Vehicle-Based Road Dust Emissions Measurements

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ABSTRACT

TRAKER is a vehicle-based method for measuring road dust emissions. Particulate matter is sampled in front and behind a vehicle's tire and the difference in PM concentration (TRAKER signal) is used to infer the airborne flux of particles from the roadway.

Two independent tests indicated that the TRAKER signal increases as the cube of the speed for a given road dust loading. Simultaneous measurement of PM_{10} dust emitted behind the tires by TRAKER with PM_{10} flux measured using upwind/downwind towers suggested that the emissions factor for road dust was proportional to the cube root of the TRAKER signal. The results also showed a linear relationship between distance based unpaved road dust PM_{10} emission factors and vehicle speed.

Once calibrated with the flux tower measurements, the system was used to investigate temporal changes in emissions from paved roads in both the winter and summer in the Treasure Valley in Southwest Idaho. Measurement of road dust emissions potential after road sanding on dry roads indicated a 75% increase in PM_{10} emissions after 2.5 hours. This effect was short lived and emissions returned to their pre sanding levels within 8 hours of the sand application. Street sweeping with mechanical and vacuum sweepers was found to offer no immediate measurable reduction in PM_{10} emissions potential however long term effects of street sweeping on road dust emissions were not evaluated as part of this study.

The TRAKER signal was also associated with individual links (section of road) in the Traffic Demand Model network for the Treasure Valley, ID; each link was in turn associated with a number of characteristics including posted speed limit, vehicle kilometers traveled (vkt), road class (local/residential, collector, arterial, and interstate), county, and land use (urban vs. rural). The relationship between these characteristics and road dust emissions potential was assessed. The analysis suggested that while high speed roads are much cleaner (factor of 5.4 in summer), on a vehicle kilometer traveled basis, emissions from high and low speed roads are on the same order.

INTRODUCTION

Fugitive dust constitutes nearly two-thirds of the primary PM_{10} emissions according to the US National Emissions Trends inventory for 1997[1]. Particles suspended by vehicular movement on paved and unpaved roads are a major contributor to fugitive dust emissions. Yet, traditional methods for quantifying road dust emissions have been a subject of controversy in recent years[2,3]. The most common method involves measuring the silt loading or silt content from road surfaces by vacuuming (paved roads) or sweeping (unpaved roads). Laboratory analysis of samples requires dry sieving the bulk material through sequentially smaller sieves. The material that passes through a 200 mesh sieve is the silt fraction of the sample and corresponds approximately to particles with diameter less than 75 μm. The total amount of silt on a section of road (paved roads) or the fractional silt content of the bulk sample (unpaved roads) is then used to estimate the PM_{10} emissions[4]. A limitation of the silt loading technology is that measurements are expensive and time consuming to acquire. This limits the number of data points used to represent road dust emission potential over an air shed. Moreover, silt loading measurements are usually collected over a brief (< 1 month) period and are unlikely to reflect seasonal changes in emission potential.

In recent years new method for estimating road dust emissions has been being developed[5]. The TRAKER (Testing Re-entrained Aerosol Kinetic Emissions from Roads) allows for measurement of PM_{10} and $PM_{2.5}$ emissions from a large number of roads with great economy. The concentration of airborne particles in a specific size range is monitored with particle sensors that are mounted behind the front tires of a vehicle. These particle sensors are influenced by the road dust generated from the interaction of the vehicle tire and the road. A background measurement of particle concentrations is obtained simultaneously at a location on the vehicle away from and in front of the tires. The difference in the signals between the influence monitors and the background monitor is related to the amount of road dust generated. This paper summarizes recent developments of the TRAKER technology and describes some of the findings resulting from these measurements.

BODY

TRAKER Configuration

The TRAKER results shown in this paper were collected onboard a 1979 Chevy G20 Cargo Van platform (Figure 1 a and b). The vehicle is equipped with three permanently-mounted, metal tubes that act as inlets for the onboard instruments (Figure 1c). Two of the inlets are located behind the front left and right tires and are used to measure the road dust emissions from those tires. The third inlet runs underneath the body of the van and extends through a hole in the front bumper. This “background” PM concentration measurement is subtracted from the measurements behind the left and right tires to account for dust and exhaust emissions from other vehicles on the road. Each of the three plena is attached to two DustTraks (TSI, Model #8520), one with a 10 μm size selective inlet (SSI) and the other with a 2.5 μm SSI, and a particle size analyzer (PSA) manufactured by GRIMM Technologies (Model# 1.108).

A global position system receiver (Ashtek, ProMark GPS) provides the position, speed, and acceleration of the TRAKER vehicle in 1-second intervals. All the data generated by the TRAKER instruments are collected and displayed by an onboard computer in real-time (Figure 1 d and e). A more detailed description of the TRAKER instrumentation is described elsewhere[6].

Relationship of TRAKER Signal to Vehicle Speed

The variation of the TRAKER signal with vehicle speed was assessed during two similar tests on paved roads, one at Fort Bliss, TX, and the other at a rural suburban location in the Treasure Valley near Boise, ID. At Fort Bliss, a straight 1,200 m section of road was traveled in the northbound direction only. Three passes were completed at each of six speeds (4.5, 8.9, 13.4, 17.9, 22.3, and 26.8 m/s) for a total of 18 passes. The TRAKER signals, both from DustTraks and PSAs, were averaged over each pass and measurements from left and right inlets were averaged together.

