

Review of Street Sweeping Measures for Reducing PM Road Dust Emissions

Megan McCabe and Kenneth Craig
A&WMA Upper Midwest Conference
November 7, 2024

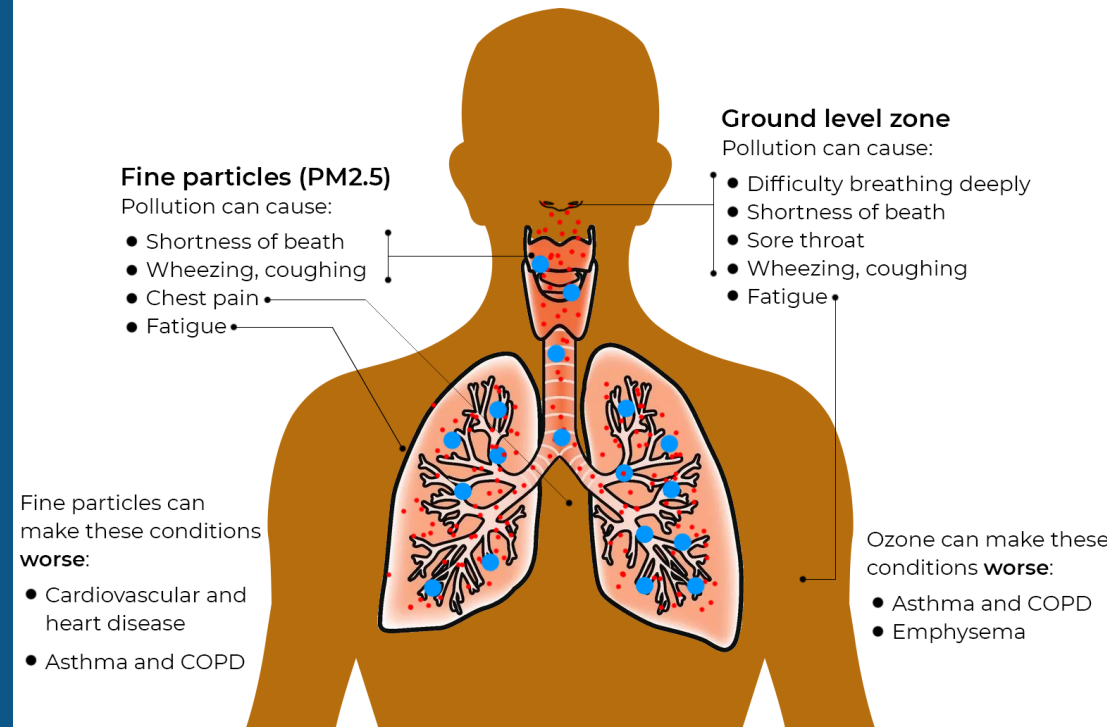
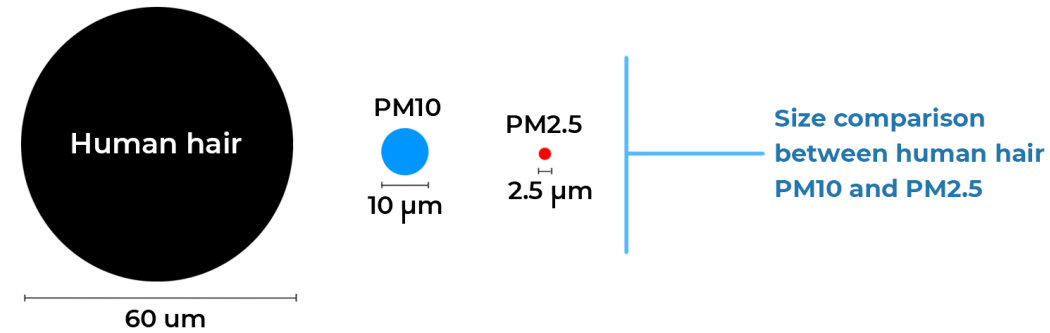
Outline

- Introduction
 - Roadway Emissions
- Background
 - Types of Sweepers
- Effectiveness of Street Sweeping
- Examples of Street Sweeping Practices
- Conclusions

So What?

What is particulate matter (PM)? Why should we care?

- Tiny solid and liquid particles suspended in the air
 - Dust, pollen, and microscopic pollutants
- Small PM can be inhalable and can penetrate deep into lungs, causing serious health issues
 - PM < 10 μm (PM₁₀)
 - PM < 2.5 μm (PM_{2.5})



So What?

Traffic pollution is a significant contributor to PM emissions

- Exhaust emissions – tailpipe emissions
- Nonexhaust emissions – emissions from mechanical abrasion of brakes, tires, road surfaces, and resuspension of road dust
 - Re-entrained road dust is a significant contributor to nonexhaust emissions

Nonexhaust PM₁₀ emissions factors

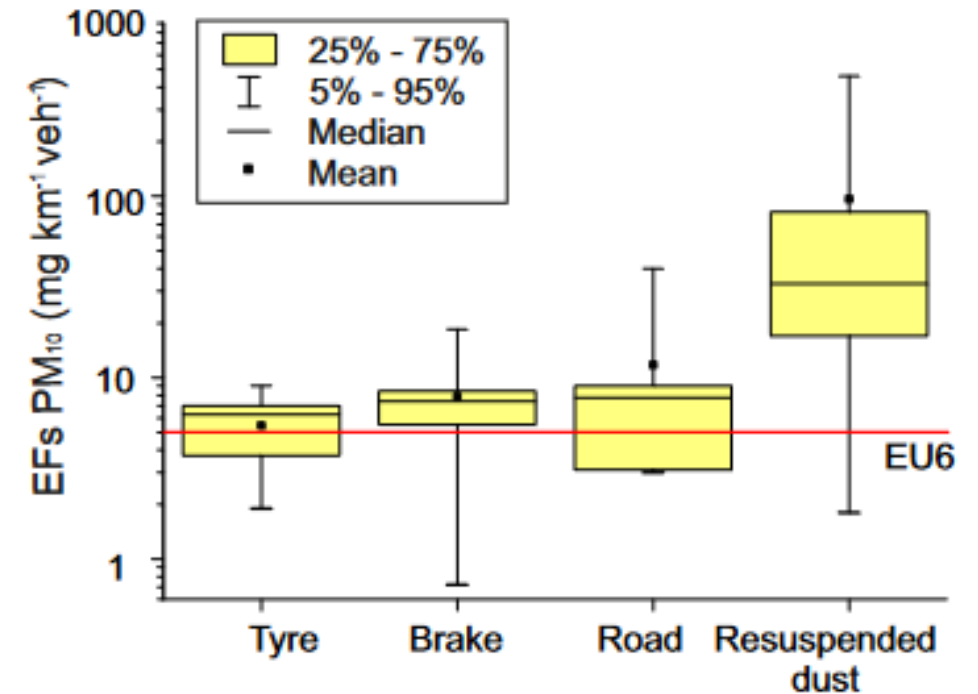


Fig. 4. Mean, median, 25/75 percentiles for box, and 5/95 percentiles for PM₁₀ emission factors of NEE sources, based on the literature review reported in Table 3 (brake wear), Table 6 (tyre wear), Table 7 (LDV road wear), and Table 8 (resuspended dust).

