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Fugitive Dust Emissions from Paved Road Travel in the Lake Tahoe Basin

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ABSTRACT

The clarity of water in Lake Tahoe has declined substantially over the past 40 yr. Causes of the degradation include nitrogen and phosphorous fertilization of the lake waters and increasing amounts of inorganic fine sediment that can scatter light. Atmospheric deposition is a major source of fine sediment. A year-round monitoring study of road dust emissions around the lake was completed in 2007 using the Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER) system developed at the Desert Research Institute (DRI). Results of this study found that, compared with the summer season, road dust emissions increased by a factor of 5 in winter, on average, and about a factor of 10 when traction control material was applied to the roads after snow events. For winter and summer, road dust emission factors (grams coarse particulate matter [PM_{10}] per vehicle kilometer traveled [g/vkt]) showed a decreasing trend with the travel speed of the road. The highest emission factors were observed on very low traffic volume roads on the west side of the lake. These roads were composed of either a 3/8-in. gravel material or had degraded asphalt. The principle factors influencing road dust emissions in the basin are season, vehicle speed (or road type), road condition, road grade, and proximity to other high-emitting roads. Combined with a traffic volume model, an analysis of the total emissions from the road sections surveyed indicated that urban areas (in particular South Lake Tahoe) had the highest emitting roads in the basin.

IMPLICATIONS

Atmospheric deposition of fine particulate matter is partially responsible for degradation of water clarity at Lake Tahoe. Road dust emissions from paved roads are a major source of PM_{10} emissions, especially in winter. A year-round study using TRAKER, a vehicle-based PM_{10} road dust emissions sampling system, indicates that urban roads with higher traffic volume are the highest emitters of road dust in the basin. Secondary roads with chip gravel or degraded asphalts have the highest emission factors but have lower traffic volume and are therefore a smaller source. Mitigation resources should be targeted at the highest emitting roads to maximize PM_{10} emission reductions.

INTRODUCTION

Fugitive dust emissions originating from motor vehicle travel on paved and unpaved roads constitute a significant fraction of the PM_{10} (particulate matter [PM]with aerodynamic diameter <10 μm) in many areas of the western United States.[1] These non-tailpipe emissions are largely composed of resuspended loose material from the road surface. Elevated ambient PM_{10} levels can result, especially in winter when sand and salt are applied to roads for traction control.[2] Studded snow tires also increased road dust emissions by abrading asphalt pavement.[3] Controlled measurements of road dust emissions are difficult to conduct because factors such as pavement condition, pavement composition, vehicle weight, vehicle speed, tire types, road moisture level, and surface loading and type of suspendible material can all affect the magnitude of PM_{10} emissions. The U.S. Environmental Protection Agency's (EPA) emission factor compilation database, AP-42, summarizes paved road dust emission factors and methods developed in the early 1990s and has been critically evaluated in the literature.[4–7] AP-42 recommends collecting site-specific silt loading measurements from local roadways as a surrogate for estimating PM_{10} road dust emission potential. Silt loading is the mass of silt-size material less than 75 μm in physical diameter per unit area of the travel surface.

Road dust emissions have been measured directly beside the road using upwind/downwind monitoring stations[8] and flux towers.[9,10]

Langston et al.[11,12] evaluated the System of Continuous Aerosol Monitoring of Particulate Emissions from Roadways[13] (SCAMPER, mobile sampling system with PM sensors mounted on a trailer) and Testing Re-Entrained Aerosol Kinetic Emissions from Roads (TRAKER)[14,15] system (mobile system PM sensors mounted behind front tire) and compared the mobile measurements with direct emission factors measured with towers. Other adaptations of these technologies have emerged, including measurements of dust emission in the wake of a vehicle with a DustTrak sampling inlet fixed to the back windscreen wiper.[16] A modified version of TRAKER has been reproduced by Hussein et al.[17] to make on-road measurement in Sweden to study the effects of season, tire types, and asphalt composition on-road dust emissions. Each technology has proven to be useful for quantifying the real-world road dust emissions.

Located on the California-Nevada border, Lake Tahoe is a world-renowned scenic basin with exceptional water clarity. The surface of Lake Tahoe is at an elevation of 1897 m above seal level. Snow, rain, and streams feed the alpine lake, which covers an area approximately 35 km long by 19 km wide. EPA granted the California part of Lake Tahoe the status of Outstanding National Resource Water to protect its water quality. Between 1968 and 1997, water clarity (measured by Secchi depth) decreased from to 31 to 20 m. Clarity continues to decrease at an average rate of 0.25 m/yr.[18] This is the result of increased algal growth and particulate light scattering from excess nutrient inputs (nitrogen [N] and phosphorus [P]) and from the accumulation of fine sediment particles in the lake because of watershed runoff and atmospheric deposition.[19–21] It is estimated that each year around 590 t of PM are deposited into Lake Tahoe through dry atmospheric deposition.[22] Recent work[23] has shown that fine inorganic particles are causing approximately 58% of light attenuation in Secchi disk measurements of water clarity. That study noted that particle sizes from 0.5 to 10 μm are of particular concern because of their light scattering characteristics and relative abundance. Studies conducted for development of the Lake Tahoe total maximum daily load (TMDL) estimate[24] have determined that atmospheric deposition is a major source of fine sediment, and that the control of local atmospheric sources could provide significant load reductions.

This paper documents a year-round monitoring study of road dust emissions around Lake Tahoe using the TRAKER system developed at the Desert Research Institute (DRI). TRAKER measures the real-time concentration of road dust suspended behind a vehicle tire as it travels on a road. TRAKER measurements of PM_{10} were calibrated with the flux of PM_{10} measured downwind of a paved road using flux towers. Each peak in PM concentration recorded by the flux tower dust monitors was associated with an individual TRAKER pass. Using this calibration, TRAKER measurements were converted into emission factors (EFs) in units of grams PM_{10} per vehicle kilometer traveled (g/vkt). TRAKER measurements took place on a prescribed route around the lake on 23 days during the 13-month period between August 3, 2006 and September 2, 2007. The route included major highways, urban roads in the cities, and neighborhood roads. The objectives of the study were (1) survey the emissions potential of paved roadways in the Lake Tahoe Basin over a period of 1 yr to examine the spatial and seasonal variation of road dust emission; (2) reduce the TRAKER survey data to calculate average paved road EFs on the basis of precipitation history, posted speed limit, annual average daily traffic, and surveyed road type (i.e., rural, urban, residential, etc.); and (3) examine the effectiveness of emissions controls (i.e., sweeping, use of anti-icing solutions, paved shoulders, and track-out prevention) for reducing PM_{10} emissions.

