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16. Abstract

This report summarizes the research undertaken to identify the sources of highway pollutants, and to determine their deposition and accumulation within the highway system and subsequent removal from the highway system to the surrounding environment. The purpose of this research was to identify opportunities to practice pollution mitigation. Research efforts included a literature review and field monitoring activities to determine, and quantify wherever possible: sources of highway pollutants, atmospheric deposition and removal, saltation, highway surface loads, runoff quantity and quality, groundwater percolation, accumulation of pollutants in soil and vegetation and the variables which affect the process of pollutant deposition, accumulation and removal. Titles of the volumes of this report are:

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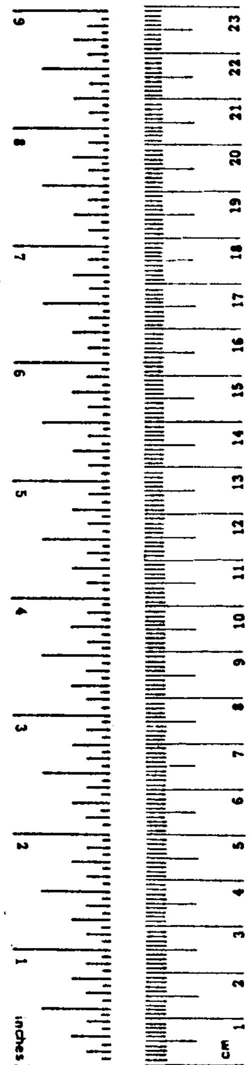
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

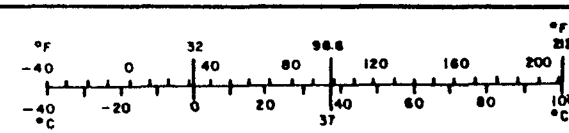
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The highway system is a potential source of a wide variety of possible pollutants to surrounding surface and subsurface waters through the mechanisms of the natural hydrologic cycle. The effects of a highway system on the environment plays an increasingly important role in the planning, design, construction, and operation of a transportation system. The Federal Highway Administration (FHWA), charged with the responsibility of protecting the environment from pollution from highway sources, has approached the problem in a multiphase research effort having the following objectives:

Phase 1: Identify and quantify the constituents of highway runoff.

Phase 2: Identify the sources and migration paths of these pollutants from the highways to the receiving water.

Phase 3: Analyze the effects of these pollutants in the receiving waters.

Phase 4: Develop the necessary abatement/treatment methodology for objectionable constituents.

The results of the Phase 1 study were reported in a six-volume document series entitled "Constituents of Highway Runoff" (1 through 6).

This research deals with the Phase 2 objective. Research was conducted to identify the sources of highway pollutants, and to investigate their deposition, accumulation , and subsequent removal from the highway system to the surrounding environment. This research was also performed to identify opportunities to practice pollution mitigation. To accomplish these objectives, a literature search and field monitoring program were conducted. The field monitoring program was divided into two categories:

1. Source investigative studies
2. Migration and fate studies

A four-volume series describes the results of the Phase 2 research. The titles of the various reports are:

Volume I - Sources and Migration of Highway Runoff Pollutants - Executive Summary

Volume II - Sources and Migration of Highway Runoff Pollutants - Methods

Volume III - Sources and Migration of Highway Runoff Pollutants - Research Report

Volume IV - Sources and Migration of Highway Runoff Pollutants - Appendix

This report, Volume I, summarizes the research conducted for Phase 2 of FHWA's four-phase program. Volume II, Methods, presents the details of the monitoring site selection and field monitoring procedures. Volume III contains the results of the literature search, analysis of the accumulated data, and conclusions and recommendations formulated from the data analysis. Volume IV, Appendix, contains the detailed data collected as a result of the field monitoring program.

METHODOLOGY

Potential sites from many States around the country were evaluated based upon the following considerations:

1. Adjacent land usage
2. Traffic characteristics
3. Precipitation characteristics and geographic location
4. Drainage area and highway design characteristics
5. Pavement characteristics
6. Logistical characteristics

The four sites selected were located in Milwaukee, WI; Sacramento, CA; Harrisburg, PA and Efland, NC. A summary of site characteristics is presented in Table 1.

Sources of many highway pollutants were found to be adequately documented in the literature (1) while further investigation was required for others including; pathogenic indicator bacteria, asbestos and polychlorinated biphenyls (PCB's). Significant data were collected with respect to presence and quantification of these constituents during FHWA's study on the

Table 1. Characteristics of selected sites.