(Piscitello et al., 2021)

Emissions From Re-Entrained Road Dust

- Vehicles traveling over the road cause loose material (road dust) to be resuspended into the air
- Originate from loose material present on the road surface, known as "silt loading"

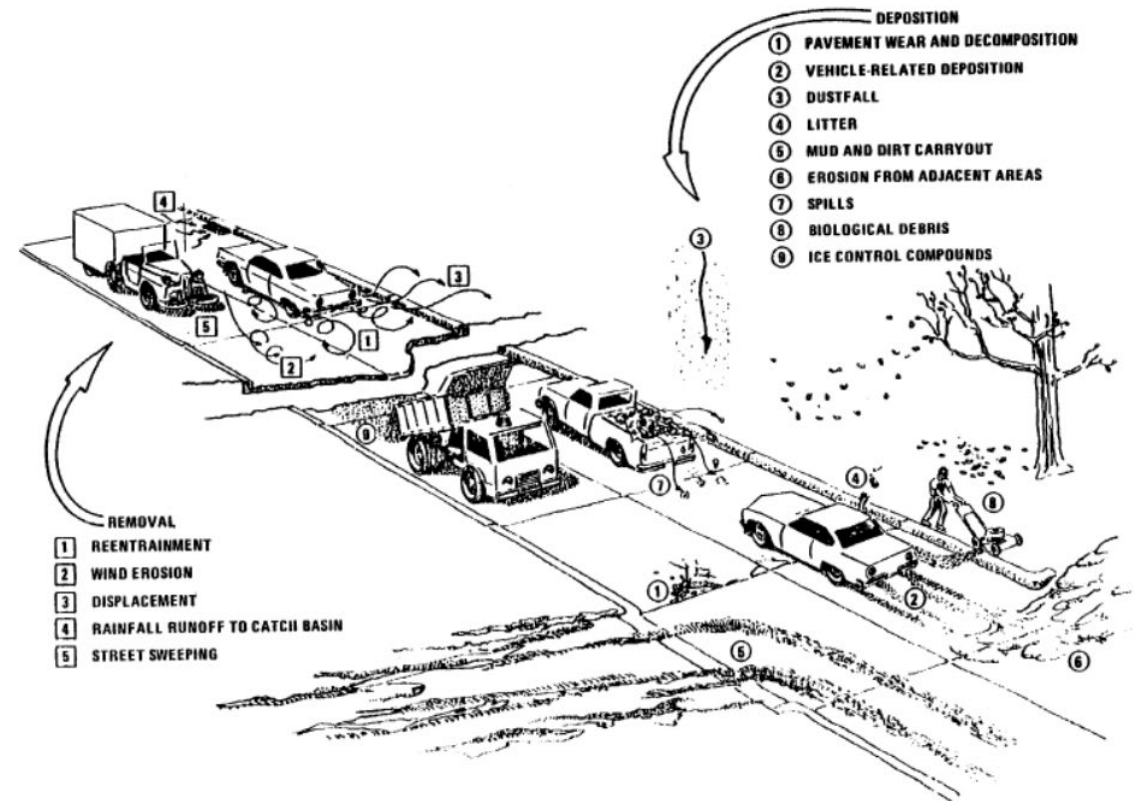


Figure 13.2.1-1. Deposition and removal processes.

(AP-42 13.2.1 Paved Roads)

Factors Affecting Re-Entrained Road Dust Emissions

- Silt loading
- Vehicle speed
- Average daily traffic
- Number of lanes and average daily traffic (ADT) per lane
- Fraction of heavy vehicles
- Presence of curbs, storm sewers, and parking lanes
- Climate factors – precipitation

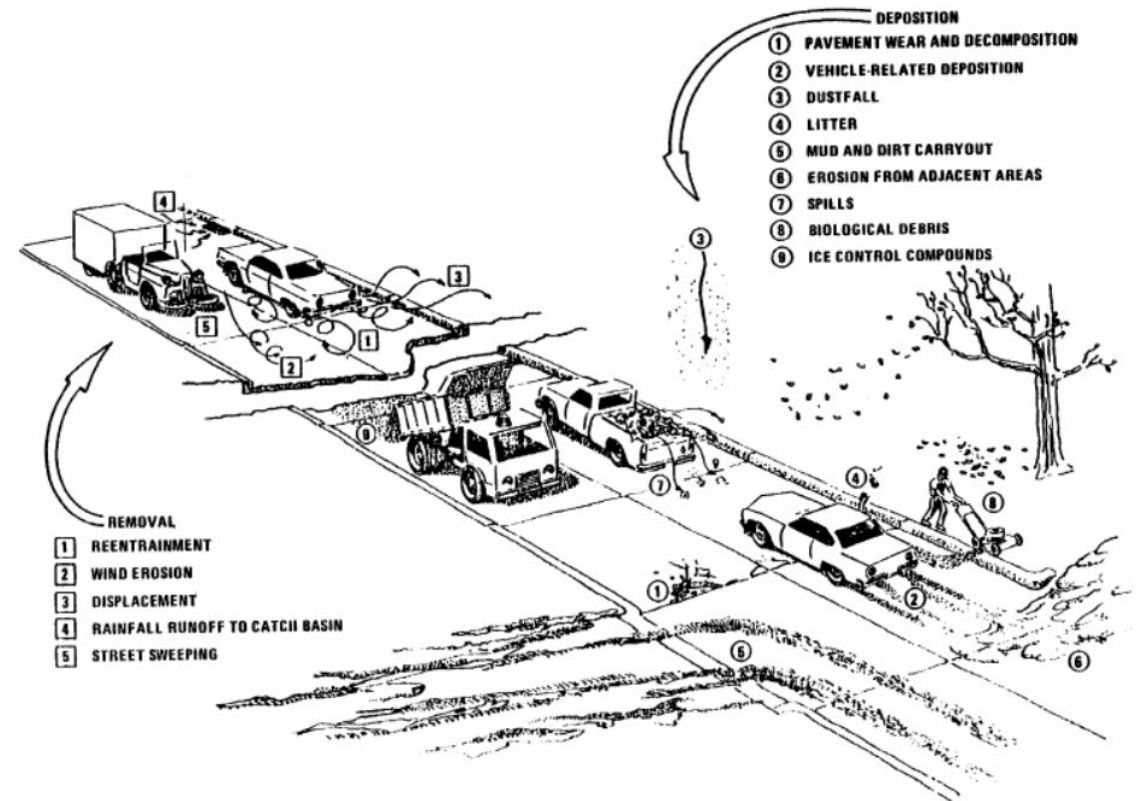


Figure 13.2.1-1. Deposition and removal processes.