EXPERIMENTAL METHODS

TRAKER Measurements

TRAKER provides vehicle-based, real-time measurement of road dust PM EFs. It was developed as an alternative to silt loading measurements prescribed in the EPA AP-42 guidance document. The TRAKER system is mounted inside of a cargo van utilizing three inlets, two that are behind each of the front tires and one that extends through the front bumper of the vehicle. As the TRAKER is driven on a road, air laden with particles suspended behind the front tires and background air sampled ahead of the front bumper are channeled to nephelometer-style DustTrak monitors (TSI, Model 8520) located inside of the vehicle. DustTraks are nephelometer-type instruments that infer particle mass on the basis of the magnitude of 90° light scattering from a 780-nm wavelength laser. The U.S. Federal Reference Method to measure PM_{10} is a filter-based gravimetric method. Measurements of PM using DustTraks and other nephelometer-type instruments have shown good correlations with filter-based gravimetric samplers.[25] Real time Federal Equivalent Method (FEM) monitors can provide hourly concentration readings, but they lack the precision or time resolution needed to measure road dust emissions on-board the TRAKER. DustTraks record PM_{10} concentrations in 1-sec intervals and can provide sequential readings as the TRAKER vehicle drives down the roadway. An on-board global positioning system (GPS) logs the location of each 1-sec measurement as well as other parameters such as the speed, acceleration, and heading of the TRAKER. All data are collected in real time by a laptop computer in the vehicle. Three measurement conditions for data validity have been established for TRAKER: (1) vehicle speed more than 5 m/sec to mitigate the impact of crosswinds, (2) acceleration or deceleration less than 0.5 m/sec^2 to avoid high PM concentration due to braking or hard acceleration, and (3) wheel angle less than 3° from the line of travel to remove the impact of sample inlet orientation change with respect to the tires. Detailed descriptions of the TRAKER vehicle and its operation are described in previous work.[15,26] When traveling at different speeds on the same road, the background-subtracted PM concentration behind the tire varies with speed so that:

$$T = T_{\mathrm{T}} - T_{\mathrm{B}} = a s_{\mathrm{T}}^{\mathrm{b}} \tag{1}$$

where T is the background-corrected TRAKER signal (mg/m^3), T_T is the PM_{10} concentration measured behind the tire (mg/m^3), T_B is the PM_{10} concentration measured ahead of the front bumper (mg/m^3), s_T is the speed of the TRAKER (m/sec; range from 5 to 35 m/sec on the multirun tests on the same roadway), and a and b are fitted constants. T_T and T_B represent DustTrak-measured concentrations that are corrected for particle losses within the TRAKER inlet lines. On the basis of tests conducted in Treasure Valley, Idaho, and at the Fort Bliss military installation near El Paso, TX, for paved roads the value of b is approximately equal to 3, the value of a is specific to the road measured.[26]

In this study, gravimetric PM_{10} mass concentrations measured by on-board Mini-Vol filter samplers were in good agreement with DustTrak PM_{10} readings ($R^2 = 0.91$, slope = 1.01 ± 0.10, intercept = 0.23 ± 0.17, n = 12). Each sample collected 12 times during the year represented a filter exposed for one circuit around the lake (~120 km) and the average DustTrak PM concentration over that interval.

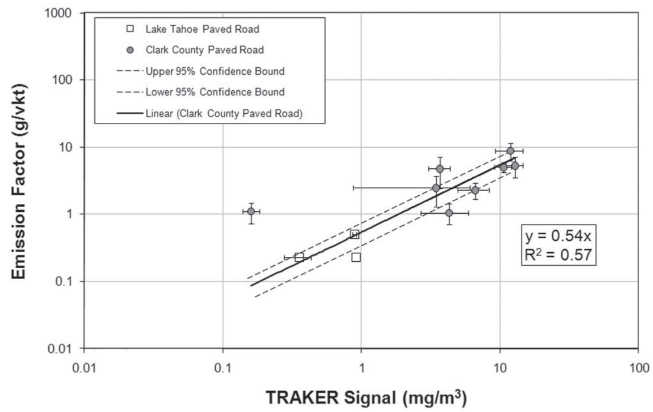

Figure 1. PM_{10} EFs vs. TRAKER average signal. Solid squares are data from the Boulder City, NV, study. The solid line represents a least-squares linear fit to the data from the Boulder City study with a zero intercept. The white squares represent data collected during an earlier study near Lake Tahoe, NV.[27] The dashed lines are 95% confidence bounds of the regression of Boulder City data.

Calibration with Flux Towers

Two studies comparing TRAKER measurements of paved road dust emissions and downwind flux towers measurements were conducted at Lake Tahoe, NV, in 2003[27] and Boulder City, NV, in September 2006.[11,12] The flux of PM downwind of the test roadway was quantified using a vertical array of PM measurements collocated with wind vanes and anemometers similar to that described in previous work.[9] During the Boulder City study, a "master" tower was erected downwind of the road. The master tower was instrumented with TSI DustTraks (Model 8520) configured to measure PM_{10} at five heights above the ground surface. Road dust material was resuspended in the laboratory and sampled using a DustTrak and filter cassettes preceded with PM_{10} impactors. The filter measurements were used to calculate a conversion factor to relate the light scattering DustTrak measurement to a mass concentration measurement. For this study, the filter PM concentrations were 2.4 times larger than the reported DustTrak concentrations. To link light scattering magnitude with aerosol mass concentration, the DustTrak instruments are calibrated at the factory with Arizona road dust (National Institute for Standards and Technology SRM 8632), which likely has different optical properties than the dust collected at this site.

TRAKER measurements were averaged for each pass along the approximately 1-km test roadway. These data were compared with the tower flux measurements at the midpoint of the road segment. A linear, least-squares best-fit line was calculated using the data points from the Boulder City study (Figure 1). Other types of relationships such as power law and exponential fits were also examined; however, they provided little additional benefit in terms of R^2 values compared with the linear fit. In addition, the linear form also provided a better fit to earlier calibrations on a paved road conducted at Lake Tahoe.[27] In the controlled Boulder City test, road dust was preselected from local natural mineral dust, with a silt loading content of 14% and volumetric soil moisture range from 1.9 to 4.1%.[11,12] The Lake Tahoe, NV, study was conducted in spring after the brine and sanding applications to the road. Although the data are from two locations with different types of dust, most of the Lake Tahoe data (shown as open squares) fell in the 95% confidence bounds (dashed line) of the regression slope of the Boulder City data. The agreement reflects a consistency between the DustTraks inside of the TRAKER vehicle and those mounted on the downwind flux towers, indicating the uncertainty of the validation is in a rather narrow range for different regions and different dust concentrations.

The linear fit equation was adopted in the study presented here to calculate the EFs (g/vkt) from the TRAKER signal T (mg/m^3), as shown in eq 2:

$$EF = 0.54T \quad (2)$$

Combining Eqs 1 and 2, the EF of a paved road will depend strongly on the speed of travel on that road, because EF would be proportional to the speed cubed. Prior work has shown and the Boulder City study has reinforced the important relation describing the response of the TRAKER signal to the speed of travel. For a given loading of road dust material, the TRAKER signal is approximately proportional to the cube of the speed of travel at the time of measurement. Although there may be complex relationships between road dust loading and vehicle travel speed (usually higher speed roads are cleaner than low-speed roads), the EF proportional to the speed cubed relation seem to be at odds with current versions of the AP-42 guidance document, which does not account for vehicle speed when estimating EFs from paved roads. A study involving a modified TRAKER system assembled in Sweden also found a strong dependence on vehicle speed from measurements on urban roads.[17]

Table 1. TRAKER EFs (g/vkt) for 41 sections at 23 sampling dates and season average EFs and emission rates.