Location	Type	ADT, vehicles day	Precipitation in/year		Drainage area, acres		% Paved	Surface Type	Hwy. length, ft.	Number of travel lanes	Type of section	Curb/ barrier
			Total	snow-fall	Total	Paved						
Milwaukee, Wisconsin I-94	Urban	116,000	30	45	7.60	4.90	64	Asphalt	1,373	8	Cut/fill	yes
Sacramento, California Hwy. 50	Urban	85,900	17	0	2.45	2.01	82	Concrete	1,400	8	At grade	yes
Harrisburg, Penn. I-81	Rural	27,800	38	35	2.81	1.05	45	Concrete	1,345	4	Cut/ At grade	no
Efland, North Carolina I-85	Rural	25,000	41	9	2.49	1.27	51	Asphalt	1,025	4	At grade	no

Metric Conversion units: 1 in = 2.54 cm, 1 ft = 0.305 m; 1 acre = 0.405 ha.

constituents of highway runoff, Phase 1 (4). However, there remained a gap in the understanding of the origin and fate of these constituents within the highway environment. Source investigative studies were conducted at the Milwaukee site in an attempt to fill those gaps. This information would be valuable in developing control and mitigation measures, by defining points at which abatement strategies can be effectively applied.

Monitoring was conducted at all sites to evaluate the qualitative and quantitative aspects of background pollutant loading to the highway system, pollutants originating from the highway system, and the mechanism of pollutant dispersion within and transfer out of the highway system. Measurement of variables which effect pollutant deposition, accumulation, and removal were also measured to facilitate data evaluation. These variables are traffic characteristics, maintenance activities, and climatic conditions. Field studies were conducted at each of the four sites for a minimum of twelve months to evaluate seasonal effects on these processes. Field monitoring included:

1. Atmospheric deposition
2. Total suspended particulates
3. Saltation
4. Highway surface loads monitored through sweeping/flushing studies
5. Runoff quantity and quality
6. Groundwater percolation monitored by lysimeters
7. Soil and vegetation studies
8. Traffic characteristics
9. Highway maintenance data
10. Climatological data

SUMMARY OF FINDINGS

Source Studies

Sources of many materials which deposit and accumulate on highway surfaces, median areas, and adjoining right-of-ways are documented in the literature (Table 2). Order of magnitude deposition rates are also available for many of these constituents. However, the deposition and subsequent

Table 2. Common highway runoff constituents and their primary sources (1, 7 through 17).

Constituent	Primary sources
Particulates	Pavement wear, vehicles, atmosphere, maintenance
Nitrogen, phosphorus	Atmosphere, roadside fertilizer application
Lead	Leaded gasoline (auto exhaust), tire wear (lead oxide filler material), lubricating oil and grease, bearing wear
Zinc	Tire wear (filler material), motor oil (stabilizing additive), grease
Iron	Autobody rust, steel highway structures (guard rails, etc), moving engine parts
Copper	Metal plating, bearing and bushing wear, moving engine parts, brake lining wear, fungicides and insecticides applied by maintenance operations
Cadmium	Tire wear (filler material), insecticide application
Chromium	Metal plating, moving engine parts, brake lining wear
Nickel	Diesel fuel and gasoline (exhaust) lubricating oil, metal plating, bushing wear, brake lining wear, asphalt paving
Manganese	Moving engine parts
Bromide	Exhaust
Cyanide	Anticake compound (ferric ferrocyanide, Prussian Blue or sodium ferrocyanide, Yellow Prussiate of Soda) used to keep deicing salt granular
Sodium, Calcium	Deicing salts, grease
Chloride	Deicing salts
Sulphate	Roadway beds, fuel, deicing salts
Petroleum	Spills, leaks or blow-by of motor lubricants, antifreeze and hydraulic fluids, asphalt surface leachate

(continued)

Table 2. (Continued)

Constituent	Primary source
Polyclorinated biphenyls, pesticides	Spraying of highway right-of-ways, background atmospheric deposition, PCB catalyst in synthetic tires
Pathogenic bacteria (indicators)	Soil, litter, bird droppings and trucks hauling livestock and stockyard waste
Rubber	Tire wear
Asbestos	Clutch and brake lining wear

magnitude of these constituents in highway runoff are site-specific and affected by such parameters as traffic characteristics, highway design, maintenance activities, surrounding land use, climate, and accidental spills.