(AP-42 13.2.1 Paved Roads)

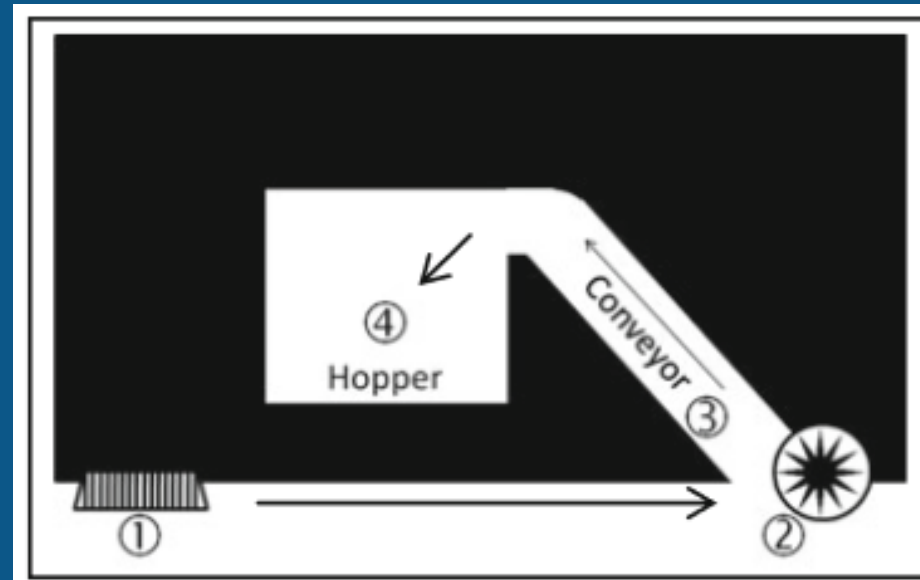
Common Types of Street Sweepers

- Mechanical Broom Sweeper
- Vacuum Sweeper
- Regenerative Air Sweeper



Mechanical Broom Sweeper

Uses rotating cylindrical brooms to sweep debris onto conveyor belt, and deposits debris into a collection hopper



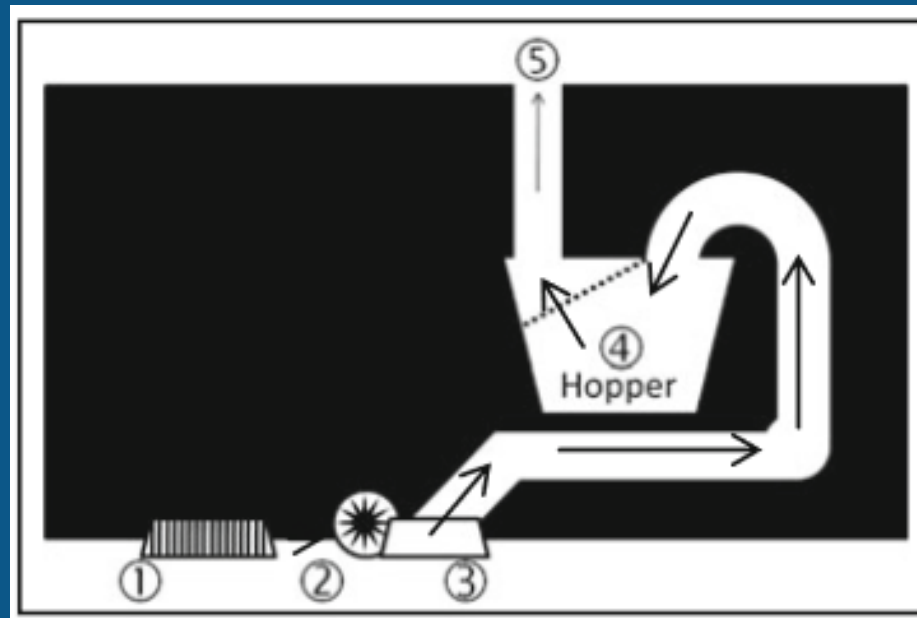
(Calvillo et al., 2015)



<https://www.bortekpx.com/wp-content/uploads/2019/07/Global-R4-Regenerative-Air-Street-Sweeper-neighborhood-municipal-bortek-pwx.jpg>

Vacuum Sweeper

Uses powerful suction to remove debris from the road surface



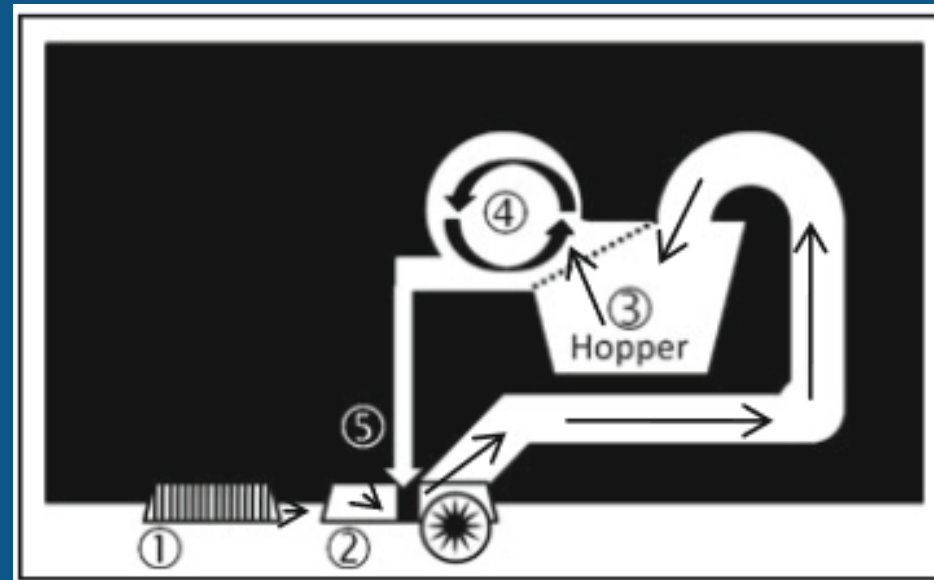
(Calvillo et al., 2015)



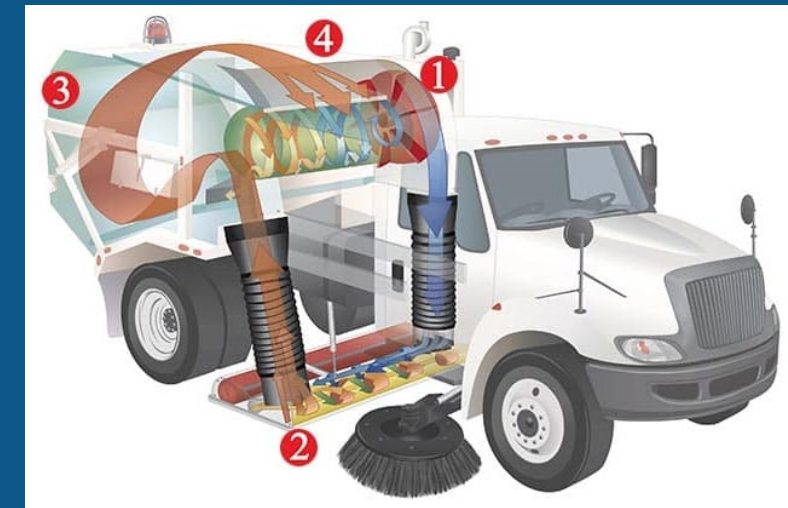
https://cdn11.bigcommerce.com/s-j6108ta7u/images/stencil/1280w/products/6013/4563/Bucher-V80_72457.1612379379.jpg?c=2