Section ID	Location	Road Type	Posted Speed Limit (mph)	AADT	Winter Average EF	Summer Average EF	Winter Average Emission Rate (g/km·day)	Summer Average Emission Rate (g/km·day)	August 3, 2006	August 18, 2006	September 7, 2006	October 3, 2006
1	Country Club Drive at Incline Village, NV	Secondary	35	2,080	0.5	0.1	1,065	193	0.07	0.10	0.04	0.20
2	Second Tee Drive at Incline Village, NV	Tertiary	25	197	1.5	0.3	291	69	0.47	0.24	0.25	0.21
3	Village Boulevard at Incline Village, NV	Secondary	35	2,296	0.8	0.2	1,860	465	0.09	0.17	0.23	0.19
4	Lake Shore Drive at Incline Village, NV	Secondary	35	7,723	0.6	0.1	4,273	1,133	0.04	0.14	0.20	0.14
5	SR-28 at Washoe County, NV	Primary	45	10,046	0.2	0.04	2,451	452	0.07	0.05	0.04	0.03
6	SR-28 at Sand Harbor, NV	Primary	45	8,351	0.2	0.03	2,052	289	0.03	0.02	0.02	0.01
7	US-50 at Douglas County, NV	Primary	50	14,541	0.3	0.03	4,110	470	0.02	0.01	0.01	0.01
8	US-50 at Douglas County, NV	Primary	45	14,592	0.3	0.03	3,763	383	–	0.01	0.01	0.02
9	US-50 at Douglas County, NV	Primary	45	14,742	0.2	0.02	3,124	261	–	0.00	0.01	0.00
10	US-50 at Lincoln Park, NV	Primary	45	15,015	0.2	0.04	3,481	622	–	0.04	0.03	0.02
11	US-50 at Zephyr Cove, NV	Primary	45	16,460	0.3	0.03	4,384	510	–	0.03	0.03	0.02
12	Lake Shore Boulevard at Marla Bay, NV	Tertiary	20	450	2.1	0.6	944	248	–	1.03	0.14	0.37
13	US-50 at Marla Bay, NV	Primary	45	20,163	0.2	0.1	4,658	2,177	–	0.09	0.06	0.51
14	Elks Point Road at Round Hill, NV	Tertiary	25	2,995	1.1	0.3	3,315	839	0.21	0.35	0.28	0.24
15	US-50 at Round Hill, NV	Primary	35	31,810	0.4	0.1	11,510	2,588	0.10	0.05	0.04	0.03
16	Lake Parkway at Stateline, NV	Tertiary	25	4,113	3.3	1.0	13,728	4,125	1.68	0.60	1.18	0.10
17	US-50 at South Lake Tahoe, CA	Primary	35	31,346	0.4	0.1	13,742	3,793	0.18	0.06	0.02	0.03
18	Pioneer Trail at South Lake Tahoe, CA	Primary	30	13,918	1.0	0.2	14,447	3,472	0.25	0.51	0.07	0.11
19	Glenwood Way at South Lake Tahoe, CA	Tertiary	25	1,723	1.6	0.8	2,679	1,343	1.39	0.40	0.18	0.15
20	US-50 at South Lake Tahoe, CA	Primary	35	36,938	0.5	0.1	18,942	4,783	0.13	0.10	0.06	0.06
21	Lake View Ave at South Lake Tahoe, CA	Tertiary	25	1,785	1.2	1.1	2,193	2,032	1.09	3.40	0.85	0.77
22	US-50 at South Lake Tahoe, CA	Primary	45	28,653	0.5	0.1	15,448	3,725	0.26	0.14	0.13	0.06
23	Tahoe Keys Boulevard at South Lake Tahoe, CA	Tertiary	25	4,494	0.7	0.2	3,277	679	0.32	0.24	0.08	0.05
24	SR-89 at South Lake Tahoe, CA	Primary	35	9,206	0.7	0.1	6,209	943	0.16	0.10	0.06	0.03
25	SR-89 at Cascade Lake, CA	Primary	40	7,254	1.0	0.1	7,609	434	0.05	0.02	0.15	0.01
26	SR-89 at Eagle Falls, CA	Primary	40	5,069	0.7	0.1	3,659	255	0.04	0.02	0.03	0.02
27	Sierra Drive at Meeks Bay, CA	Tertiary	25	256	3.7	2.4	944	623	1.56	1.69	1.83	1.23
28	SR-89 at Meeks Bay, CA	Primary	40	6,103	0.7	0.1	4,414	818	0.14	0.08	0.34	0.05
29	McKinney Rubicon Springs Road at Tahoma, CA	Tertiary	25	214	6.5	1.1	1,396	239	0.91	0.79	1.37	0.85
30	SR-89 at Tahoma, CA	Primary	40	6,372	0.6	0.1	3,547	869	0.22	0.05	0.08	0.03
31	Cherry Street at Tahoe Pines, CA	Tertiary	25	334	8.8	3.3	2,941	1,092	7.57	0.24	0.17	0.08
32	SR-89 at Tahoe Pines, CA	Primary	40	6,875	0.5	0.2	3,410	1,575	0.39	0.03	0.13	0.06
33	Sugar Pine Road at Sunnyside, CA	Tertiary	25	442	7.1	1.8	3,136	811	1.66	–	2.38	1.13
34	SR-89 at Sunnyside, CA	Primary	40	7,427	0.7	0.2	5,519	1,167	0.28	0.02	0.14	0.35
35	SR-28 at Tahoe City, CA	Primary	40	8,594	0.9	0.1	7,452	1,180	0.23	0.16	0.04	0.15
36	Lake Forest Road at Tahoe City, CA	Tertiary	25	903	2.8	0.8	2,488	706	0.56	0.81	0.63	0.43
37	SR-28 at Tahoe City, CA	Primary	45	11,906	0.5	0.1	6,187	1,690	0.30	0.09	0.08	0.29
38	SR-267 at Kings Beach, CA	Secondary	25	8,945	2.4	0.7	21,561	5,993	0.54	0.58	0.95	0.25
39	SR-28 at Kings Beach, CA	Primary	45	15,960	0.6	0.1	9,106	2,262	0.19	0.17	0.11	–
40	SR-28 at CA/NV border	Primary	35	19,688	0.4	0.1	8,013	1,145	0.06	0.03	0.04	–
41	Red Cedar Drive at Incline Village, NV	Tertiary	25	861	2.3	0.8	1,959	718	0.34	0.28	0.25	0.25

Survey of Road Maintenance Districts in the Tahoe Basin

As part of the Lake Tahoe road dust study, the Nevada Tahoe Conservation District (NTCD) surveyed procedures from road maintenance groups around Lake Tahoe. Twenty-two organizations were surveyed, including all counties, CalTrans, the Nevada Department of Transportation (NDOT), General Improvement Districts (GIDs), and some homeowners' associations (HOAs) responsible for winter road maintenance. The surveys were intended to identify procedures for application and recovery (e.g., road sweeping) of sand and salt for winter traction control.

There are three basic materials used for traction control in the Tahoe Basin. The City of South Lake Tahoe, El Dorado County, and the Douglas County School District use cinders. Three GIDs use 3/8-in. "chip" gravel, and the remaining Tahoe Basin organizations use sand. Nearly all traction control material includes added salt. The salt is used to keep the sand pile from freezing and creating clumps of frozen sand, as well as to enhance snowmelt on the road. Major road maintenance organizations in the Tahoe Basin own and operate their own sweepers. These organizations generally sweep roads as soon as roads are dry (or almost dry) following a snow event.