The rainfall monitored at the Milwaukee site, the most urbanized and industrialized of the sites, contained highest maximum and median values for most parameters (mg/l) (Table 3). However, Sacramento, Efland, and Harrisburg often had larger constituent loadings per precipitation event (mg/m^2) than Milwaukee. This was probably a function of the larger total rainfall volume per event monitored at Sacramento, Efland, and Harrisburg. Deposition of chlorides via precipitation was higher during the winter than summer at Milwaukee and Harrisburg which may be attributable to chloride aerosols from street and highway salting activities.

Background bulk precipitation data (wet and dry deposition) indicate that total particulate matter (TPM) loadings were approximately four times higher at the urban sites than at the rural sites (Table 4). Similarly, background metals deposition was higher at the urban sites. The data also indicate that dry deposition is a more important source of metals than wet deposition.

Although enteric bacteria (total coliform, fecal coliform, and fecal streptococci) were present in paved and unpaved runoff at the Milwaukee site, they were not detectable in precipitation, dustfall, or ambient air samples. It appears that the roadway surface is periodically "seeded" with debris containing enteric bacteria. A possible source could be trucks carrying livestock and stockyard waste. This is consistent with the fecal coliform to fecal streptococcus ratios monitored in runoff which indicated the enteric bacteria on roadway surfaces appeared to be of animal origin. Bacteriological data also indicated fecal coliforms remained viable within roadway dust and dirt for relatively long periods of time (at least seven weeks). Fecal coliform and fecal streptococcus bacteria remain viable in stagnant storm sewer water for at least 13 days.

Asbestiform material was not detected in precipitation, runoff, dustfall, or air samples collected at the Milwaukee I-94 site. These results are

Table 3. Summary of precipitation quality (mg/l) at monitoring sites.

Parameter	Milwaukee I-94 Range	Median	n	Sacramento Hwy. 50 Range	Median	n	Harrisburg, I-81 Range	Median	n	Efland, I-85 Range	Median	n
pH	2.7-6.8	3.8	16	4.9-6.3	5.0	5	3.2-5.6	4.3	10	3.4-5.4	4.2	14
TS	16-210	44	16	20-84	64	5	4-68	30	10	2-33	12	13
TVS	7-70	19	16	6-20	13	4	5-48	12	8	ND-24	7	6
SS	3-55	12	16	2-18	4	5	2-30	5	10	ND-9	1	13
VSS	2-12	5	15	ND-12	1	5	1-3	2	8	ND-5	ND	6
TOC	ND-26	8	7	ND-11	11	4	ND-19	5	5	5-16	11	2
COD	11-45	23	7	8-32	11	4	ND-12	ND	5	8-17	13	2
Pb	ND-0.3	ND	16	ND-0.1	ND	5	ND-0.2	0.02	10	ND-0.02	ND	13
Zn	ND-3.9	0.17	16	0.03-0.20	0.11	5	0.048-0.29	0.08	10	ND-0.05	0.03	13
Fe	ND-1.0	0.20	16	ND-0.3	0.18	5	0.15-0.82	0.30	10	0.05-1.50	0.08	13
Cr	ND-0.04	ND	16	ND-0.02	ND	5	ND-0.11	ND	8	ND-0.01	0.002	13
Cu	ND-0.71	0.04	16	ND-0.06	0.035	5	0.020-0.16	0.04	8	0.01-0.09	0.03	13
Cd	ND-0.02	ND	16	ND-0.04	0.008	5	ND-0.04	ND	8	ND-0.004	ND	13
Ni	ND-0.2	ND	16	ND-0.1	0.05	5	ND-0.2	ND	8	ND-0.02	ND	13
As	ND	ND	2	ND	ND	2		ND	1		ND	1
Hg x 10^{-3}	ND	ND	2	ND	ND	3	ND	ND	2		ND	1
NO_2+NO_3	0.25-1.96	0.79	16	0.07-0.52	0.16	4	0.03-1.03	0.20	8	0.03-0.81	0.19	7
TKN	1.0-3.2	2.0	16	ND-1.3	1.1	4	ND-1.1	0.64	8	ND-2.00	0.84	7
PO_4-P	ND-0.14	0.05	16	ND-0.06	ND	4	ND-0.04	ND	8	ND-0.03	ND	7
Sulfate	ND-12	3	15	ND-1	ND	5	ND-13	ND	8	ND-5.00	ND	5
Na		1.25	1	0.3-14	2.0	3	ND-1.4	0.2	5	ND-2.00	0.23	8
Cl	ND-27	9	15	ND-25	3	5	ND-5	1	9	ND-6.00	3.00	8
PCB x 10^{-3}	ND-0.10	0.05	3		0.31	1	0.14-0.26	0.20	2		ND	1
Rubber		0.275	1		ND	1			0			0
Oil & grease		ND	1			0	ND-2	ND	4	ND	ND	2
Precipitation, in	0.10-1.18	0.25	16	0.50-1.47	1.14	5	0.10-1.18	0.54	10	0.22-3.70	1.15	14

n = Number of observations.
ND = Not detectable.

