fitz, K. Bumiller, D.E. James, and H. Teng (2008). Clark County (Nevada) Paved Road Dust Emission Studies in Support of Mobile Monitoring Technologies: Final Report, 122 pages.

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Appendix A

Mobile Monitoring Sample Pre-Test Checklist

Mobile Monitoring Pre-test Checklist

Test Date: 07/04/11 Time: 11:20 Operator: G.N.
 Test Name: VEGAS SURVEY Platform: TRAKER I
 Date and Location of Applicable Platform Calibration: 07/2010 JEAN, NV
 Speed Range of Applicable Platform Calibration: 15-45 MPH
 Raw Signal Range of Applicable Platform Calibration: 0.150 - 22.2 $\mu\text{g}/\text{m}^3$
 Flow Transfer Standard Last Calibration date: 06/30/11
 Sample Lines Clean Date Log Book Entry: 07/03/11

Item	Parameter	Entry	Comment/Exception
PM Monitor 1	Inlet line:	L1	
	Serial No:	54210	
	Cal Date:	04/20/11	
	Logbook OK and Cal w/in 1 year?:	Y	
	Connected to plenum and data line?:	Y	
PM Monitor 2	Inlet line:	L2	
	Serial No:	54221	
	Cal Date:	04/20/11	
	Logbook OK and Cal w/in 1 year?:	Y	
	Connected to plenum and data line?:	Y	
PM Monitor 3	Inlet line:	R1	
	Serial No:	54009	
	Cal Date:	04/20/11	
	Logbook OK and Cal w/in 1 year?:	Y	
	Connected to plenum and data line?:	Y	
PM Monitor 4	Inlet line:	R2	
	Serial No:	54616	
	Cal Date:	04/20/11	
	Logbook OK and Cal w/in 1 year?:	Y	
	Connected to plenum and data line?:	Y	
PM Monitor 5	Inlet line:	B1	
	Serial No:	55510	
	Cal Date:	04/20/11	
	Logbook OK and Cal w/in 1 year?:	Y	
	Connected to plenum and data line?:	Y	
PM Monitor 6	Inlet line:		NONE USED FOR
	Serial No:		PM 2.5 LINE
	Cal Date:		EXPECTED BACKGROUND
	Logbook OK and Cal w/in 1 year?:		VERY LOW. SPARE
	Connected to plenum and data line?:		INSTRUMENT IN REPAIR

Item	Parameter	Entry	Comment/Exception
Flow Rate Line L (Left)	Set Value (lpm) (A):	112	
	Onboard pitot report (lpm) (B):	112	
	Transfer Standard (lpm) (C):	114	
	B within 3% of A?:	Y	
	C within 3% of A?:	Y	
	Line Vacuum " H2O:	1.2	
Flow Rate Line R (Right)	Set Value (lpm) (A):	112	
	Onboard pitot report (lpm) (B):	112	
	Transfer Standard (lpm) (C):	110	
	B within 3% of A?:	Y	
	C within 3% of A?:	Y	
	Line Vacuum " H2O:	0.5	
Flow Rate Line B (Background)	Set Value (lpm) (A):	112	
	Onboard pitot report (lpm) (B):	112	
	Transfer Standard (lpm) (C):	108	
	B within 3% of A?:	Y	
	C within 3% of A?:	N	NO LEAKS BASED ON VACUUM
	Line Vacuum " H2O:	0.6	
GPS	Lock Achieved?:	Y	
Clock	Within 2 seconds of GPS LST?:	Y	
Logbook	In Vehicle?:	Y	

Post-Test Checklist

End Date: 07/04/11 Time: 14:41

Item	Parameter	Entry	Comment/Exception
Flow Rate Line L (Left)	Set Value (lpm) (A):	112	
	Onboard pitot report (lpm) (B):	111	
	B within 3% of A?:	Y	
	Line Vacuum " H2O:	1.1	
Flow Rate Line R (Right)	Set Value (lpm) (A):	112	
	Onboard pitot report (lpm) (B):	112	
	B within 3% of A?:	Y	
	Line Vacuum " H2O:	0.8	
Flow Rate Line B (Background)	Set Value (lpm) (A):	112	
	Onboard pitot report (lpm) (B):	112	
	B within 3% of A?:	Y	
	Line Vacuum " H2O:	0.4	
Date File	Start time with Noted Time?:	Y	FILE LENGTH 3.7 MB
	Stop Time with File write Time?:	Y	
Instrument check	Connected to plenum and data line?:	Y	