Sampling Route, Traffic Model, and Data Analysis

The route traveled by the TRAKER vehicle was sampled once every 2 weeks between August 3, 2006 and September 2, 2007 (23 different occasions). The direction of the survey was clockwise around the lake starting from Incline Village, NV. The route was subdivided into 41 sections on the basis of common parameters of the roadway such as road type (i.e. primary, secondary, tertiary), road maintenance organization, and slope (Table 1). Figure 2 shows the location of each of these road sections around the lake; connecting sections were assigned different gray

Table 1. (Cont.)

October 25, 2006	November 17, 2006	November 30, 2006	December 20, 2006	December 30, 2006	January 19, 2007	January 31, 2007	February 16, 2007	March 2, 2007	March 14, 2007	March 29, 2007	April 25, 2007	May 12, 2007	May 31, 2007	June 15, 2007	July 4, 2007	July 6, 2007	July 31, 2007	September 2, 2007
0.04	0.05	0.55	1.13	0.74	0.99	0.34	0.48	0.57	0.23	0.30	0.24	0.06	0.14	0.05	0.06	0.14	0.19	0.02
0.20	0.21	0.11	1.06	0.64	2.69	2.54	2.31	2.35	1.67	1.44	0.79	0.62	0.50	0.35	0.40	0.62	0.52	0.21
0.20	0.18	0.04	1.47	0.28	1.53	1.19	1.31	0.72	0.99	0.78	0.35	0.24	0.31	0.32	0.17	0.36	0.11	0.09
0.14	0.17	0.10	0.29	0.14	0.86	0.69	0.48	0.08	1.90	1.05	0.31	0.18	0.17	0.23	0.15	0.22	0.08	0.07
0.02	0.03	0.17	0.48	0.18	0.43	0.51	0.14	0.10	0.29	0.24	0.07	0.06	0.06	0.05	0.04	0.09	0.04	0.03
0.01	0.02	0.27	0.38	0.24	0.44	0.38	0.16	0.24	0.16	0.16	0.15	0.11	0.11	0.04	0.05	0.05	0.02	0.02
0.01	0.03	0.18	0.89	0.04	0.43	0.81	0.15	0.14	0.14	0.08	0.11	0.15	0.05	0.04	0.03	0.09	0.03	0.04
0.03	0.02	0.40	0.38	0.18	0.51	0.52	0.11	0.32	0.12	0.11	0.16	0.02	0.04	0.02	0.02	0.05	0.03	0.03
0.01	0.01	0.43	0.21	0.11	0.33	0.35	0.33	–	0.17	0.09	0.04	0.04	0.03	0.01	0.04	0.04	0.01	0.01
0.02	0.13	0.68	0.33	0.25	0.29	0.23	0.18	–	0.20	0.06	0.06	0.03	0.03	0.03	0.06	0.05	0.03	0.02
0.02	0.08	0.79	0.36	0.06	0.23	0.76	0.12	–	0.12	0.11	0.06	0.04	0.02	0.02	0.02	0.06	0.02	0.03
0.44	0.88	1.06	0.32	0.05	0.47	5.48	2.88	–	5.41	2.68	2.01	0.61	0.41	0.82	0.61	0.59	0.40	0.38
0.02	0.10	0.24	0.25	0.15	0.27	0.55	0.18	–	0.33	0.10	0.16	0.09	0.05	0.06	0.08	0.09	0.06	0.05
0.11	0.14	1.18	0.50	–	1.47	1.83	0.76	2.11	1.56	0.95	0.49	0.22	0.38	0.27	0.55	0.56	0.12	0.15
0.03	0.07	0.71	0.23	0.41	0.44	0.48	0.21	0.25	0.31	0.39	0.42	0.12	0.09	0.16	0.13	0.08	0.15	0.05
0.62	1.33	0.78	0.60	0.23	1.91	3.16	5.60	7.08	7.19	3.83	4.44	1.90	0.67	1.20	0.27	1.38	1.28	1.71
0.04	0.11	0.29	1.51	0.02	0.69	0.46	0.34	0.12	0.52	0.41	0.19	0.30	0.20	0.21	0.08	0.08	0.35	0.09
0.66	0.18	0.43	1.69	0.65	3.84	0.85	0.63	1.16	0.57	1.14	0.37	0.10	0.17	0.33	0.18	0.20	0.14	0.20
0.09	4.50	0.05	3.85	0.02	2.08	1.62	1.83	2.32	1.76	1.71	1.35	0.53	0.29	0.60	0.61	0.80	0.18	0.15
0.07	0.21	0.17	1.31	0.07	1.07	0.75	0.37	0.51	0.44	0.40	0.31	0.25	0.09	0.27	0.08	0.17	0.23	0.09
0.83	1.36	0.01	1.53	0.00	0.32	0.81	3.10	0.42	3.41	1.91	1.53	0.47	0.96	0.75	1.01	1.27	1.11	0.26
0.10	0.18	0.13	0.84	0.43	0.89	0.79	0.38	0.49	0.63	0.85	0.39	0.10	0.13	0.16	0.13	0.08	0.08	0.10
0.11	0.16	0.09	0.99	0.16	1.04	0.72	1.62	1.55	0.58	0.78	0.34	0.17	0.21	0.16	0.14	0.19	0.09	0.07
0.05	0.10	0.02	0.92	0.01	1.36	1.97	0.41	0.96	0.68	0.63	0.26	0.19	0.10	0.13	0.22	0.13	0.07	0.08
0.02	0.18	1.59	0.98	0.16	1.58	1.18	0.76	–	0.95	2.72	0.30	0.28	0.15	0.06	0.03	0.02	0.02	0.03
0.02	0.19	0.90	1.02	0.06	1.55	0.89	0.55	0.80	0.81	0.94	0.26	0.16	0.09	0.04	0.04	0.04	0.04	0.03
1.75	7.71	–	–	–	–	3.13	5.47	–	5.48	1.26	2.83	4.00	2.61	2.62	2.73	1.85	1.60	2.06
0.05	0.18	0.20	0.90	0.24	1.73	1.25	0.71	0.75	1.05	0.51	0.35	0.26	0.15	0.18	0.10	0.16	0.09	0.10
0.92	0.72	–	–	–	0.54	4.53	11.87	–	14.34	8.80	3.26	2.43	1.57	1.60	1.47	1.47	1.06	0.71
0.07	0.13	0.01	0.40	0.01	1.02	0.86	1.01	0.26	1.02	0.79	0.56	0.19	0.20	0.30	0.27	0.12	0.10	0.07
4.16	2.63	–	–	–	–	2.34	3.80	–	17.11	9.67	8.29	11.58	6.38	3.53	6.20	3.87	3.68	0.69
0.11	0.19	0.01	0.55	0.02	0.88	0.71	0.27	0.25	0.47	0.96	0.58	0.75	0.45	0.46	0.39	0.28	0.12	0.14
2.17	1.46	–	–	–	–	1.06	0.86	–	15.25	12.13	6.05	7.21	4.86	1.80	1.70	1.10	1.12	0.81
0.08	0.20	0.01	0.86	0.21	1.76	1.41	0.90	0.29	1.19	0.89	0.45	0.20	0.21	0.19	0.16	0.12	0.08	0.05
0.09	0.22	0.05	1.48	0.10	1.37	1.36	1.53	0.30	1.34	1.03	0.57	0.41	0.18	0.16	0.11	0.12	0.07	0.11
0.44	0.50	0.02	1.70	–	0.87	4.41	5.63	–	5.11	3.87	2.13	1.04	1.33	1.98	0.59	1.15	0.57	0.37
0.14	0.26	0.06	0.53	0.06	1.00	0.81	0.69	0.13	1.06	0.85	0.30	0.22	0.10	0.13	0.08	0.11	0.08	0.06
0.56	1.32	–	4.51	–	0.94	2.22	1.65	–	3.81	2.81	2.25	1.08	0.56	0.57	0.57	0.70	0.88	0.55
0.07	0.15	0.28	–	0.05	0.87	0.80	0.40	0.34	1.31	0.99	0.47	0.19	0.12	0.13	0.14	0.12	0.26	0.12
0.02	0.10	0.46	–	0.27	0.59	0.54	0.36	0.25	0.60	0.69	0.17	0.14	0.05	0.07	0.12	0.06	0.04	0.05
0.17	0.30	–	–	–	3.73	2.88	3.05	0.94	3.51	2.18	1.33	0.59	1.29	0.98	0.79	1.38	3.85	0.13