In the Treasure Valley, a straight 500 m section of two-lane road was selected for testing. Passes were run over the same range of speeds as in the Fort Bliss tests. The eastern lane of the road was surveyed with the vehicle traveling in both northbound and southbound directions. Using this approach, both the left and right inlets sampled the same tracks on the road. TRAKER signals from the left and right inlets were averaged separately by pass.

The resulting TRAKER signals from the Ft. Bliss and Treasure Valley speed tests were regressed against a power function of speed using the following equation:

Equation (1) $T = T_T - T_B = \mathrm{a}\, s^{\mathrm{b}}$

where T_T is the aerosol concentration at the vehicle tire, T_B is the background aerosol concentration measured through the vehicle's front bumper, and s is the speed of the vehicle. The parameters a and b were iteratively calculated by minimizing the least squares error between the observed and predicted values.

Figure 2 a and b show the regression for DustTrak PM_{10} measurements from the Treasure Valley and Ft. Bliss speed tests, respectively. Speed explains 97% of the variability of the average measurement from each vehicle pass on the same road segment for the Treasure Valley test (i.e., $R^2 = 0.97$) and 92.3 % of the variability for the Ft. Bliss test. When traveling over the same roadway, the TRAKER signal increases proportionally with vehicle speed raised to the 3rd power.

TRAKER Comparison with Instrumented Flux Towers

Unpaved road emission flux experiments were conducted at Ft. Bliss from May 18 through May 24, 2001. The procedure was based on an upwind/downwind technique that has been used by other investigators[7,8]. Three towers were set up collinearly and perpendicular to a 200 m section of unpaved road that was oriented in the north-south direction. Historical meteorological data indicated that winds at this time of year in this area were predominantly from the west. The upwind tower was 9 m high and 30 m from the road.

Each downwind tower was instrumented with four DustTraks that were spaced logarithmically (see **Error! Reference source not found.**a) in the vertical direction starting at 1.25 m above ground level (AGL). The DustTraks were equipped with PM_{10} inlets and measured particle concentrations at intervals of 1 second. Five anemometers, one wind vane, and one temperature probe were mounted on the upwind tower in order to characterize the local meteorological conditions. The meteorological data were averaged and stored onto a datalogger (Campbell Scientific, Model # 10X) in 5-minute intervals.

The emission factor per vehicle pass for each downwind tower was calculated using the following equation:

Equation (2) $$EF = \cos(\theta)\sum_{i=1}^{4} u_i\, C_i\, \Delta z_i\, \Delta t$$

where EF is the emission factor of PM_{10} in grams per vehicle kilometer traveled, θ is the angle between the wind direction and a line perpendicular to the road, i is one of the four positions of the monitors on the tower, u_i is the average wind speed in m/s over the interval represented by the i^{th} monitor, C_i is the average PM_{10} concentration in mg/m^3 as measured by the i^{th} monitor over the period Δt, Δz in m is the vertical interval represented by the i^{th} monitor, Δt in s is the duration that the plume impacts the tower.

Figure 3 show the relationships between emission factors calculated from the towers and vehicle speed. The lines in the Figure represent the best fit least squares linear regression equation of emission factor vs. speed with a forced intercept equal to zero. The linear relationship between emission factor and vehicle speed is consistent with a recent analysis of unpaved road emission factors from other studies and vehicle speed[9]. The dependence of road dust emissions on vehicle speed critical to accurate estimation of road dust emissions. Travel speeds on residential roads are approximately 1/3 of those on freeway interstate roads. Thus, neglecting vehicle speed can result in emission estimation errors by as much as a factor of 3.

Figure 4 is a plot of the average emission factor from two down wind towers (9 m and 50 m from the road) vs. the TRAKER signal for PM_{10}. The result of a log-log regression also appears in the figure and indicates that the emission factor is proportional to the cube root of the TRAKER signal. This relationship can be independently and more generally deduced by considering the dependence of both the TRAKER signal and the road dust emission factors on vehicle speed. The TRAKER signal increases with the cube of the speed (Figure 2) while the emission factor increases linearly with speed (Figure 3). Therefore, the emission factor is proportional to the cube root of the TRAKER signal:

Equation (3) $$EF = kT^{1/3}$$

where T is the TRAKER signal, EF is the emission factor, and k is a constant (equal to 8.8 g/vkt for the TRAKER vehicle based on the regression shown in Figure 4). Assuming that the relationship beteen TRAKER signal and emission factor is consistent on paved roads as well as unpaved roads, the relationships in equations 1 and 3 permit the inference of a road dust emissions potential (i.e. θ = EF/s) for roads surveyed by the TRAKER vehicle.

The emission potential is used hereafter to describe the dirtiness of a road. Since the emission factor is dependent on the speed of the vehicle traveling on the road, it is not a property of the road itself. The emission potential with units of (g/vkt)/(m/s) represents the downwind flux of particles that would result from the TRAKER vehicle traveling over the road divided by the vehicle's speed.

Equation (4) $$\theta = \frac{kT^{1/3}}{s}$$

The emission potential is independent of the speed of the vehicle traveling over the road is a property of the state of the road.

Effects of Sweeping and Sanding on Paved Road Dust Emission Potential

Given the relationship between the TRAKER signal *T*, the vehicle speed *s*, and the emission potential *EP*, TRAKER was used to investigate the effects of wintertime road sanding and subsequent street sweeping on the emission potential on paved roads in Boise, ID.