Regenerative Air Sweeper

Uses a closed-loop air system to dislodge debris with air blasts and then vacuum it up



(Calvillo et al., 2015)



<https://www.tymco.com/wp-content/uploads/regenerative-air-sweeper.jpg>

PM₁₀-Certified Sweepers

California's South Coast Air Quality Management District (SCAQMD) developed a street sweeper testing protocol that certifies equipment based on two factors:

- A pick-up efficiency greater than or equal to 80%
- An ability to limit PM₁₀ entrainment during the sweeping process



TYMCO Sweeper Model 435 | Mid-Atlantic Waste Systems (mawaste.com)

Methodology

Reviewed studies that investigated street sweeping as a control measure for road dust PM emissions

- Searched for the following terms: "street sweeping," "street cleaning," "street sweepers," "emission factors," "resuspension," "road dust," "air quality," "PM," etc.
- Only reviewed studies investigating particles that could become airborne
- Did not include studies that focused solely on street washing without incorporating street sweeping techniques

Results

Reviewed 18 studies that investigated street sweeping and PM measurements within the last 30 years

- Ten studies reported positive results (reduced PM emissions or ambient PM concentrations)
- Five studies reported negative results (increase PM emissions or ambient PM concentrations)
- Two studies reported no change
- One study had mixed results



Highlights & Common Trends

- Measurement techniques of effectiveness were inconsistent across the studies
- Most studies were short-term
- Multiple factors influenced effectiveness
- Sweeping and washing showed improvements over the short term
- Type of sweeper improved the likelihood at reducing PM emissions or concentrations
- Studies lacked detail about the type of street sweeper (if PM₁₀-certified or not), pavement conditions, drainage/curb information, and traffic information

Measurement Techniques

Silt Loading

- Measure silt loading on ground to apply to emission rate calculations
- Compare to before/after or reference site

Emission Rates

- Directly measure emission rate by mobile platform or downwind and upwind measurements

Ambient Air Concentrations

- Measure nearby ambient PM
- Compare to a reference site

Factors Influencing Effectiveness

- Type of Sweeper
- Climate Conditions
 - Humidity
 - Rainfall
- Roadway Type
 - Drainage near roadway
- Frequency
 - Sweeping after snow events

Effectiveness of Sweeper Type

Mechanical

- Most studies showed mechanical sweepers had negative impacts
- Increased PM concentrations during and directly after sweeping

Vacuum

- Least studied sweeper
- Unclear if studies used dust suppression or not
- Vacuum alone did not produce positive results
- Vacuum and washing showed to be beneficial

Regenerative Air

- Showed the most positive results
- One study showed negative results (increase in emission rates)

Mechanical Versus Regenerative Air Sweepers

Toronto Street Sweeping Studies 2005 & 2015

- Compared entrainment and the efficiency of the removal of material
 - Tunnel study in 2005
 - Further studies in 2014
- Created their own PM₁₀ and PM_{2.5} Street Sweeper Testing Protocol



Mechanical Versus Regenerative Air Sweepers

City of Toronto (2005)

- Regenerative air street sweepers performed the best
- Clean Streets to Clean Air



Mechanical Versus Regenerative Air Sweepers

Toronto 2015
(Buckley, 2015)

Table 3: Ambient Air Quality Results during Street Sweeping Test

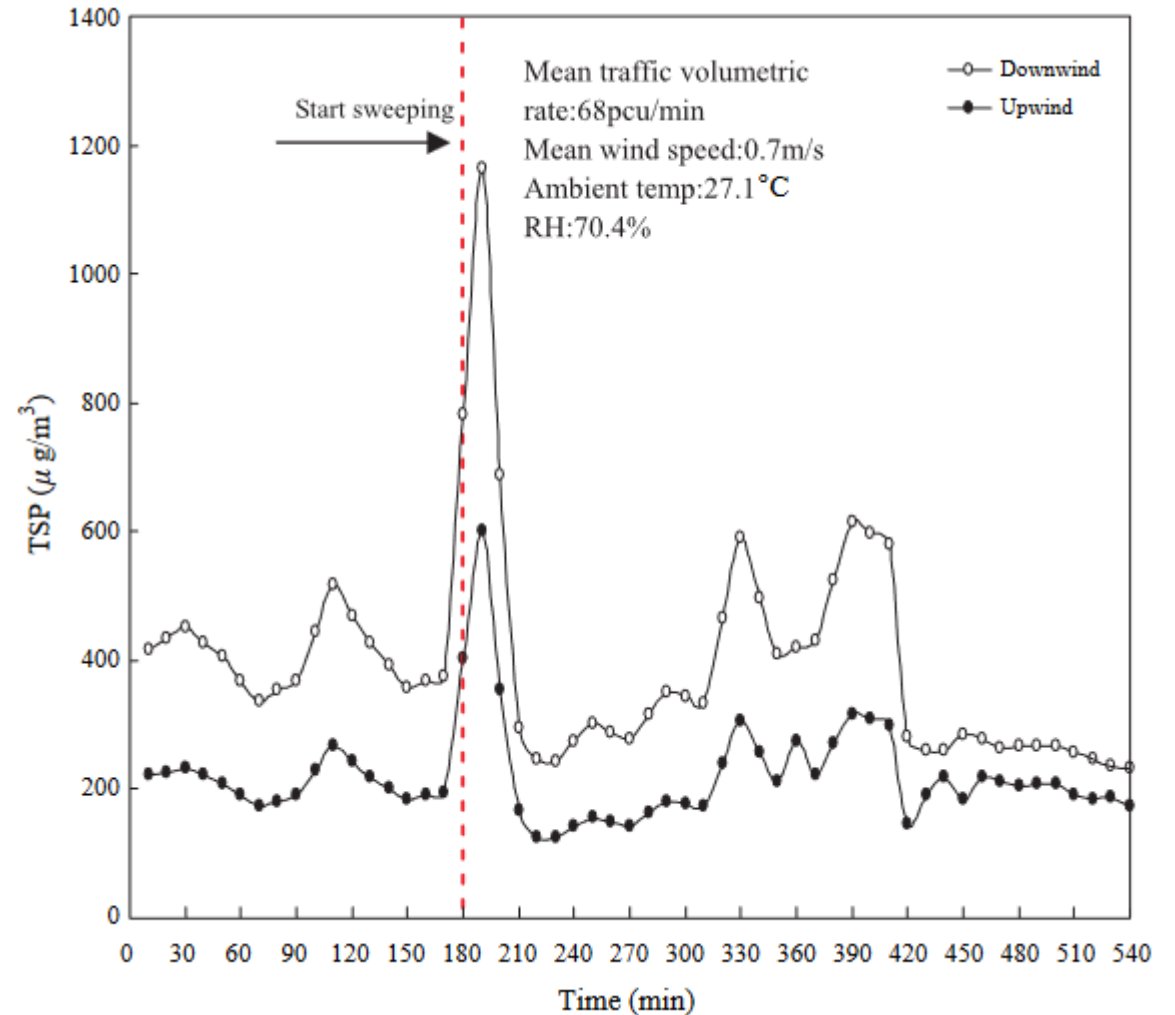
Efficiency Criteria	During Street Sweeping Test		
	Mechanical Sweeper	Regenerative-air Sweeper	Entrainment Efficiency Improvement
Maximum PM ₁₀ Concentration [(mg/m ³)]/kg	0.139	0.005	96%
Maximum PM _{2.5} Concentration [(mg/m ³)]/kg	0.112	0.004	96%
Total PM ₁₀ Concentration [(mg/m ³)]/kg	3.028	0.496	84%
Total PM _{2.5} Concentration [(mg/m ³)]/kg	2.768	0.463	77%
Average PM ₁₀ Concentration [(mg/m ³)]/kg	0.030	0.003	90%
Average PM _{2.5} Concentration [(mg/m ³)]/kg	0.027	0.003	89%