scales for presentation clarity. On some days in the winter, the road section on California SR-89 (western side of the lake, see Figure 3) and other secondary/tertiary roads were closed because of snow accumulation (null cells in Table 1). On those days, only the passable sections of the route were surveyed.

The Tahoe TransCAD travel model is a microsimulated tour-based model that reflects resident, seasonal resident, and visitor travel behavior in the Lake Tahoe Basin Region. The TransCAD model output was provided to DRI for integration with the TRAKER measurements by the Tahoe Regional Planning Agency. The database was queried to produce annual average traffic flow volumes for each of the segments on the TRAKER survey route, as shown in Table 1.

The raw TRAKER data were grouped to each section using a spreadsheet macro that separated the points on the basis of their geographic coordinates and sequence within the daily TRAKER data file. The average, standard deviation, and number of TRAKER EF measurements (in g/vkt) of the left and right wheels were calculated for each section on each survey day using eq 2 (see Figure 3 for sampling day of January 31, 2007). In addition, the background concentration (in $\mu g/m^3$) and TRAKER speed (in m/sec) were also calculated for each section. To ensure a representative sample on each section, a minimum of 10 valid data points was required for the average to be included in the data analysis.

The grouping of roads as primary, secondary, or tertiary is not strictly tied to traffic volume. On the basis of the TransCAD output, primary road sections have two-way vehicle flow that ranges from 5000 to approximately 40,000 vehicles per day (annual average daily travel [AADT]) and posted speed limits that range from 24 (15 mph in urban areas) to 88 km/hr (55 mph). Secondary roads have AADT between 2000 and 10,000 with speed limits between 56 (35 mph) and 72 km/hr (45 mph). Tertiary roads are typically neighborhood roads but can

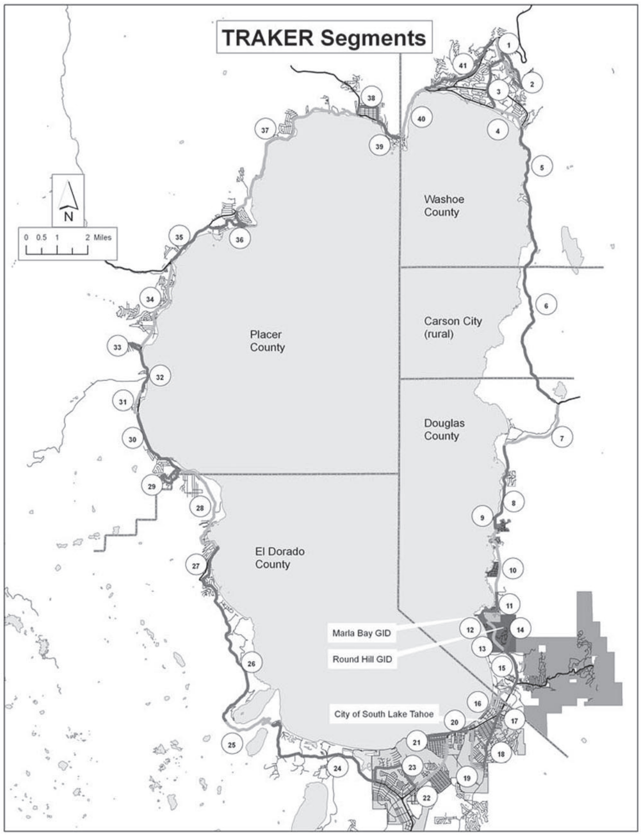

Figure 2. Location of TRAKER road sections overlaid with the GIDs responsible for road maintenance.

have AADTs up to 5000; speed limits on tertiary roads range from 32 (20 mph) to 64 km/hr (40 mph).

RESULTS AND DISCUSSIONS

Road Dust Emissions Related to Precipitation Season

The Natural Resources Conservation Service (NRCS) installs, operates, and maintains an extensive automated system to collect snowpack and related climatic data in the western United States called SNOTEL (for SNOwpack TELemetry). The network of sites is designed to measure snowpack in the mountains of the West and forecast the water supply. For comparison with EF data, road links were paired with the nearest SNOTEL stations in the Tahoe Basin. Data from the Tahoe City Cross, Marlette Lake, Heavenly Valley, Fallen Leaf, and Rubicon #2 stations were included in the relational database (The five SNOTEL stations locations are shown in Figure 3). For perspective, the 2007 water year was one of the driest on record, with the April first snowpack water equivalent (SWE) in the Tahoe Basin at only 39% of the 1971–2000 average. The shortage of snow in the Tahoe Basin during the winter 2006–2007 resulted in very low amounts of traction control material applied to the roads.

On the basis of the time series of EFs and nearby SNOTEL snowpack depth as seen in Figures 4 and 5, the primary factor that influenced road dust emissions in the Tahoe Basin was the application of traction control material on roadways in the winter. All time series of EFs indicated that for some winter sampling days, emissions

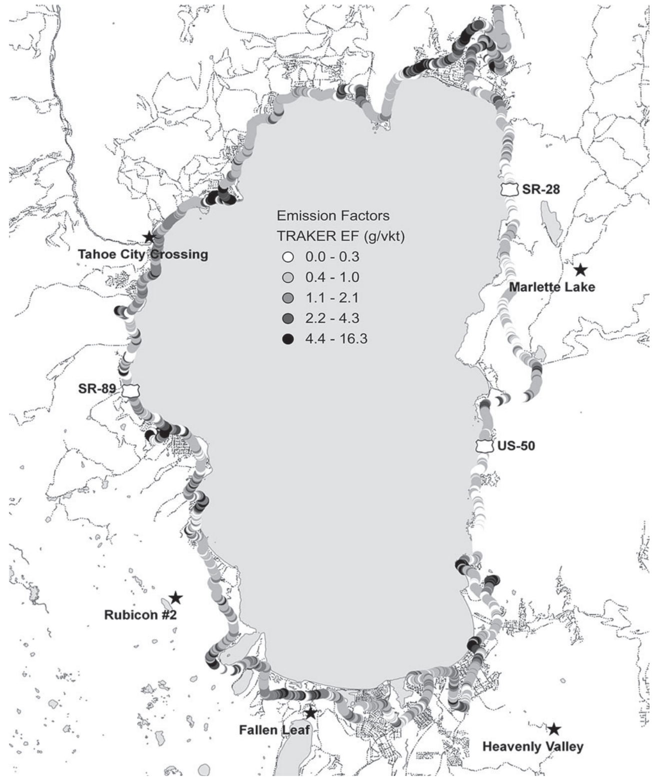

Figure 3. EFs along the sampling route on January 31, 2007. The star points show the SNOTEL stations around Lake Tahoe.

increased by a factor of 10 or more compared with the summer level. On average, winter EFs were 5 times greater than summer EFs. The increase was coincident with the development of a snowpack at nearby SNOTEL stations—directly associated with the time when road maintenance crews must apply de-icing and traction control material to the roads. Road dust EFs returned to summer levels by the beginning of May, coinciding with the complete melting of the snowpack.