Metric units: To convert in to cm multiply by 2.54.

Table 4. Summary of bulk precipitation loadings (mg/m^2/day) at monitoring sites.

Parameter	Milwaukee I-94 Range	Milwaukee I-94 Mean Median*	Milwaukee I-94 n	Sacramento Hwy. 50 Range	Sacramento Hwy. 50 Mean Median*	Sacramento Hwy. 50 n	Harrisburg I-81 Range	Harrisburg I-81 Mean Median*	Harrisburg I-81 n	Efland I-85 Range	Efland I-85 Mean Median*	Efland I-85 n
TPM[a]	60-230	130	10	20-890	160	24	11-65	30*	22	8.66-103	40.3	27
Pb	0.008-0.124	0.057	3	0.033-1.00	0.245	5	ND-0.063	ND	4	0.001-0.015	0.006	7
Zn		0.258	1	0.009-0.042	0.023	5	0.008-0.026	0.015	4	0.00004-0.018	0.007	7
Fe	0.327-4.17	1.86	3	1.00-4.70	2.59	5	0.236-0.617	0.382	4	0.024-0.672	0.424	7
Cr	0.001-0.012	0.005	3	0.009-0.120	0.033	5	0.001-0.002	0.002	4	0.00002-0.005	0.002	7
Cd		ND	1	ND-0.11	ND*	5	ND-0.001	ND*	4	ND-0.0007	ND*	7
Ni	0.001-0.012	0.008	3	ND-0.663	0.004*	5		ND	4	ND-0.002	ND*	7

[a] TPM = Total particulate matter.
n = Number of observations.

consistent with those of FHWA's Phase I Study on highway runoff constituents (4). During this study no asbestiform material was detected in 19 out of 21 runoff samples. For the two samples which contained asbestiform material, no firm conclusions could be drawn. These data indicate that the quantity of asbestiform material present in the highway system, is either below detection limits, or difficult to detect.

Polychlorinated biphenyls were detected in soil, vegetation, precipitation, highway surface dust and dirt, and runoff samples. Runoff studies indicated the low levels of PCB's in the highway environment are transported via runoff during storm events. Sources of PCB in highway runoff included precipitation, highway surface dust and dirt, and contaminated soil eroded by the runoff from unpaved surfaces adjoining the highway.

The deicing salt used at Milwaukee was analyzed for contaminants. The salt contained lead, zinc, chromium, copper, cadmium, nickel, and cyanide. Cyanide is an anticake compound used to keep salt granular. The loading of cyanide to the highway surface from rock salt was approximately 0.79 kg/km/yr. When comparing the estimated metals deposition from rock salt to the metals load per runoff event at Milwaukee during the winter , it appears rock salt may be an important source of cadmium (0.035 kg/km/yr) and nickel (0.225 kg/km/yr).

At Efland, deicing agents (rock salt and calcium chloride/sand mixture) were also analyzed for contaminants. Lead, iron, chromium, copper, and cyanide were found to be present in the rock salt sample analyzed. However, the salt used at Efland was lower in contaminants than at Milwaukee. Whereas, the salt applied at Milwaukee was an important source of cadmium and nickel, it was not detectable in the salt used at Efland. The contaminants associated with deicing agents appear to vary with the source of the deicing agent and additivies used.

Migration Studies

Field studies were conducted at the four sites to evaluate the quantitative and qualitative aspects of background pollutant deposition (source studies), pollutant accumulation due to background and highway related sources, and the mechanisms of pollutant dispersion.