The winter road sanding experiment took place on the morning of March 15, 2001 (Thursday) at two different locations in the Boise area. The first test location was on the rightmost eastbound lane on Chinden Road between 50th and 42nd St (Figure 5). In this area, Chinden is a principle arterial with commercial zoning on both sides of the street. The road has four traffic lanes and a turn lane in the middle. The shoulder of the road is paved and at least 1 m wide in areas where there are no ingress-egress points such as driveways and intersections. Traffic counts obtained by the Ada County Highway District on September 24, 1997 (Wednesday) were 14,192 vehicles per day in one direction or approximately 7,000 per lane. The local traffic demand and forecasting model calculated year 2001 average daily traffic (ADT) of 23,392 in both directions or approximately 6,000 ADT per lane. The standard error of the regression of modeled ADT versus actual traffic counts in Ada county is ~2000 ADT or 30% of the average modeled ADT. Sections 1 through 3 were 500 m, 600 m, and 600 m long, respectively. The posted speed limit on this road is 45 mph (20 m/s or 72 kph).

The second location was the westbound lane on Rose Hill/Franklin Road between Owyhee and Orchard. Rose Hill Road turns into Franklin Road west of Roosevelt. This road section has 2 traffic lanes and a turn lane. It is located in a residential neighborhood with curbing on both sides. Modeled 2001 ADT for the road was 17,910 in both directions or approximately 9,000 ADT per lane. The posted speed limit on Rose Hill/Franklin is 35 mph (16 m/s or 56 kph). Lengths of sections 1 through 3 were 400 m, 400 m, and 800 m, respectively.

Both roads were surveyed twice with the TRAKER vehicle early on the morning of March 15, 2001. After initial surveying, a sand truck was operated at 5 mph (2.2 m/s or 8 kph) over all sections of both roads. The rate of sand flow was measured at 2.0 kg/s. The swath of sand thrown from the truck was estimated to span 6 meters in diameter. Visual observation of the sand on the test sections indicated that the truck did not uniformly disperse the sand across the lane. The sand in the truck was wet and had a tendency to clump as it was applied. While the sand deposits were not uniform in the across-lane direction, there is no basis for presuming that any test section received more or less sand than the others.

Immediately after sanding, a vacuum sweeper (Elgin Whirlwind) began operating on Section 1 and a mechanical broom sweeper (Johnson model HSD) began operating on Section 2. Sweeper operators were instructed to follow routine sweeping procedures to collect all visible sand within their respective sections. The mechanical broom sweeper uses a broom to lift material from the street surface onto a conveyer belt. The material is then delivered to a collection hopper. The vacuum sweeper uses a gutter broom to loosen dirt and debris from the road surface and direct it to a vacuum nozzle that sucks it into a hopper. Section 3 was used as a control and was not swept after sanding. Once the sand had been swept from sections 1 and 2, the TRAKER vehicle resurveyed the test sections. TRAKER surveys were repeated at several intervals after sweeping to evaluate how emissions from the three test sections evolve over time.

Figure 5 shows the locations and results of the winter sanding/sweeper tests. Because Chinden Street (left panels) was also on the TRAKER loop, this location was sampled on five different occasions prior to the experiment. The figure shows that prior to the sanding/sweeping test, the emission potential for the three test sections from Chinden varied less than 15%.

Ten minutes after sand application, no significant change was detected in the emission potential from the road surface with the exception of the vacuum swept portion of Chinden. The emission potential from this section dropped from 0.47 to 0.27 [g/vkt]/[m/s]. This initial drop in potential is probably due to moisture from the sand on the road; the first section on Chinden received the sand that had been sitting at the bottom of the truck hopper overnight and was probably wetter than sand that was applied later in the test (i.e on road sections 2 and 3).

At 2.5 hours after sand application, the emission potential had increased at all test sections with respect to the baseline value prior to sanding. At the Chinden test area, the vacuum swept section S1 emission potential increased by 26%, the mechanically swept section S2 emission potential increased by 42%, and the unswept section S3 emission potential increased by 46%. At the Rose Hill/Franklin test area; emission potentials increased 69% on the vacuum swept section, 63% on the mechanically swept section, 61% on the unswept section.

Approximately 8 hours after the initial sanding and sweeping, the emission potentials from all sections of both roads had returned to within 15% of their pretreated levels. At this time, the travel lanes of all road sections were clear of visible sand. However much of the sand in the unswept sections had migrated to the untraveled portions of the road (i.e. shoulders and center turn lanes). Sand was not visible on the sections where the road had been swept using either a vacuum or mechanical sweeper. Traffic counter data from Rose Hill on 03/16/01 indicated that 40% of the measured ADT or ~2,000 cars traveling at 35 mph (16 m/s or 56 kph) passed over the road in the first 8 hours. Similarly, on Chinden it is estimated that 2,000 to 2,500 cars traveling at 45 mph (20 m/s or 72 kph) passed over each lane in the first 8 hours.

The results of the winter sanding and sweeping experiment indicate that the direct impacts of road sanding on PM_{10} emissions are short lived lasting no more than 8 hours or 2,500 vehicle passes. While both the vacuum and mechanical sweepers did an excellent job collecting the visible sand on the roads, the systems tested were ineffective at removing the source of the PM_{10} road dust particles. The application of sand initially increased PM_{10} emissions from the roads, though only for a short. On unswept sections, sand was transported to the shoulders within a few hours of application. On the short time-scale of these experiments, it was not possible to determine whether or not sand blown to the side of the road can serve as a long-term reservoir for subsequent PM_{10} emissions.