Traffic Volume and EFs

The TRAKER data indicate that roads with the highest EFs are the lowest volume secondary or tertiary roads. Primary

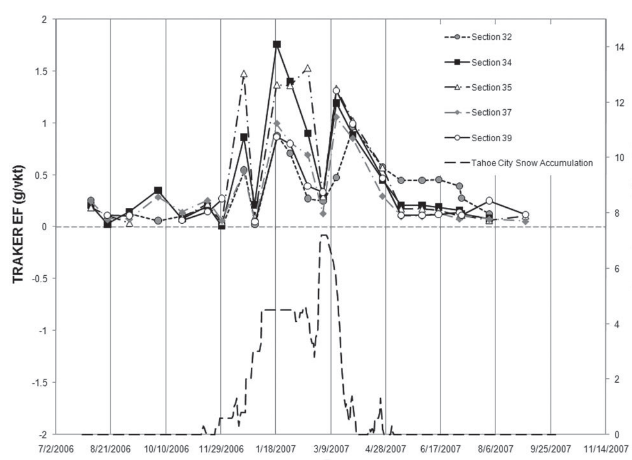

Figure 4. PM_{10} road dust EFs of primary road sections near Tahoe City SNOTEL station.

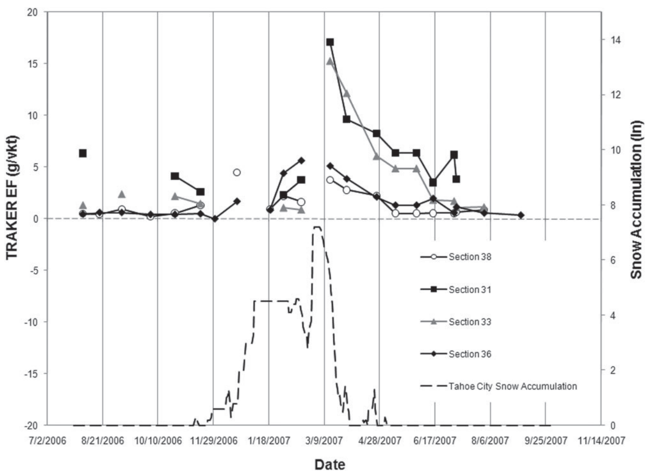

Figure 5. PM_{10} road dust EFs of secondary road sections near Tahoe City SNOTEL station (missing data in the winter because of the sections covered by snow).

high-speed (64–88 km/hr, or 40–55 mph) roads have the lowest EFs. As seen in Figures 4 and 5, the EFs for the primary roads near the Tahoe City SNOTEL station peak at approximately 2 g/vkt in mid-winter, whereas the nearby secondary roads Interlaken and Timberland Road emit more than 15 g/vkt. The trend of increasing EFs with decreasing traffic volume is consistently observed for most groups of roads in the basin.

There are two factors controlling this pattern. First, the primary and most highly traveled roads have the most active road maintenance practices. As the survey indicated, CalTrans and NDOT roads are swept regularly throughout the winter as soon as the roads are dry after a snow event (typically within 4 days). The second factor is that high-volume roads tend to have the highest posted speed limits in the Tahoe Basin. The residence time of road dust on the higher speed roads is shorter than for lower-speed roads. As described above, emissions from the same road appear to increase with vehicle speed to the power of approximately 3 (speed response relationship obtained by TRAKER traversing the same section of road at varying speeds). On high-speed roads with all vehicles traveling close to the posted speed limit, vehicles quickly resuspend material deposited on these roads.. Thus, compared with low-speed roads, high-speed roads tend to have less suspendible material. Several other researchers have also observed this. Paved major roads had an average EF of 1 g/vkt, whereas the EFs of paved collector roads averaged 6.7 g/vkt in Spokane, WA.[28] EFs of 0.2 g/vkt for freeways and approximately 3 g/vkt for city roads near Riverside, CA, have been reported.[29] In other studies in Las Vegas, NV, and Boise, ID[14,15] roads with minimal sweeping maintenance (i.e. every 2 weeks to 1 month) exhibited the trend that high-speed, high-volume roads have much less suspendible material than do low-speed neighborhood roads.

During winter, road dust emissions are suppressed when there is a snowpack on the roads or when they are wet because of different sun shading conditions along the sampling route. In the vicinity of Tahoe City (Figure 4), the EFs from primary roads decreased to summer levels on December 30, 2006, after a storm that deposited 0.6 in. of SWE 3 days before sampling with TRAKER and again on March 7, 2007 when a storm deposited 4.4 in. of SWE 5 days before sampling. Secondary roads in the same region were covered with snow during such periods, prohibiting measurement of road dust EFs (Figure 5). For each of these cases, road dust EFs had returned to typical winter levels when the roads dried and were resampled 12 and 20 days later, respectively.

Summer EFs

Summer road dust EFs based on TRAKER data are defined as those collected between August 3, 2006 and November 17, 2006 and then again from May 31, 2007 through the end of the study on September 2, 2007. During this period, EFs remained relatively constant because of lower overall precipitation rates in the form of rain and an absence of freshly applied traction control material. Some high-EF areas were observed on road sections during the summer because of track-out of material by vehicles from unpaved roads or construction sites. For example, a peak in the EF of 3.8 g/vkt (range from 0.2 to 67.9 g/vkt, 36 samples) on Section 41 (Sugarpine Drive in Incline Village) on July 31, 2007 was due to active road construction and housing construction sites. The EF from this road returned to an annual low of 0.12 g/vkt (range from 0.01 to 0.4 g/vkt, 40 samples) on the next survey on September 2, 2007 after the construction was completed.

Road Speed and EFs

As an initial grouping of the EF dataset, summer EFs are defined as those collected from August 3, 2006 to November 18, 2006 and from May 30, 2007 to September 2, 2007. Winter EFs are defined as between November 18, 2006 and May 30, 2007. Within the seasonal categories, the primary factor controlling EFs is the average vehicle speed. The speed measured on-board the TRAKER is used as a surrogate for the speed of all vehicles on a given road because it reflects the normal mode of travel with the flow of traffic. Figures 6 and 7 show the average EFs for summer and winter, respectively, for each of the TRAKER route sections plotted versus the average vehicle speed. The error bars on the figure are the standard error of the summer and winter average EFs. In summer and winter,

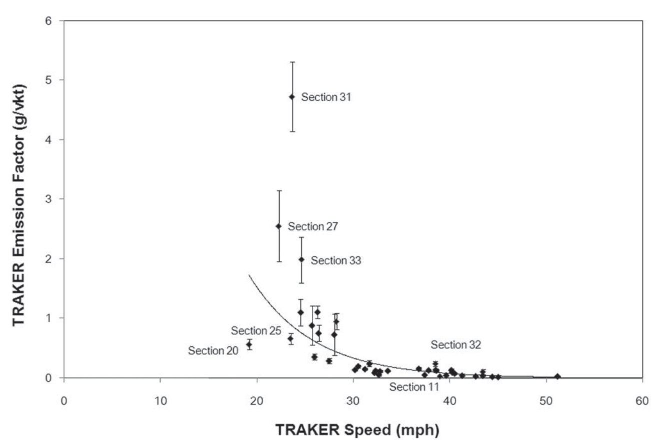

Figure 6. Relationship between TRAKER vehicle speed and measured average summer PM_{10} EFs.