- Real-world environment
- Mechanical street sweepers' removal efficiency of silt loading was -26% compared to -66% for regenerative air street sweepers
- Suggests regenerative air street sweepers can reduce airborne fine particulate matter by 27% in Toronto

Sweeping and Washing

Chang et al., 2005

- Regenerative air sweeper and washing technique
- Decrease in silt load
- Short-lived decrease in ambient PM; no more than 3-4 hr
- Found a correlation between silt load and ambient PM



Sweeping Versus Sweeping/Washing

Lin et al., 2023

- Tested three different techniques
 - Sweeping only
 - Sweeping before washing
 - Washing before sweeping
- Decrease in ultra fine particles with all techniques
- Decrease in $PM_{2.5}$ with street sweeping
- Sweeping before washing yielded the best results

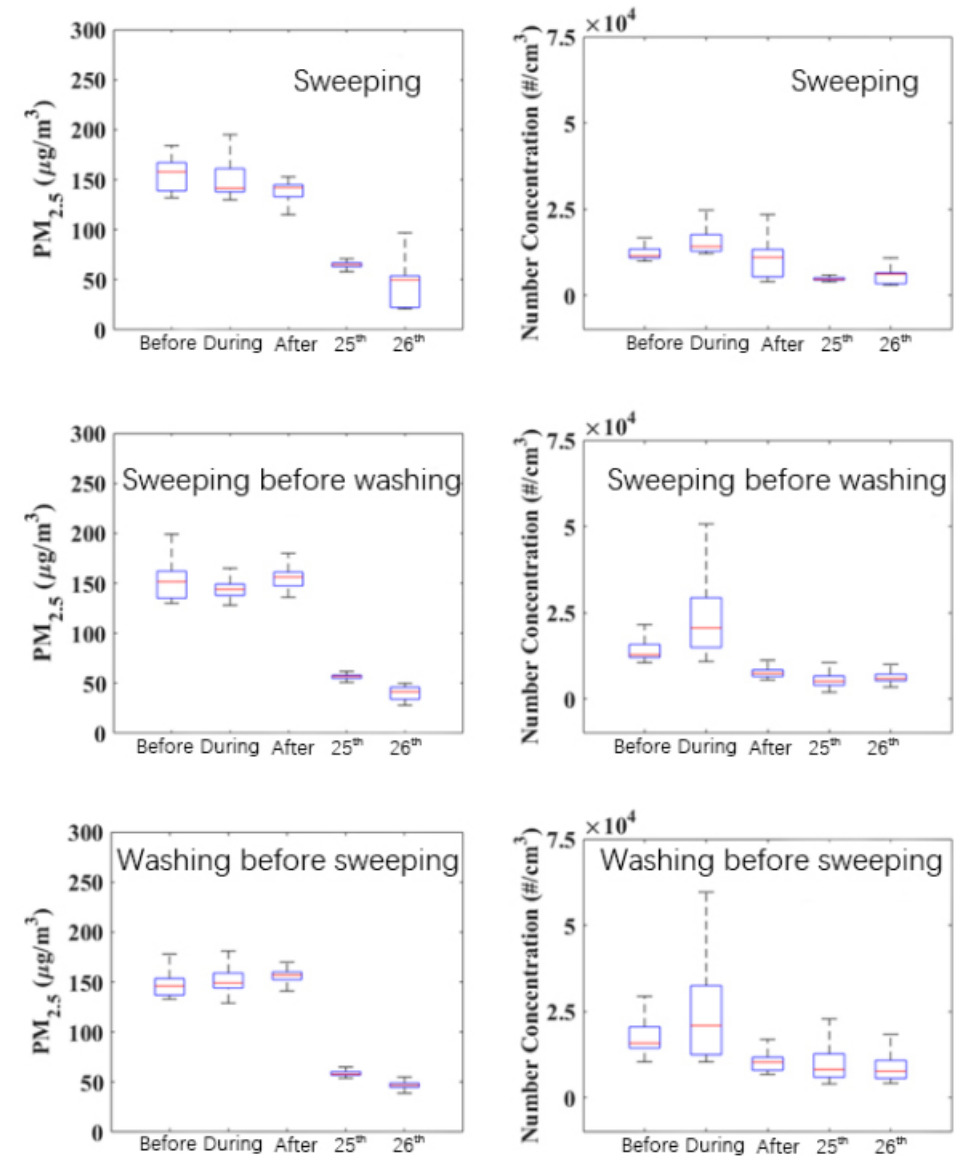


Fig. 9. The temporal variations of the $PM_{2.5}$ mass and UPF number concentrations with three street-cleaning sequences at Y road.

Humidity

Kantamaneni et al., 1996

- Used a regenerative air sweeper
- Street sweeping has a measurable effect on PM_{10} emission reduction during periods of low relative humidity