Emission Inventory Implications of Emission Potentials Measured by TRAKER

The TRAKER vehicle was used to evaluate spatial patterns and trends in emissions potential for paved road in the Treasure Valley, ID. During the winter season (February 26, 2001 to March 17, 2001) and the summer season (July 10, 2001 to July 28, 2001), paved road were surveyed in the Treasure Valley, ID to collect a dataset that would capture emission potential variations by season, road type, and traffic volume.[10,11]

More than 400 km of roads were surveyed. The emission potential was calculated for each valid data point using Equation (4). It was assumed that the emission potential for the TRAKER vehicle is representative of the vehicle fleet ($\theta_{fleet\_average} = \theta_T$). That is, all vehicles were assumed to behave like the TRAKER (1979 Chevy van) with regard to road dust emissions. While this assumption may introduce biases in calculating absolute PM_{10} emissions, it should not affect the inter-comparison of emission potentials among roads with different attributes.

The Community Planning Association of Southwest Idaho (COMPASS) maintains a GIS-comaptible Traffic Demand Model (TDM). The TDM is used for traffic analysis and contains information on road classifications, speeds, number of lanes, and vehicle volume. Within the TDM, major roadways such as arterials, collectors, and interstates, are physically represented as a series of nodes that are connected by links, one per direction of travel. For TRAKER measurements on such roads, a software utility for joining spatial data was used to associate the GPS coordinates of each TRAKER measurement with the corresponding link within a 10 meter radius.

Emission potentials based on one-second TRAKER measurements were averaged by link separately for the winter and summer seasons. Only links with 10 or more valid measurements per season were considered. In addition to the information available from the TDM, each link was labeled by county and by setting. Using year 2000 census data, the setting was considered "urban" if the link was located in a census tract with a population density greater than 385 per km^2 and "rural" otherwise.

The effects of vehicle speed and traffic volume on road dust emission potentials were assessed for all non-residential roads. When the effect of vehicle speed was factored out of the relationship, traffic volume was not found to have an effect on emissions potential. The dependence of emission potentials on speed was examined using the assumption of an exponential relationship which has the form:

Equation (5) $\theta = C_{C,S,T} \cdot e^{-c_2 s}$

or equivalently,

Equation (6) $\ln(\theta) = \ln C_{C,S,T} - c_2 \cdot s$

where θ is the emission potential in units of [g/vkt]/[m/s], $C_{C,S,T}$ is a constant that is specific to the county (Ada or Canyon), setting (urban or rural), and time of year (winter or summer), s is the traffic speed, and c_2 is a positive empirical constant. The least-squares residual fit to Equation (5) is shown Figure 7 for wintertime urban measurements in Ada County. A thorough analysis of the additional factors affecting road dust emissions potential is provided by Etyemezian et al.[11]

While the assumed exponential relationship captures the shape of the emission potential speed curve, there is substantial scatter associated with the curve fit. Some of the scatter may be due to the precision of the TRAKER data. Etyemezian et al.[6] report that for speeds between 10 m/s and 30 m/s, the precision of the TRAKER measurement is between 10% and 20%. However, their analysis was for two different sections of road with lengths of 500 m and 1,200 m. Over links that are shorter, the uncertainty is likely to be larger since fewer 1-second data points would be included in the average for the link. In addition to the TRAKER precision, the scatter in the data may be partly caused by parameters other than the speed, county, season, and setting. Factors not explicitly accounted for on a link-by-link basis include the presence of trackout/carryout from construction sites and unpaved roads, the condition of the road with respect to maintenance requirements, the proximity of known fugitive dust sources such as mines and farmland, and whether or not the road shoulders are paved or curbed. The lane of travel of the TRAKER at the time of the measurement may also have an effect.

CONCLUSIONS

The results presented here indicate that the TRAKER has the ability to measure a road's potential to emit dust. Comparison of measurements obtained by the TRAKER on an unpaved road with simultaneous measurement of road dust emissions flux downwind of the same road suggests that emission factor are proportional to vehicle speed and to the cube root of the TRAKER signal. This result is in agreement with expectation since the TRAKER signal (i.e., the PM_{10} dust concentrations measured behind the front tire minus the background concentration) is related to the speed raised to the third power. The TRAKER has been calibrated over a small range of conditions - unpaved road, 5 to 20 km/hr, neutral to slightly unstable conditions, and open desert topography.

The application of sand for traction control on dry roads was found to increase PM_{10} emissions by up to 75% 2.5 hours after application. The dust emission effects of sanding were short lived and emissions returned to the pre-sanding levels within 8 hours. The rapid removal rate of the sanding material from the road surface suggests the that the levels of loading on street surfaces are dynamic. If fine material loading on the road (i.e. PM_{10} sized particles) exhibit a similar behavior, the loading of suspendable material must be recharged quickly or else there would be negligible reservoir of fine material on the road. The paved road PM_{10} material on the road surface likely exists at an equilibrium with a balance of deposition and emission processes. Deviations from this equilibrium appear to be short lived (on the order of several hours) on typical urban roads.

Emission potentials were compared with average travel speed for hundreds of road segments throughout the Treasure Valley, ID. A definitive relationship between typical vehicle speed of the road segment and emissions potential was observed. Higher speed roads had lower emission potentials than lower speed roads. This trend has a neutralizing effect on the fact that distance based emission factors increase with vehicle speed. Consequently, emissions factors with units of g/vkt are relatively consistent across a wide variety of roads from residential streets to freeways.