Bulk precipitation data (wet and dry atmospheric deposition) were collected to establish the level of pollutants migrating from the highway to the surrounding environment through atmospheric processes. The impacted area (area adjacent to the highway receiving total particulate matter [TPM] and associated metals) was defined using bulk precipitation and soils data. Metals content of the first cm of soil was used to reflect the atmospheric deposition of highway related metals in the topsoil layer of areas adjacent to the highway. Based upon TPM, associated metals deposition, and data from the one-centimeter soil study, the impact area was approximately 35 m from the edge of pavement at Milwaukee, 35 m at Sacramento, 15 m at Harrisburg, and 12 m at Efland. The smaller impact areas at Harrisburg and Efland, compared to Milwaukee and Sacramento, are probably a function of average daily traffic (27,800 and 25,500 vehicles per day at Harrisburg and Efland compared to 116,000 and 85,900 vehicles per day at Milwaukee and Sacramento). Mean TPM transport rate for the period monitored was 29.6 kg/km/day at Milwaukee, 29.8 kg/km/day at Sacramento, 12.3 kg/km/day at Harrisburg, and 1.14 kg/km/day at Efland. TPM transport from the highway system was seasonal for all sites. At sites with winter seasons, TPM rates were generally highest during the winter period. At Sacramento, the summer drought period produced the highest TPM rates.

Atmospheric deposition of highway-generated TPM and associated metals onto areas adjacent to the highway surface appear to be related to:

1. Average daily traffic.
2. Wind speed and direction.
3. Available surface load.
4. Terrain and landscape features.

Studies were performed at Milwaukee to determine the precision (closeness of repeated measurements of the same quantity) of bulk precipitation measurements. Bulk precipitation, as monitored during this study, provided precise measurements of TPM deposition. However, the data showed these measurements can be affected by:

1. Localized effects due to vehicular turbulence.
2. Severe meteorological conditions.

Another mechanism for the removal of pollutants from the highway through the atmosphere is saltation. Saltation is transport through bouncing particles. The quantity of saltating particles (sand-sized particles injected into the atmosphere by vehicular turbulence) reaching areas adjacent to the highway appears to be related to:

1. Average daily traffic
2. Wind speed and direction
3. Available surface load (seasonal variation)
4. Highway drainage design
5. Proximity of travel lanes to right-of-way area
6. Landscape features near the highway affecting wind patterns.

Milwaukee, Harrisburg, and Efland had higher average monthly saltation rates during winter and spring. This period was generally characterized by high surface loads and high average wind speeds. A correlation exists between metals and saltating particles, and the quantity of lead and iron, associated with saltating particles, is related to average daily traffic.

Monitoring of runoff from the paved and unpaved areas was segregated to determine pollution loadings leaving the highway drainage system and develop insights into the hydraulics of pollutant movement and concentrations at various points in the drainage scheme. At the Milwaukee and Sacramento sites (curb and gutter drainage design), the contribution of the unpaved area to the total constituent load removed via runoff was negligible. At Harrisburg (flush shoulder drainage design), the unpaved area contributed approximately 17 percent of the total load for most constituents. However, the overall constituent load at Harrisburg was extremely low compared to Milwaukee and Sacramento.

Precipitation at the four sites monitored can be characterized as acid (median pH at Milwaukee was 3.8, 4.3 at Harrisburg, 4.2 at Efland, and 5.0 at Sacramento). However, the highway system at all sites had a large capacity to neutralize the runoff of acid precipitation before it reached the surrounding environment. Ground-water percolation data indicated the soil system adjacent to the highway sections monitored at Milwaukee and Sacramento had considerable buffering capacity against acid rain while the Efland and Harrisburg soil systems had limited buffering capacity. The prevalence of acid rain in the United States (18) and the apparent ability of highway systems to neutralize this acid rain may have important implications when considering pollutant migration from the highway through the areas adjacent to the highway. For example, the solubility of metals is a function of pH (generally higher solubilities occur at the extremes of the pH scale) and the quantity of anionic complexing agents and organic matter present. Soluble metals would be easier to remove from the highway surface, tend to migrate further, and be readily assessable for bioaccumulation.

Table 5 presents a summary of highway runoff composite quality data for all storms monitored at all sites. Highway runoff at Milwaukee, the site with the highest average daily traffic, had the highest solids loadings and generally the highest loadings for most parameters. Sites where deicing agents were applied showed increases in total solids, sodium, and chloride loadings during winter periods. Correlation analysis between total solids (TS) and other runoff quality constituents indicate that TS is a good carrier parameter (parameter showing the highest degree of association with all other quality parameters). This is consistent with the results of FHWA's original study on constituents of highway runoff, Phase 1 (3).

Field surveys at two sites demonstrated priority pollutants were present in the highway environment and that they migrated via runoff during storm events. A significant number of organic priority pollutants were present in the highway environment. However, the major portion of the priority pollution

Table 5. Summary of highway runoff composite quality data for all four monitoring sites - overall monitoring period (winter and nonwinter).