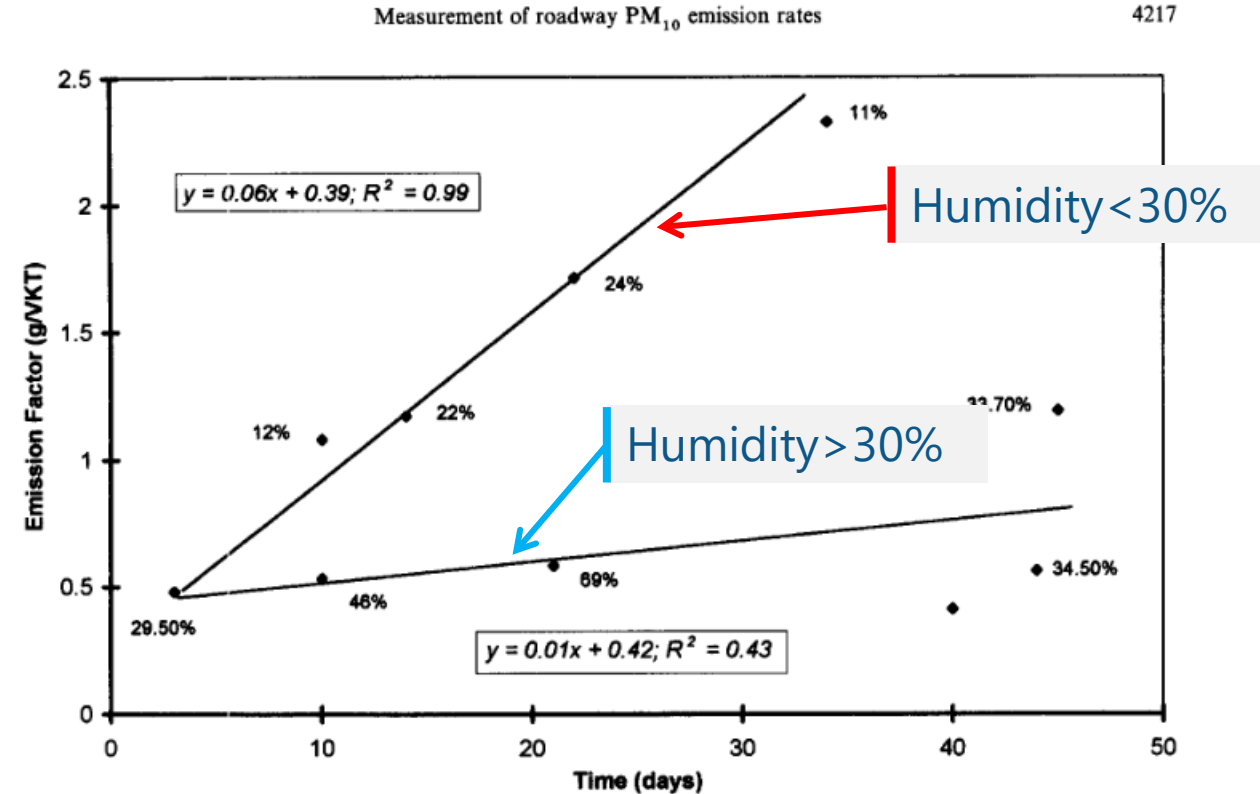
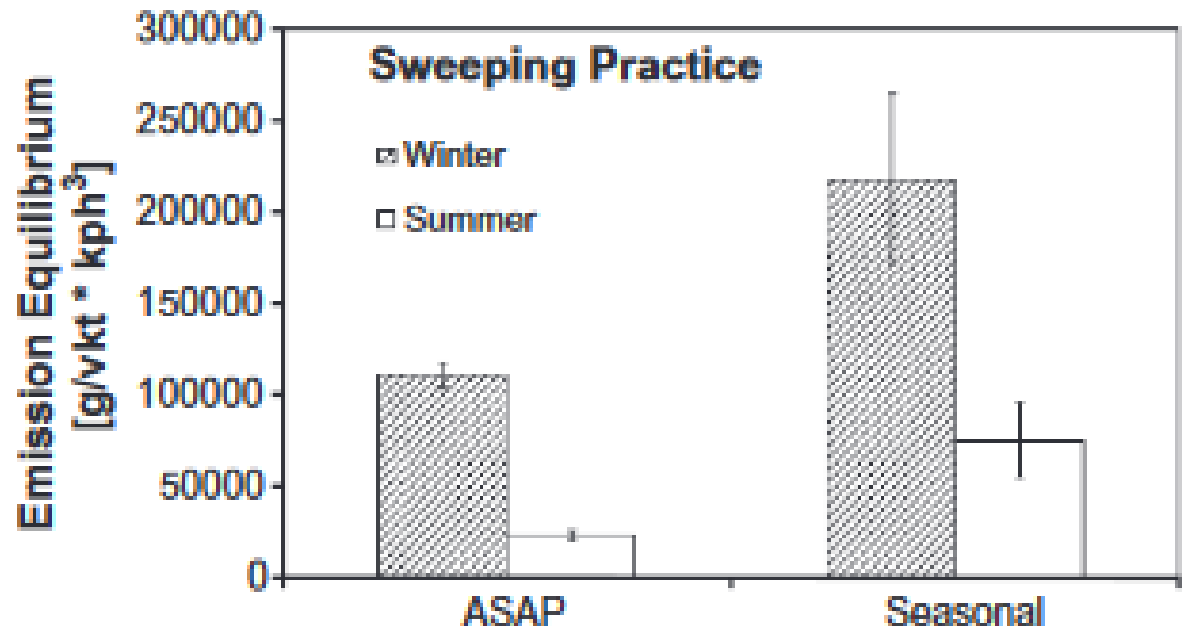


Fig. 5. Observed relationship between emission factor and the duration of time each experiment was performed after a street sweep. The data represent results obtained from the unsanded experiments at Sites 1 and 2: 11/18/93–5/21/95. Corresponding relative humidities are also illustrated at each data point.

Winter Storm Sweeping ASAP

Zhu et al., 2012

- ASAP – deploying sweepers as soon as possible after a snowstorm
- Seasonal means roads are swept one or twice a winter season
- Areas that employed ASAP sweeping had emission equilibriums that **were half of those with seasonal sweeping**, and the effect extended into the summer around the same proportion



Examples of Street Sweeping Practices

Arizona

- Street sweeping in PM₁₀-nonattainment areas
 - Maricopa
 - West Pinal
- Requires PM₁₀-certified street sweepers in nonattainment areas

Colorado

- Street sweeping after winter street sanding in PM₁₀-nonattainment areas
- Must sweep within 4 days of a snow event

Toronto, Canada

- Clean Streets to Clean Air initiative
- Must use sweepers certified by Toronto's protocol
- Estimated to decrease PM concentration by 27%

So, can Street Sweeping Reduce Silt Loading and Decrease Emissions?

Studies show that street sweepers have the potential to reduce emissions from the re-entrainment of road dust. However, several factors influence effectiveness.

Conclusions

- Newer technologies such as regenerative air sweepers or street sweeping and washing have greater potential to decrease re-entrainment of road dust emissions
- Large range of efficiencies: 6% to 94%
- Local factors matter when considering street sweeping
 - Humidity, precipitation
 - Roadway type and condition
 - Frequency of sweeping
- Need for more long-term studies
- Need for more standardization of testing for effectiveness
- Need for more shared experiences across different urban environments



Questions?