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KEYWORD

Road Dust

PM_{10} Emission Factors

Fugitive Dust

TRAKER

FIGURES

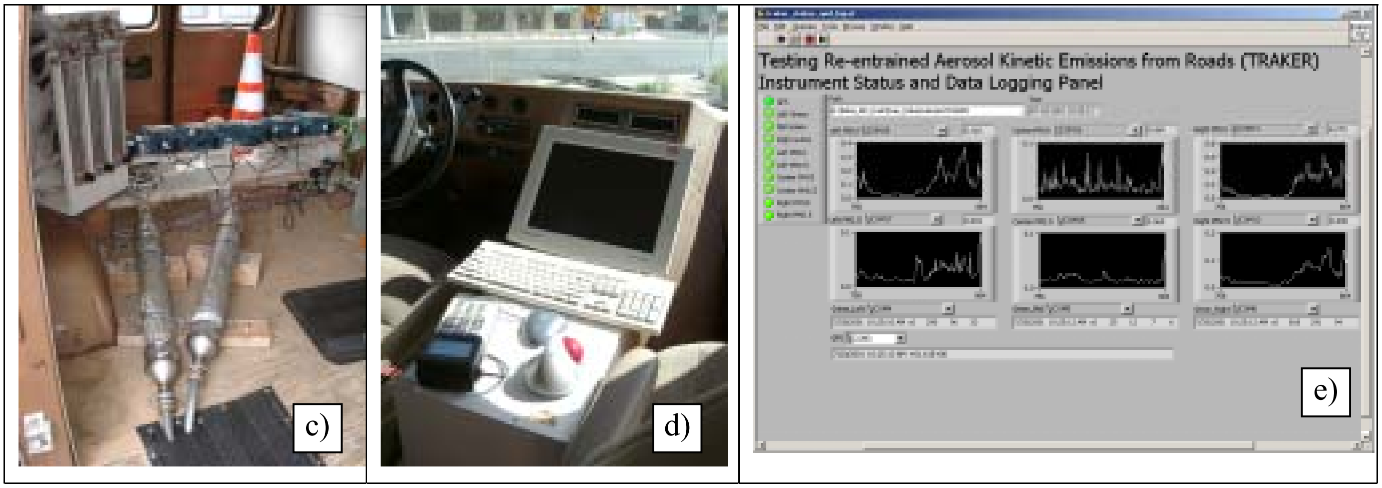
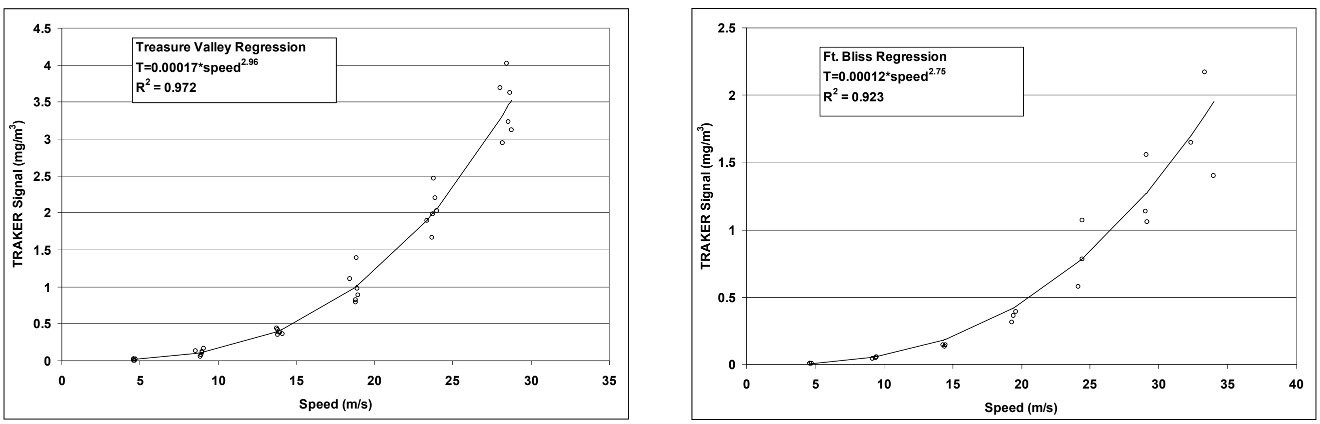


Figure 1. Images of TRAKER vehicle. Panel a shows the front view of vehicle with inlets mounted behind both tires and on front bumper. Panel b shows rear view of vehicle with generator and vacuum pumps. Panel c shows interior with manifolds directing sample air to a TSI DustTraks and Grimm 1.108 particle monitors. Panel d shows onboard display. Panel e shows screenshot of real time data acquisition software.



a. b.

Figure 2. Relationship between differential DustTrak measurements and vehicle speed for tests conducted on a common road section in the Treasure Valley, Idaho. R^2=0.97; b. Example relationship between differential DustTrak measurements and vehicle speed for tests conducted on a common road section in Ft. Bliss, TX. R^2=0.92.