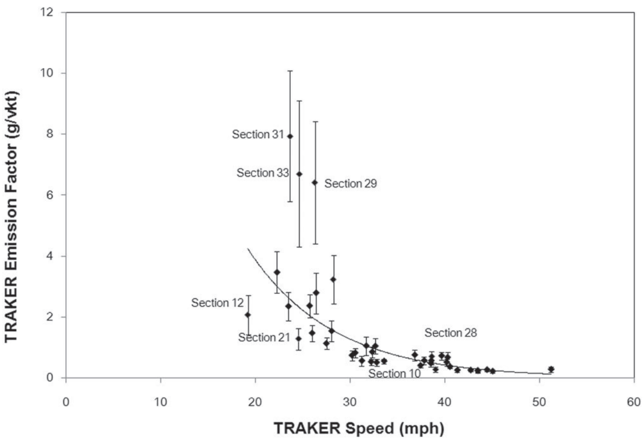

Figure 7. Relationship between TRAKER vehicle speed and measured average winter PM_{10} EFs.

the EFs show an exponential decrease with increasing vehicle speed. This trend has been observed in other TRAKER studies.[14,15] As summarized in Table 2, the winter average PM_{10} EFs for primary, secondary, and tertiary roads are 0.5, 1.1, and 3.3 g/vkt, respectively. The summer average PM_{10} EF in the basin is 0.1 for primary roads, 0.3 g/vkt for secondary roads, and 1.1 g/vkt for tertiary roads.

Road Conditions and EFs

To identify other controlling factors, road sections that deviate significantly from the exponential trend have been highlighted. For low-speed roads (<25 mph) in the summer, Sections 27 (community of Rubicon Bay/El Dorado County), 31 (community of Tahoe Pines/Placer County), and 33 (community of Sunnyside/Placer County) all had EFs higher than the exponential trend line. The Interlaken Road in Tahoe Pines (Section 31; Figure 6) has the highest summer EFs. This road was composed of 3/8-in. gravel and had EFs between 3 and 6 g/vkt during the summer. At some point, the gravel on this road may have been sealed using a chip-sealing process, but no sealant was effectively binding the gravel during the sampling year. Chip sealing is a cost-effective method to maintain a low-volume road; however, a sealing agent should be regularly applied to suppress dust emissions. In addition, there was an extensive gas line replacement project throughout this community during the study period.

During the winter, Sections 29 (McKinney Rubicon Springs Road/El Dorado and Placer Counties), 31, and 33 had the highest EFs for low-speed roads, whereas Sections 12 (Marla Bay GID) and 21 (Lake View Avenue in South Lake Tahoe) had the lowest EFs. The highest emitting roads in this class had generally poor road conditions (i.e., some crumbling asphalt or the use of fine gravel) and were swept infrequently in the winter. Marla Bay roads were swept only in the spring, but that neighborhood is relatively flat and has newer asphalt. No traction control material was applied in the Marla Bay neighborhood during the 2006–2007 winter. Section 21 roads (in South Lake Tahoe) were also very flat and regularly swept by the City of South Lake Tahoe.

Track-Out Effect and Grade Effect

For medium-speed roads (56–64 km/hr, or 35–40 mph) in the summer, the average EF from Section 32 (SR-89 near Idlewild/Caltrans) was highest, whereas the EF on Section 11 (Highway 50 near Caverock/NDOT) was lower by a factor of 8. Both roads are relatively flat and close to lake level. There are few neighborhoods in the vicinity of Section 11, whereas Section 32 is adjacent to the highest emitting low-speed roads (Section 31 and 33). In Section 32, it is visually apparent that material from the chip seal/gravel road (on Section 31) is tracked out onto SR-89 and provides a continuous source of suspendible particles throughout the summer. Section 16 (Lakeshore Boulevard in South Lake Tahoe) is adjacent to an unpaved beach parking lot. Track-out material from the lot contributed to high emissions in the summer and especially in the winter when the parking lot was periodically wet.

For low-speed roads in winter, Section 41 in the Incline Village, NV, area (from the Red Cedar Drive to Marlette Way) has a steeper road than neighboring Sections 1 and 2 (Country Club Drive and Second Tee Drive), although they have similar road conditions and are in the same area. Section 41 has higher winter EFs than Sections 1 and 2 because of additional traction control material on a steeper road. For medium-speed roads in the winter, Section 28 (SR-89 between Rubicon and Tahoma/Caltrans) had EFs that were approximately 3 times greater than Section 10 (Highway 50 near Caverock/NDOT). Although Section 28 is not very steep, it is surrounded by neighborhoods that do have substantial grades and require additional traction control material. The neighborhood adjacent to Section 10 is very flat and at lake level. Caltrans and NDOT sweep these roads regularly throughout the winter.

To summarize, the analysis above indicates that the principle factors influencing road dust emissions in the basin are season, vehicle speed (or road type), road condition, road grade, and proximity to other high-emitting roads.

Emissions Modeling

For air quality modeling purposes, the PM_{10} emissions from an area are more important than the EFs from a specific road. Overall emissions are calculated by multiplying the EF by the vehicle flow on a road. Consequently, roads with very high EFs may be insignificant sources if they are seldom traveled. Figure 8 shows the winter average of the daily emission rates (g/km·day) from each of the sections surveyed by TRAKER. These data (Table 1) allow for a comparison of the total emissions of one road to the next. The maps do not represent a complete emissions inventory because they only comprise a

Table 2. Season-average TRAKER EFs (g/vkt) in Tahoe Basin.

	Winter Average	Sample (*n*)	Summer Average	Sample (*n*)
Primary roads	0.5 ± 0.3	24	0.1 ± 0.1	24
Secondary roads	1.1 ± 0.9	4	0.3 ± 0.3	4
Tertiary roads	3.3 ± 2.6	13	1.1 ± 0.9	13