Megan McCabe
Atmospheric Scientist
mmccabe@sonomatech.com



Kenneth Craig
Manager, Atmospheric and Emissions
Modeling Group
kcraig@sonomatech.com

References

- Amato, F., Nava, S., Lucarelli, F., Querol, X., Alastuey, A., Baldasano, J.M., and Pandolfi M. (2010a) A comprehensive assessment of PM emissions from paved roads: real-world Emission factors and intense street cleaning trials. *Sci. Total Environ.* 408, 4309–4318.
- Amato, F., Querol, X., Alastuey, A., Pandolfi, M., Moreno, T., Gracia, J., and Rodriguez, P. (2009). Evaluating urban PM₁₀ pollution benefit induced by street cleaning activities. *Atmos. Environ.*, 43, 4472–4480. Available at <https://doi.org/10.1016/j.atmosenv.2009.06.037>.
- Bogacki, M., Oleniacz, R., Rzesutek, M., Szulecka, A., & Mazur, M. (2018). The impact of street cleaning on particulate matter air concentrations: a case study of a street canyon in Krakow (Poland). *E3S Web of Conferences*, 45, 00009. Available at <https://doi.org/10.1051/e3sconf/20184500009>.
- Buckley S. (2015) Street Sweeper Evaluation Results and Operational Conditions. Transportation Services Report, City of Toronto, October 21, 2015. [Street Sweeper Evaluation Results and Operational Considerations](https://www.toronto.ca/legdocs/mmis/2015/pw/bgrd/backgroundfile-85339.pdf), (accessed 18 July 2024). Available at <https://www.toronto.ca/legdocs/mmis/2015/pw/bgrd/backgroundfile-85339.pdf>.
- Calvillo, S. J., Williams, E. S., & Brooks, B. W. (2015) Street Dust: Implications for Stormwater and Air Quality, and Environmental Management Through Street Sweeping. In D. M. Whitacre (Ed.), *Reviews of Environmental Contamination and Toxicology*, 233, pp. 71–128). Cham: Springer International Publishing. Available at https://doi.org/10.1007/978-3-319-10479-9_3.
- Chang Y.-M., Chou C.-M., Su K.-T., and Tseng C.-H. (2005) Effectiveness of street sweeping and washing for controlling ambient TSP. *Atmos. Environ.*, 39, 1891–1902. Available at <https://doi.org/10.1016/j.atmosenv.2004.12.010>.
- City of Toronto (2005) PM₁₀ and PM_{2.5} Efficient Street Sweepers for the City of Toronto, June 13. [Microsoft Word - it009.doc \(worldsweeper.com\)](https://www.toronto.ca/legdocs/2005/agendas/committees/wks/wks050629/t009.pdf) (accessed 18 July 2024). Available at <https://www.toronto.ca/legdocs/2005/agendas/committees/wks/wks050629/t009.pdf>.
- Colorado Department of Public Health and Environment (2001) Colorado state implementation plan for PM10 technical support document. Prepared by the Colorado Department of Public Health and Environment, Air Pollution Control Division, adopted April 19.
- Colorado Department of Public Health and Environment (2005) Colorado state implementation plan for PM10: revised technical support document. Prepared by the Colorado Department of Public Health and Environment, Air Pollution Control Division, September.
- Das, S., & Wiseman, C. L. S. (2024) Examining the effectiveness of municipal street sweeping in removing road-deposited particles and metal(loid)s of respiratory health concern. *Environment International*, 187, 108697. Available at <https://doi.org/10.1016/j.envint.2024.108697>.
- Fitz, D.R., Bumiller, K., Etyemezian, V., Kuhns, H.D., Gillies, J.A., Nikolich, G., James, D.E., Langston, R., and Merle, R.S. (2021). Real-time PM₁₀ emission rates from paved roads by measurement of concentrations in the vehicle's wake using on-board sensors Part 2. Comparison of SCAMPER, TRAKER™, flux measurements, and AP-42 silt sampling under controlled conditions. *Atmospheric Environment*, 256, 118453. Available at <https://doi.org/10.1016/j.atmosenv.2021.118453>.
- Gertler, A., Kuhns, H., Abu-Allaban, M., Damm, C., Gillies, J., Etyemezian, V., et al. (2006). A case study of the impact of winter road sand/salt and street sweeping on road dust re-entrainment. *Atmospheric Environment*, 40(31), 5976–5985. Available at <https://doi.org/10.1016/j.atmosenv.2005.12.047>.
- Kantamaneni, R., Adams, G., Barnesberger, L., Allwine, E., Westberg, H., Lamb, B., & Claiborn, C. (1996) The measurement of roadway PM10 emission rates using atmospheric tracer ratio techniques. *Atmospheric Environment*, 30, 24, 4209–4223.
- Karanasiou, A., Amato, F., Moreno, T., Lumberas, J., Borge, R., Linares, C., et al. (2014) Road Dust Emission Sources and Assessment of Street Washing Effect. *Aerosol and Air Quality Research*, 14, 3, 734–743. Available at <https://doi.org/10.4209/aaqr.2013.03.0074>.
- Karanasiou, A., Moreno, T., Amato, F., Lumberas, J., Narros, A., Borge, R., et al. (2011) Road dust contribution to PM levels – Evaluation of the effectiveness of street washing activities by means of Positive Matrix Factorization. *Atmospheric Environment*, 45, 13, 2193–2201. Available at <https://doi.org/10.1016/j.atmosenv.2011.01.067>.
- Keuken, M., Denier Van Der Gon, H., & Van Der Valk, K. (2010) Non-exhaust emissions of PM and the efficiency of emission reduction by road sweeping and washing in the Netherlands. *Science of The Total Environment*, 408(20), 4591–4599. Available at <https://doi.org/10.1016/j.scitotenv.2010.06.052>.
- Kryłów, M., Generowicz, A. (2019) Impact of street sweeping and washing on the pm10 and PM2.5 concentrations in Cracow (Poland). *Rocznik Ochrona Srodowiska*, 21, 691–711. Available at <https://bit.ly/3pvWDBa>.
- Kuhns, H., Etyemezian, V., Green, M., Hendrickson, K., McGown, M., Barton, K., & Pitchford, M. (2003) Vehicle-based road dust emission measurement—Part II: Effect of precipitation, wintertime road sanding, and street sweepers on inferred PM₁₀ emission p
- Kuhns, H., Etyemezian, V., Green, M., Hendrickson, K., McGown, M., Barton, K., & Pitchford, M. (2003) Vehicle-based road dust emission measurement—Part II: Effect of precipitation, wintertime road sanding, and street sweepers on inferred PM₁₀ emission potentials from paved and unpaved roads. *Atmospheric Environment*, 37, 32, 4573–4582. Available at [https://doi.org/10.1016/S1352-2310\(03\)00529-6](https://doi.org/10.1016/S1352-2310(03)00529-6).
- Lin, S.-L., Deng, Y., Lin, M.-Y., & Huang, S.-W. (2023) Do the Street Sweeping and Washing Work for Reducing the Near-ground Levels of Fine Particulate Matter and Related Pollutants? *Aerosol and Air Quality Research*, 23, 1, 220338. Available at <https://doi.org/10.4209/aaqr.220338>.
- Maricopa Association of Governments (2007) MAG 2012 Five
- Norman M., and Johansson C. (2006) Studies of some measures to reduce road dust emissions from paved roads in Scandinavia. *Atmos. Environ.* 40, 6154–6164. Available at <https://doi.org/10.1016/j.atmosenv.2006.05.022>.
- otentials from paved and unpaved roads. *Atmospheric Environment*, 37, 32, 4573–4582. Available at [https://doi.org/10.1016/S1352-2310\(03\)00529-6](https://doi.org/10.1016/S1352-2310(03)00529-6)
- Percent Plan for PM-10 for the Maricopa County Nonattainment Area. December. Available at https://azmag.gov/portals/0/Documents/pdf/cms.resource/PM10_2007_Main-Plan.pdf.
- Zhu D., Kuhns H.D., Gillies J.A., Etyemezian V., Brown S., and Gertler A.W. (2012) Analysis of the effectiveness of control measures to mitigate road dust emissions in a regional network. *Transport. Res. Part D*, 17, 332–340.