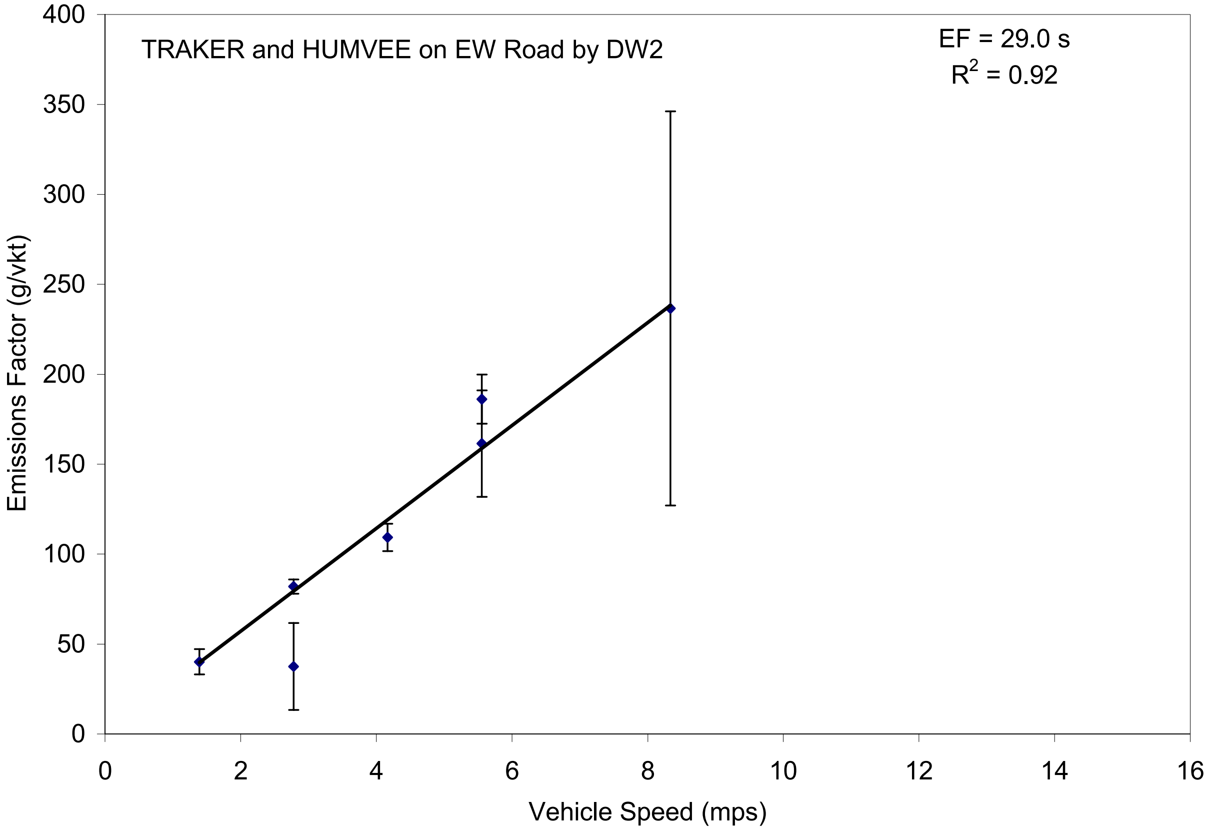


Figure 3. Relationship between vehicle speed and distance based emission factor measured on a tower 50 m downwind of an unpaved road in Ft. Bliss military base near El Paso, TX.