Parameter	Pollutant concentration, mg/l		Pollutant loading, lb/mi[a]/event	
	Minimum	Maximum	Minimum	Maximum
pH	4.90	7.95		
TS	68	57,400	0.85	17,400
TVS	10	510	0.25	1,200
SS	6	2,160	0.22	6,080
VSS	4	317	0.04	915
Pb	ND	6.30	ND	20.3
Zn	0.036	2.90	0.0004	7.52
Fe	0.30	115	0.012	150
Cr	ND	0.19	ND	0.556
Cu	ND	0.59	ND	1.93
Cd	ND	0.06	ND	0.010
Ni	ND	0.22	ND	0.66
Hg	ND	0.001	ND	0.001
As	ND	0.03	ND	0.13
Na	2.1	22,500	0.02	12,600
Ca	4.0	450	0.92	202
Cl	2.0	35,000	0.07	13,500
Oil & grease	1	21	0.3	69
PO_4-P	0.03	4.45	0.01	11.5
TKN	ND	9.80	ND	15.5
NO_2+NO_3	ND	9.00	ND	8.67
TOC	4	182	2.45	425
COD	16	660	4.92	1930
SO_4	ND	180	ND	51

[a]Both directions irrespective of number of lanes.

ND = Not detectable.

Metric units: To convert lb/mi to kg/km multiply by 0.2819.

load in the highway runoff was attributed to the metal priority pollutants - lead, zinc, and copper.

Mean highway surface constituent loads were generally highest at Milwaukee, lowest at Harrisburg, and intermediate at Sacramento and Efland (Table 6). The range of loading values at the Sacramento Hwy. 50 site showed more variability than at Harrisburg, while order of magnitude differences existed between the minimum and maximum constituent values at Milwaukee. The differences in the magnitude of surface loads and variability in the range of loading values are probably attributable to differences in site drainage and traffic characteristics, seasonal variations, and maintenance activities.

Solids and pollutants associated with solids tend to accumulate in the distress and median lanes. Pollutants which are more soluble tend to be more uniformly distributed across the distress, median, and travel lanes. Apparently, vehicular turbulence tends to move any solids deposited on travel lanes to the outer lanes (distress and median lanes). Lateral variation in surface load at a given point in time appears to be a function of profile, grade, and other factors including inlet placement, seasonal characteristics, maintenance activities, and traffic patterns.

Commercial street sweeper efficiency studies performed at Milwaukee showed that efficiency of pick-up was generally highest for solids and those constituents associated with solids, and lowest for the more soluble constituents. Sweeper efficiency was higher in summer than spring. The surface load was more compacted in spring than summer. Presumably the compacted spring surface load was more difficult to remove by surface sweeping.

At the sites monitored, the major removal mechanism of runoff and atmospheric removal appear to involve particles in size generally less than 250 microns. Approximately 21 to 57 percent of the total highway surface metals load at the Milwaukee site, 69 to 91 percent at the Sacramento site, and 27 to 54 percent at the Efland site are associated with the less-than-250-micron particle size class. A mass balance was calculated for

Table 6. Surface constituent loadings at the sites monitored - pounds per highway mile[a] (all lanes).