Street Sweeping Background

- Initiated to improve aesthetics, safety, and public health and for environmental reasons
- Best management practice for stormwater pollution control (FHWA)
- Used as a form of PM control



<https://i.pinimg.com/originals/d0/3b/aa/d03baaf9e4dcae555b852f0be1ee6880.png>

EPA AP-42 Paved Road Emission Calculation

$$E = k (sL)^{0.91} \times (W)^{1.02} \quad (1)$$

where: E = particulate emission factor (having units matching the units of k),
 k = particle size multiplier for particle size range and units of interest (see below),
 sL = road surface silt loading (grams per square meter) (g/m^2), and
 W = average weight (tons) of the vehicles traveling the road.

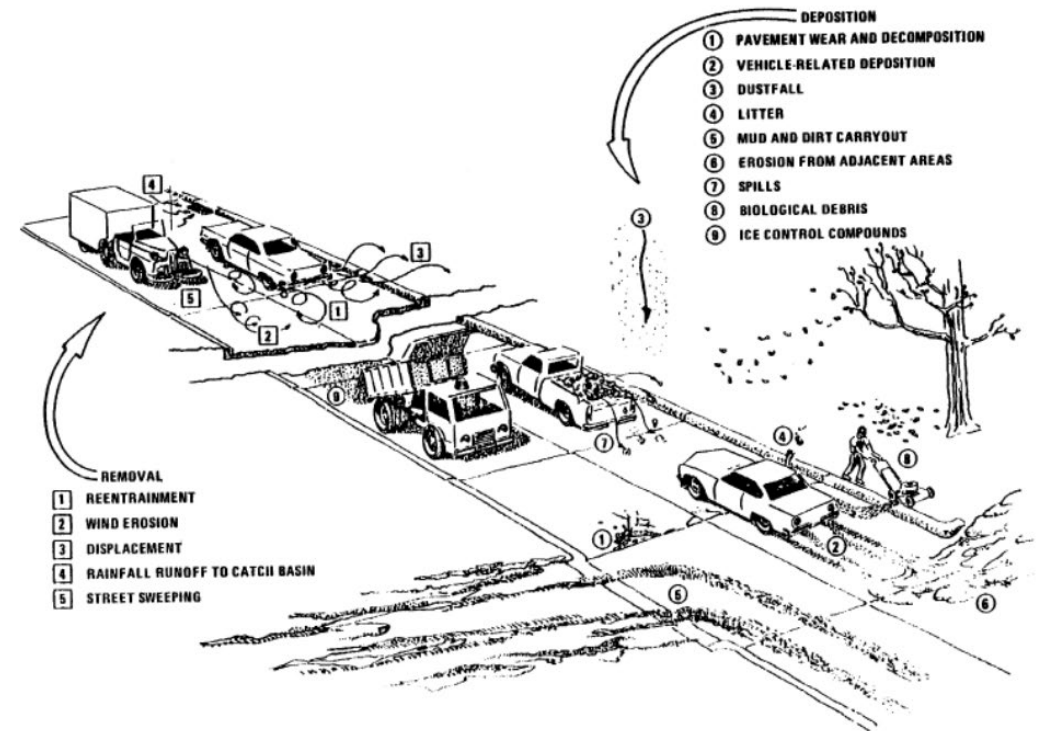


Figure 13.2.1-1. Deposition and removal processes.

(AP-42 13.2.1 Paved Roads)

Mechanical Versus Regenerative Air Sweepers

Toronto 2015 (Buckley, 2015)

Table 2: Regenerative-air Street Sweeper Results

Efficiency Criteria	Before Street Sweeping	After Street Sweeping	Percentage Change Pre- versus Post-Sweeping
Removal Efficiency of Silt Loading (kg)	10.345	3.552	-66%
Maximum PM ₁₀ Concentration (mg/m ³)	0.319	0.156	-51%
Maximum PM _{2.5} Concentration (mg/m ³)	0.331	0.177	-47%
Average PM ₁₀ Concentration (mg/m ³)	0.028	0.018	-36%
Average PM _{2.5} Concentration (mg/m ³)	0.026	0.016	-39%

Compared to -26% for Mechanical Street Sweepers

- Real-world environment
- Suggests regenerative air street sweepers can reduce airborne fine particulate matter by 27% in Toronto

Additional Benefits of Street Sweeping

- Water Quality
- Cost-Effective Pollution Control
- Pavement Preservation

Mobile Platforms

Fitz et al., 2021



Fig. 5. Photograph of the SCAMPER.

Upwind/downwind Platforms

Chang et al., 2005

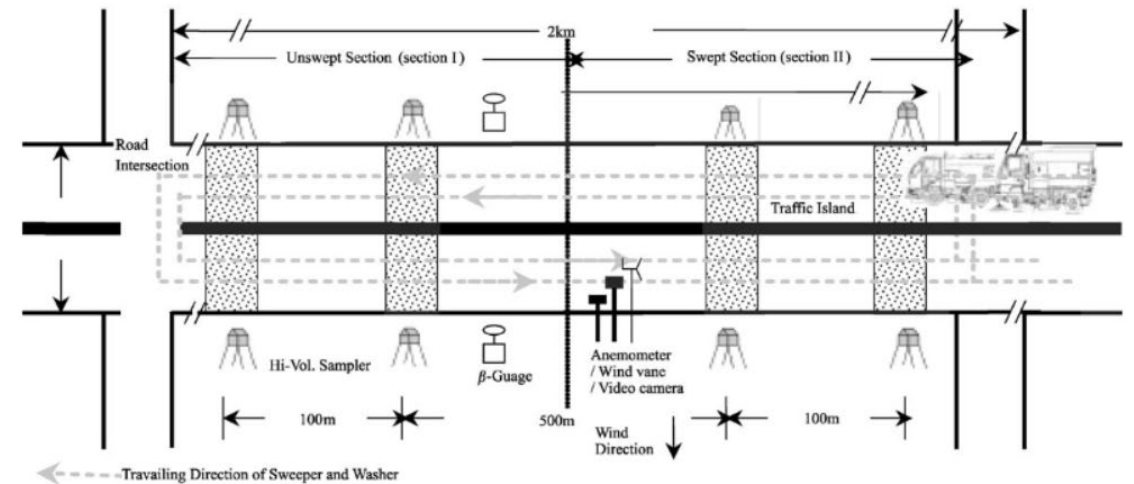


Fig. 2. Illustration diagram of equipment and sampling locations in this study.

Extra Slides – Examples and Instructions