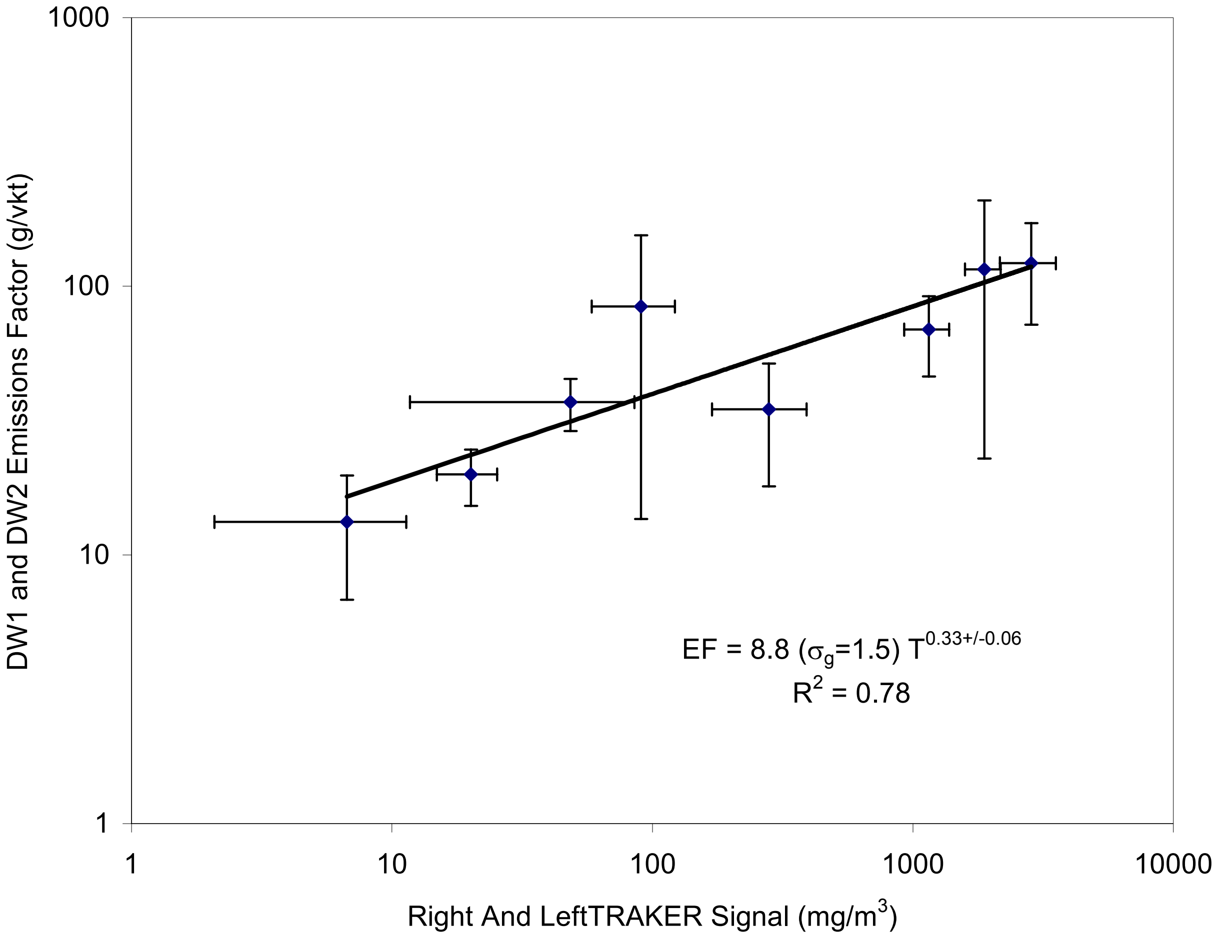


Figure 4. Relationship between TRAKER signal and emission factors measured at varying vehicle speed on an unpaved road on the Ft. Bliss military base.

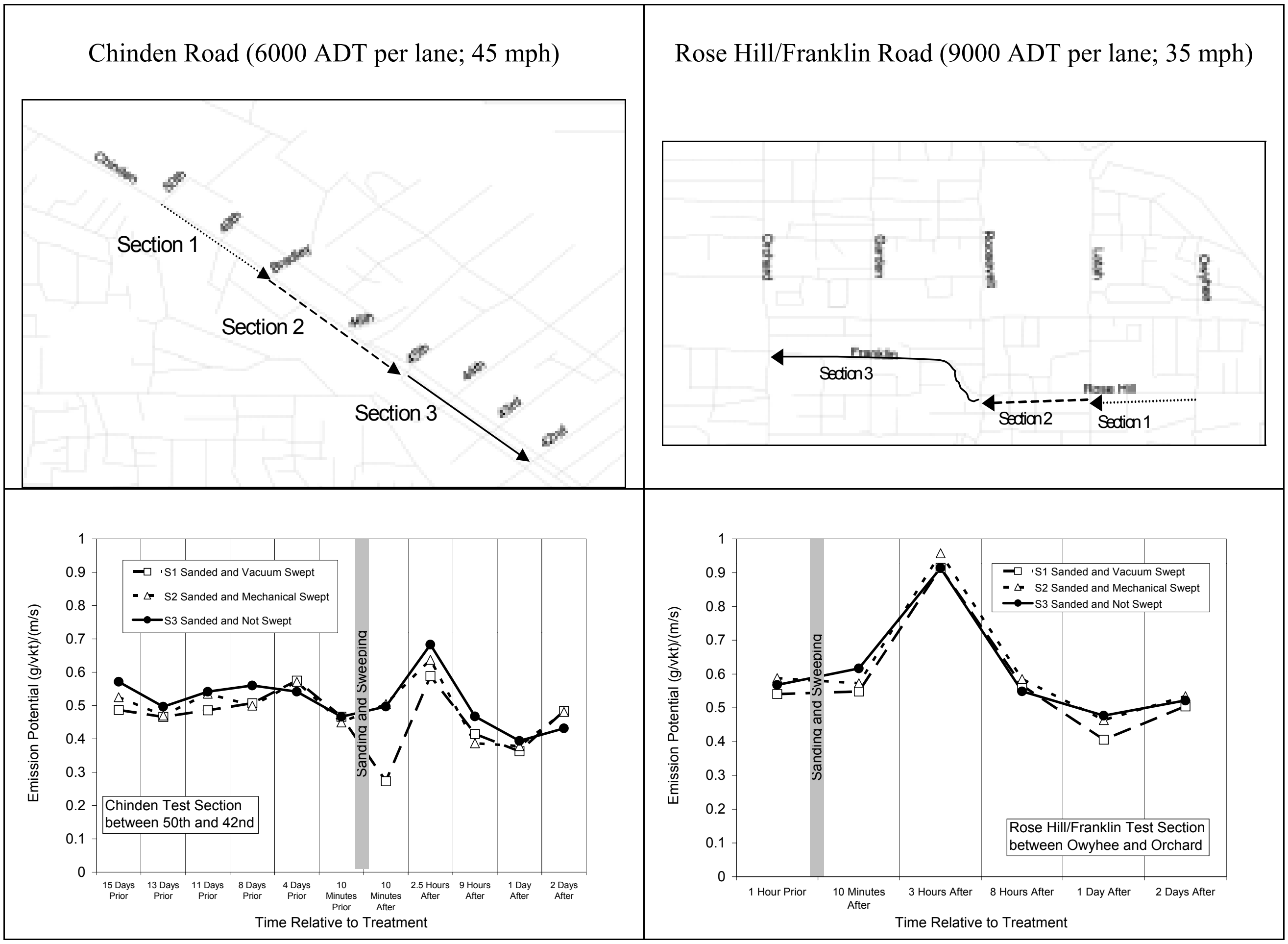


Figure 5. Maps of road sanding and sweeping experiments in Boise, ID. Lower panels show changes in road dust emission potential prior to and after road sanding. Emission potentials from roads swept immediately after sanding show no reduction when compared to the unswept sections.