Parameter	Milwaukee I-94		Sacramento Hwy 50		Harrisburg I-81		Efland I-85	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Gross material[c]	112-1,900	669	ND-214	ND[b]	31.6-75.8	53.7	3.86-747	224
Litter[d]	746-13,400	4,070	93.2-379	245	2.46-4.98	3.72	1600-7090	4,040
TS[e]	2,440-66,400	18,100	282-433	360	32.9-40.0	36.5	40.5-1940	566
TVS	146-6,550	1,400	22.0-36.4	26.6	12.3-12.6	12.5	7.24-122	41.3
TOC	25.1-1140	228	5.98-12.1	8.72	--	3.77	--	4.28
COD	106-3,660	1,020	16.5-56.8	33.8	--	8.11	--	14.3
Pb	3.64-293	64.8	0.914-2.23	1.43	0.032-0.056	0.044	0.058-1.90	0.593
Zn	1.74-96.1	18.2	0.158-0.342	0.23	0.042-0.054	0.048	0.024-0.646	0.208
Fe	8.86-4,290	1200	9.70-13.8	12.4	0.324-0.532	0.428	0.722-41.6	12.2
Cr	0.026-5.46	1.68	0.026-0.075	0.043	0.002-0.004	0.003	0.002-0.036	0.013
Cu	0.138-36.1	6.75	0.032-0.040	0.037	0.006-0.010	0.008	0.004-0.112	0.036
Cd	0.008-0.426	0.115	0.0005-0.002	0.001	0.0006-0.0009	0.0008	0.002-0.004	0.003
Ni	0.032-6.05	1.45	0.008-0.026	0.020	0.006-0.012	0.008	0.002-0.030	0.010
As	0.004-0.044	0.017	0.0002-0.004	0.002	--	ND[b]	--	ND[b]
$Hg \times 10^{-3}$	0.1-4.0	0.3	0.01-0.02	0.02	--	ND[b]	--	ND[b]
NO_2+NO_3	0.050-0.318	0.170	0.018-0.176	0.117	0.138-0.316	0.227	0.042-0.064	0.049
TKN	1.45-36.8	8.53	0.366-0.730	0.521	0.296-0.348	0.322	0.194-1.36	0.773
PO_4-P	1.02-23.7	5.46	0.176-0.228	0.205	0.022-0.024	0.023	0.042-1.18	0.368
Ca	666-4,130	1,930	0.694-5.74	3.76	--	3.32	--	0.414
Na	6.35-110	37.2	0.264-0.934	0.521	0.720-0.899	0.810	0.394-0.624	0.497
Cl	4.75-91.4	25.4	0.408-1.82	0.922	1.44-1.76	1.60	0.646-1.00	0.826
SO_4	3.82-16.8	9.79	0.542-6.04	2.25	2.45-2.80	2.63	0.688-0.854	0.771
Oil & grease	17.0-730	167	0.720-4.09	1.73	0.614-1.72	1.17	0.478-0.690	0.584
Rubber	60.7-648	206	--	43.0	--	1.38	--	1.27

[a] Both directions.

[b] Median.

[c] Gross material is defined as very large litter which can be picked up by hand (hub caps, tire fragments, etc.).

[d] Litter is defined as particles larger than 3.35 mm not including gross material.

[e] Total solids are defined as particles less than 3.35 mm.

ND = Not detectable. Metric units: To convert lb/mi to kg/km multiply by 0.2819.

total solids less than 250 microns (TS_{250}) and associated metals at the Milwaukee site for the period April 17 through October 31, 1979 (summer period). The mass balance is summarized in Table 7. A plus (+) next to a mass balance component indicates an input to the system while a minus (-) indicates an output from the system. The mass balance indicated in all cases, vehicles were the largest source of TS_{250} and associated metals. Vehicular deposition during the summer period was calculated to be 0.31 g/km/vehicle. The quantity of surface load removed by runoff, atmospheric processes, and maintenance activities (sweeping the highway surface) varied by constituent parameter. A mass balance was also calculated for TS_{250}, sodium, and chloride at the Milwaukee site for the period November 1 through May 21, 1980 (winter and spring period). The mass balance for this period indicated the major source of these constituents was maintenance (deicing agent application). The major removal mechanism was runoff and baseflow (Table 8). Vehicular deposition during the winter period was calculated to be 0.98 g/km/vehicle, approximately three times higher than the summer period. The higher winter vehicular deposition rate is probably due to increased exhaust emissions from stop-and-go driving during hazardous conditions, increased autobody rusting from corrosive deicing agents, and "carry on" deposition.

Mass balances for TS_{250}, and selected metals were calculated for the period June 30, 1981 through April 22, 1982 at the Efland site (Table 9). Average vehicular deposition rate for this period was 0.15 g/km/vehicle. Similar to Milwaukee, the mass balance indicated vehicles were the largest source of TS_{250} and associated metals. A mass balance was also calculated for TS_{250}, sodium, and chloride at Efland for the period when deicing agents were applied (December 3, 1981 through March 30, 1982). During this period, the majority of the TS_{250} deposited on the highway was due to deicing agent application (Table 10). Runoff was the major removal mechanism.

Soils data all sites indicated metals and sodium concentrations were generally higher in the topsoil layers (major rooting zone usually 10 cm deep) than substrate layers, and were highest for the near highway samples decreasing with distance from the highway. Chlorides did not show this gradient. Lysimeter data indicated that chlorides are removed from the

Table 7. Mass balance for TS_{250} and associated metals - April 17 through October 31, 1979 at the Milwaukee I-94 site.