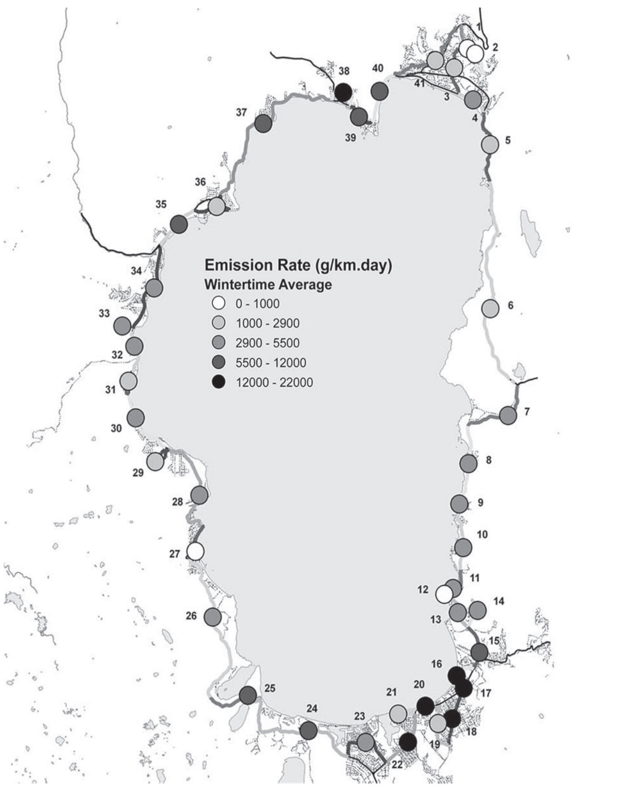

Figure 8. Winter average PM_{10} road dust emission rate (g/km · day) in 41 sampling sections around Lake Tahoe (November 18, 2006 to May 30, 2007).

subset of all roads. Major roads in South Lake Tahoe are generally the highest emitting roads owing predominantly to the large volume of traffic in the area. According to the record from the Western Regional Climate Center, the prevailing wind direction at South Lake Tahoe (on the south-southeast side of the lake) is south, south to southwest at D.L. Bliss State Park station (on the southwest side of the lake), and southwest at the Incline Village station (on the north-northeast side of the lake). Snow accumulation increases with elevation throughout the basin but is typically 2–3 times greater on the west side of the lake than on the east side of the lake. Because of prevailing south wind directions year round in the South Lake Tahoe area, which will enhance atmospheric deposition into the lake, active road maintenance should be emphasized in this area. On the basis of geographic information system (GIS) software estimation of the distance of each sampling section, the total distance of the TRAKER route was around 120 km around the lake. The winter (193 days, November 18, 2006 to May 30, 2007) road dust PM_{10} mass from the sampled roads was estimated at 119 t, whereas the summer (172 days, rest of the year) road dust PM_{10} mass was estimated at 23 t.

Background Concentrations Measured On-Board TRAKER

The ambient background PM concentrations reflect the ambient PM levels measured approximately 50 cm above the road surface from a moving vehicle. They are subject to large variations that may be due to regional impact (i.e., prescribed burning, wildfires, urban traffic) and very localized sources such as the emissions of a single vehicle traveling in front of the TRAKER. Therefore, only trends that show spatial and temporal consistency may be indicative of larger spatial and seasonal patterns in PM_{10} concentrations. The winter PM_{10} background concentrations for the sections of California SR-89 near Emerald Bay were in the range of 30–50 $\mu g/m^3$, around twice the summer levels of 10–20 $\mu g/m^3$. This is a very sparsely populated portion of the lake and consequently has some of the lowest ambient concentrations. In contrast, concentrations near the cities of Stateline and South Lake Tahoe, Incline Village, and Tahoe City have higher instantaneous winter concentrations as high as 50–150 $\mu g/m^3$ (range 2–7 times higher than summer level of 10–20 $\mu g/m^3$) and consistent with the timing of the increase in road dust EFs. The vehicle kilometers traveled (vkt) is higher in cities because of more traffic and consequently the road dust source is larger. Other factors may also contribute to higher urban PM level, such as stronger winter inversions that trap all emissions close to the ground and the increase in residential wood combustion activity during the cold season.

Discussion of the Control Measures

This study found the highest EFs were measured on low-traffic secondary roads with degraded asphalt and with infrequent sweeping practices after winter snow events. Roads with chip-gravel sealing and degraded asphalt had the highest summer EFs. Regardless of season, road sections impacted by track-out had elevated EFs.

In a Michigan study, street sweeping after the snow events reduced total solids and sediment in runoff by up to 80%. In urban areas, this practice was found to be most cost-effective when using a high-efficiency or regenerative air sweeper as opposed to mechanical broom sweepers.[30]

In contrast, a detectable reduction in re-entrained road dust immediately after street sweeping has not been observed in previous studies.[2,31] The authors of this study hypothesize that the sweepers remove most collectable mass from the road but leave fine particles that may still be entrained from interaction with vehicle tires. Over longer periods of time (10 vehicle passes or more), the reservoir of fine particles may be depleted from the road. The sweeper's reduction of larger dust material (that are ground by tires and serve as precursors to emittable PM_{10}) may ultimately reduce PM_{10} emissions from the road.

Using street sweepers to remove traction material from roadways after they dry is one way to reduce PM emissions due to re-entrained road dust. Anti-icing agents such as salt or other chemicals are applied before snow storms to inhibit ice formation and to help prevent ice from bonding to the road surface. Anti-icing agents can reduce the amount of traction material that needs to be applied and make it easier for snowplows to clear ice from the roads. NDOT reduced annual sand use in the Tahoe Basin from 3288 m^3 in 1990 to 650 m^3 in 2006. They also reduced salt usage by 70% through the use of anti-icing brine.[32] Some studies have shown that by using anti-icing agents the amount of abrasive sand can be reduced by up to 50%.[33] However, anti-icing agents can have adverse consequences, such as increasing chloride in water systems,[34] causing harm to vegetation,[35] and weakening cement in concrete.[36]

SUMMARY

Atmospheric deposition of fugitive dust from roadways has increased fine sediment loadings into Lake Tahoe, which has reduced water clarity. Road dust EFs were measured using the TRAKER system on a prescribed route around the lake on 23 days between August 3, 2006 and September 2, 2007 and included major highways and neighborhood roads. Calibrated with the flux of PM_{10} measured downwind of a paved road, TRAKER measurements were converted into EFs (in g/vkt).

Winter EFs were on average 5 times greater than summer EFs because of the application of traction control material. Winter emissions increased with the development of snowpack at nearby meteorological stations (mid-November) and returned to steady-state summer levels by the beginning of May when the snowpack melted. For winter and summer, road dust EFs showed a decreasing trend with the travel speed of the road. This effect has been observed during other studies and is attributed to the fact that material is suspended from roads at a rate that increases exponentially with vehicle speed. The winter average PM_{10} EFs for primary, secondary, and tertiary road roads are 0.5, 1.1, and 3.3 g/vkt, respectively. The summer average PM_{10} EF is 0.1 g/vkt for primary roads in the basin, 0.3 g/vkt for secondary roads, and 1.1 g/vkt for tertiary roads.

The highest summer and winter EFs were observed on very low traffic volume roads on the west side of the lake. Those roads were composed of either a 3/8-in. gravel material or had degraded asphalt. The principle factors influencing road dust emissions in the basin are season, vehicle speed (or road type), road condition, road grade, and proximity to other high-emitting roads. The TRAKER vehicle also measures the ambient PM concentration ahead of the front bumper. These measurements showed that urban areas had increases of PM concentrations from approximately 20 $\mu g/m^3$ in summer to approximately 100 $\mu g/m^3$ in winter. For air quality modeling purposes, the EFs produced from this study must be combined with traffic flow volumes to estimate total emissions. An analysis of the total emissions from the road sections surveyed indicated that urban areas (in particular South Lake Tahoe) with high traffic volume contain the largest emitting roads in the basin. Therefore, resources such as high-efficiency sweepers should be targeted to these roads to generate the most effective emission reductions. Additionally, roads should be maintained to a consistent standard because roads with loose gravel or degrading asphalt have the highest EFs.

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