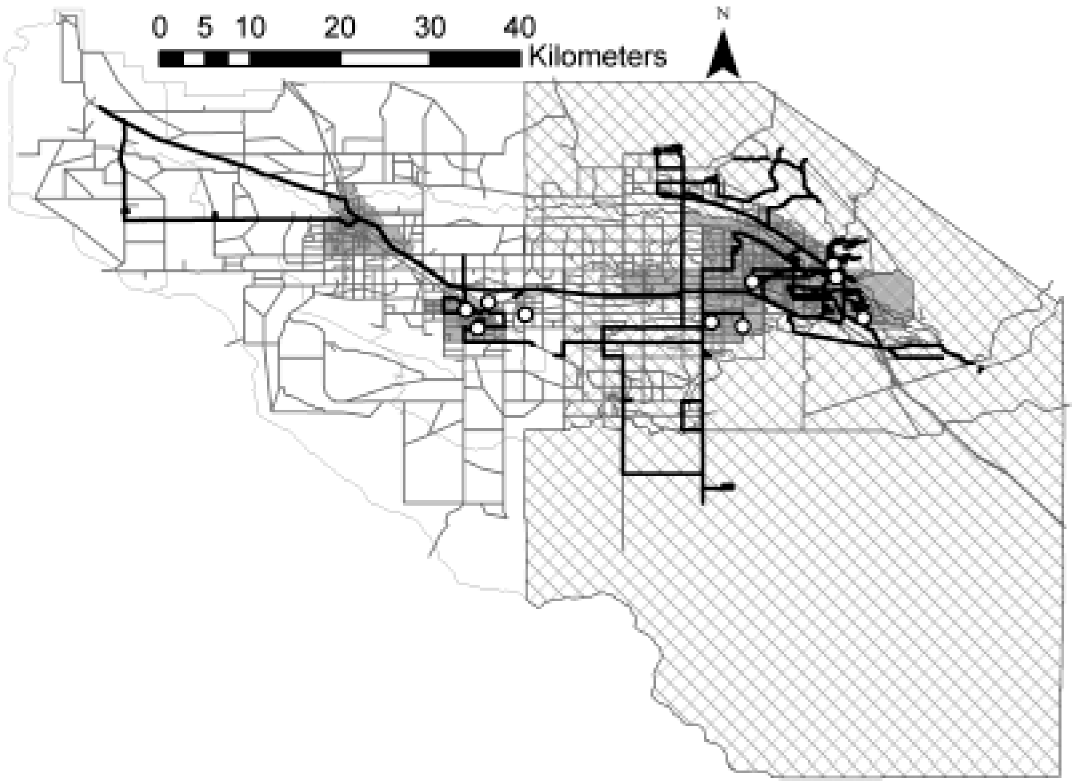


Figure 6. Map of road surveyed by TRAKER (black lines) within the Treasure Valley, ID.

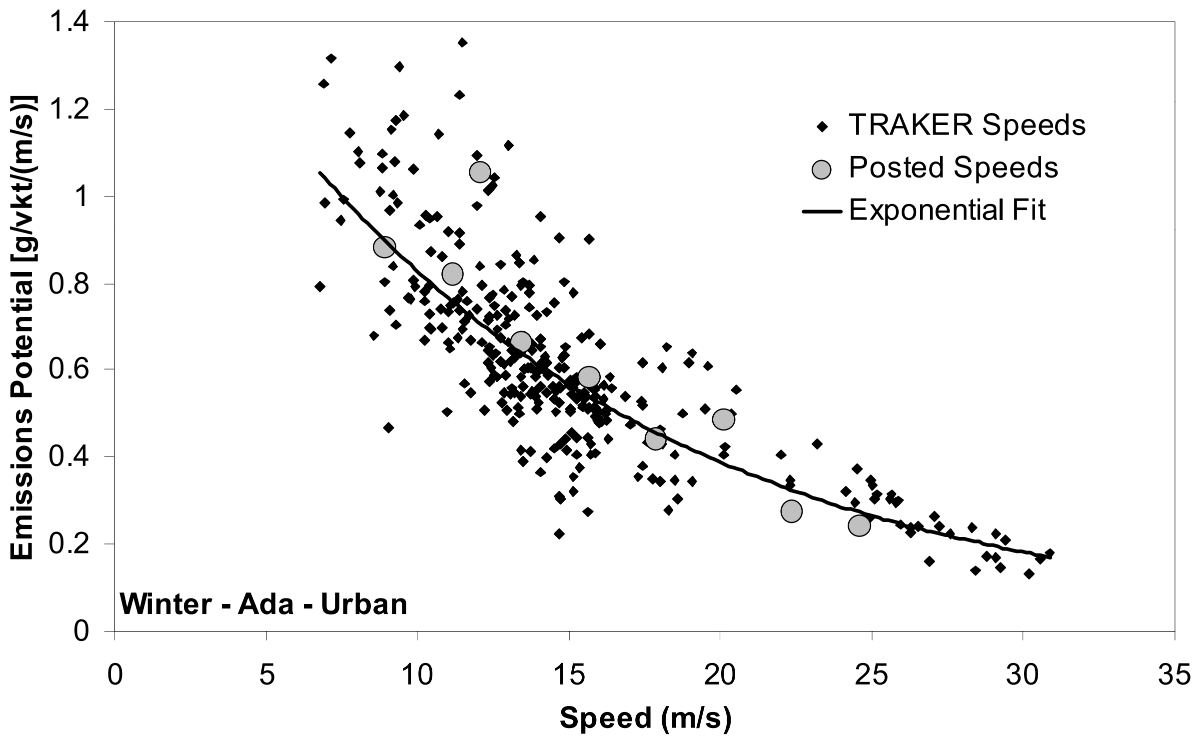


Figure 7. Comparison of link level emission potentials measured by TRAKER with average TRAKER vehicle speed over road segment (black markers). The grey markers represent the average emission potential measured on each road with a common posted speed limit.