Balance component	Balance symbol	Parameter, lb/mi[a]							
		TS_{250}	Pb	Zn	Fe	Cr	Cu	Cd	Ni
Initial load	+	3,530	17.4	3.76	235	0.450	1.64	0.032	2.91
Deposition									
Vehicle	+	25,499	62.5		1079	1.53		0.125	8.09
Rainfall	+	2,440	0.0		4.16	0.0		0.0	0.0
Dustfall	+	1,228	0.012		2.88	0.039		0.0005	0.00003
Maintenance	+	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Highway surface load	=	32,697	79.9	49.2	1321	2.02	12.4	0.158	11.0
Removal									
Runoff	-	18,783	37.8	27.2	280	1.12	8.63	0.110	4.81
Atmospheric	-	7,886	0.038		660	0.003		0.006	2.29
Sweeping	-	5,478	35.3	3.96	362	0.854	3.27	0.040	3.46
Remaining load	-	597	6.37	2.67	20.0	0.031	0.460	0.002	0.394
Surface load unaccounted for	=	-47	+0.392		-1.00	0.012		0.0	0.046
Percent error		0.1	0.5		0.1	0.6		0.0	0.4

[a]Both directions.

Metric units: To convert lb/mi to kg/km multiply by 0.2819.

Table 8. Mass balance for TS_{250}, sodium and chloride - November 1 through May 21, 1980.

Balance component	Balance symbol	Parameter, lb/mi[a] TS_{250}	Cl	Na
Initial load	+	597	0.636	0.970
Deposition				
Vehicle	+	80,377	111	
Atmospheric	+	3,217		
Maintenance	+	129,018	78,301	48,665
Highway surface load	=	213,209	78,413	48,730
Removal				
Runoff	-	111,574	90,400	43,513
Baseflow	-	65,734	8,941	5,583
Atmospheric	-	11,957		
Sweeping	-	23,716	82	66
Remaining load	-	311	1.06	0.667
Surface load unaccounted for	=	-83	-21,011	-433
Percent error		0.03	27.0	0.9

[a]Both directions.

Metric units: To convert lb/mi to kg/km multiply by 0.2819.

Table 9. Mass balance for TS_{250}, lead, zinc and iron - June 30, 1981 through April 22, 1982 at the Efland I-85 site.

Balance component	Balance symbol	Parameter, lb/mi[a]			
		TS_{250}	Pb	Zn	Fe
Initial load	+	41	0.100	0.058	0.72
Deposition					
Vehicle	+	4.061	0.836	3.289	147.98
Atmosphere	+	1,276	0.368	0.168	16.78
Maintenance	+	10,980	0.018	0.0	0.45
Highway surface load	=	16,358	1.322	3.515	165.93
Removal					
Runoff	-	14,592	0.820	2.779	144.38
Atmospheric	-	1,417	0.425	0.223	15.62
Remaining load	-	169	0.021	0.412	0.0
Surface load unaccounted for	=	180	0.056	0.101	5.93
Percent error		1.1	4.2	2.9	3.6

[a]Both directions.

Metric units: To convert lb/mi to kg/km multiply by 0.2819.

Table 10. Mass balance for TS_{250} sodium and chloride - December 3, 1981 through March 20, 1982 at the Efland I-85 site.

Balance component	Balance symbol	Parameter, lb/mi[a]		
		TS_{250}	Cl	Na
Initial load	+	449	1	1
Deposition				
Vehicle	+	893	57	37
Atmospheric	+	432		
Maintenance	+	10,980	6796	4058
Highway surface load	=	12,754	6854	4,096
Removal				
Runoff	-	11,751	6314	3,342
Atmospheric	-	540		
Remaining load	-	183	518	745
Surface load unaccounted for	=	280	22	9
Percent error		2.2	0.3	0.2

[a]Both directions.

Metric units: To convert lb/mi to kg/km multiply by 0.2819.

topsoil layer shortly after spring thaw. Accumulation of metals and sodium by vegetation was generally related to the concentration of these constituents in the topsoil layer.

At the Milwaukee site, plant litter was highest for the near highway samples, although biomass production was slightly higher for samples obtained further from the highway. The higher levels of pollutants in the soil and plant tissue near the highway's edge, especially heavy metals and soluble salts, may decrease the number and activity of the microorganisms involved in the decomposition of plant tissue. At the Sacramento site no vegetation grew near the highway. This would be expected, because soils next to the highway were sandy, low in organic matter, high in soluble salts, low in nutrients, and high in lead and zinc. The vegetation and soils data indicate that normal ecosystem processes may be affected in areas immediately adjacent to the highway (1 to 2 m), especially near highways with high ADT (greater than 85,000 vehicles per day).

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