Review of Street Sweeping Measures for Reducing PM Road Dust Emissions

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1. Introduction and Summary

1.1 Introduction

Mobile source pollutants are a significant concern for urban air quality. These emissions include gases and particulate matter (PM) released from motor exhausts and non-exhaust particles derived from the wear and tear of vehicles and road surfaces and the resuspension of loose material on the road surface (Frey, 2018; Harrison et al., 2021; Health Effects Institute, 2010, 2022). PM, including coarse PM (PM_{10}), fine PM ($PM_{2.5}$), and ultrafine particles[1] (UFPs), from mobile sources is known to have detrimental health effects (Amato et al., 2010b). Exhaust PM emissions from on road vehicles have decreased significantly over time due to regulations, but non-exhaust PM emissions are significant (Chen et al., 2023) and have now become the largest source of traffic-related PM emissions in California (Yao, 2021; California Air Resources Board, 2021). Non-exhaust PM emissions are produced regardless of vehicle type or fuel technology and are influenced by numerous factors, including vehicle miles traveled; vehicle weight and speed; brake, tire, and pavement materials and technology; road surface roughness and macrotexture; road dust loading; driving behavior; and environmental factors such as temperature, humidity, and rainfall (Arizona Department of Transportation, 2006; Fussell et al., 2022; Harrison et al., 2021; Piscitello et al., 2021).

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[1] Ultrafine particles are commonly defined as particles having a diameter of less than 0.1 micrometer (100 nanometers) and are often measured as a particle number concentration (i.e., the number of particles per cubic centimeter of air). UFPs are of concern because they may penetrate and deposit into lung tissue (Atkinson et al., 2010) and contribute to excess mortality (Kumar et al., 2011). Air quality standards typically focus on PM mass concentrations, but the Euro 5 and Euro 6 standards in Europe also limit the number concentration of tailpipe UFP emissions from motor vehicles.

The resuspension of loose material, also known as road dust, is a significant component of non-exhaust road traffic PM emissions. Studies have indicated that as much as 50% of total PM_{10} concentrations can arise from re-entrained road dust (Gulia et al., 2019). Road dust emissions can include various heavy metals, polycyclic aromatic hydrocarbons (PAHs), and microplastics (Lin et al., 2023; Polukarova et al., 2020) that can be harmful to human health and the environment. When it rains, stormwater runoff can carry particles (including microplastics), oils, and other contaminants from roadways into aquatic habitats (Werbowski et al., 2021; Gilbreath and McKee, 2015; McKee and Gilbreath, 2015).

Road dust is often cited as a concern by environmental justice communities in the AB617 Community Air Protection Program (CAPP). However, the available options for reducing PM emissions from road dust are limited. Road dust emission controls measures suggested in the U.S. Environmental Protection Agency (EPA) Compilation of Air Emissions Factors (AP-42) include AB617 Community Air Protection Program vacuuming sweeping, water flushing and broom sweeping, and flushing. By removing accumulated dust and debris from road surfaces, these control measures can reduce the resuspension of particles into the air, thereby lowering the overall concentration of airborne pollutants. However, the methods showed inconsistent results in the literature.

Currently, street sweeping is a routine activity in urban areas intended to remove debris, litter, and particulates from road surfaces. Its primary objectives include aesthetic enhancement, prevention of drainage system blockages, and reduction of pollutants entering water bodies. Recently, attention has also focused on the potential of street sweeping to improve air quality by reducing PM road dust emissions. Street sweeping measures have been suggested in Community Emissions Reduction Plans (CERP) that have been developed under the AB617 CAPP.[2] However, it is still not known to what extent street sweeping reduces road dust PM emissions and ambient PM concentrations.

1.2 Document Purpose and Organization

A comprehensive literature review was undertaken to examine and synthesize scientific literature on the effectiveness of street sweeping as a control measure for reducing road dust PM. This review primarily focuses on studies investigating the impact of street sweeping, both independently and in combination with street washing, on road dust PM emissions and near-road PM air quality. The emphasis of this review is on road dust that can become airborne (i.e., suspendible particles) and potentially degrade air quality,

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[2] As an example, the West Oakland CERP lists street sweeping along roads and highways as a measure to decrease exposure to road dust and cites that “street sweeping could reduce road dust by 10 percent.” See the **AB617 West Oakland Community Action Plan** (https://www.baaqmd.gov/en/community-health/community-health-protection-program/west-oakland-community-action-plan).

with particular attention paid to PM_{10} and $PM_{2.5}$, for which National Ambient Air Quality Standards (NAAQS) have been established. This report builds on a broader report of non-exhaust PM control measures (Caltrans, 2024) that identified street sweeping as a measure that is potentially controllable by Caltrans and might be feasible within the Caltrans right-of-way.

It is important to note that this review excludes studies primarily concerned with larger, coarser materials (i.e., particles with diameter greater than 10 micrometers) that may affect water quality and create other nuisances but do present significant inhalation health concerns. By maintaining this specific focus, the review aims to provide a targeted analysis of street sweeping's role in mitigating airborne PM and its subsequent effects on air quality.

1.3 Literature Consulted

The information provided in this report was guided by several technical and policy reviews focused on reducing PM road dust emissions and near-road PM concentrations through street sweeping. These reviews are summarized in **Table 1** and are included in the reference list (**Section 8**). Further, 18 studies conducted measurements on street sweeping technology; these studies are reviewed in **Section 4**. The studies reviewed are limited to the last 30 years, with a focus on more recent studies.

Table 1. Review articles pertaining to road dust PM emissions and street sweeping consulted for this report.

Table Summary: This table provides a list of review articles that focused on road dust PM emissions and street sweeping.

Reference	Title
Calvillo et al. (2015)	Street Dust: Implications for Stormwater and Air Quality, and Environmental Management Through Street Sweeping
AIRUSE (2013)	The scientific basis of street cleaning activities as road dust mitigation measure
Amato et al. (2010b)	A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods
Schilling (2005)	Street Sweeping – Report No. 1, State of the Practice. Prepared for Ramsey-Washington Metro Watershed District

1.4 Summary of Key Findings and Implications

In many areas, local authorities practice street cleaning—through street sweeping, washing, or a combination of both—for purposes such as aesthetics, safety, and public health. Recently, street sweeping has also been employed to control fugitive dust emissions and improve local air quality, as observed in places such as Arizona, Colorado, and Toronto, Canada (Maricopa Association of Governments, 2012; Colorado Department of Public Health and Environment, 2001, 2005; Buckley, 2015). Additionally, street sweeping has been included in State Implementation Plans (SIPs) and for transportation conformity purposes. However, the effectiveness of street cleaning methods has yielded inconsistent results within the literature.

This report reviewed 18 studies pertaining to the effectiveness of street sweeping as a control measure for reducing road dust PM emissions. According to the available literature, there is no consensus on the effectiveness of street sweeping, or a combination of street sweeping and washing, when it comes to improving near-road air quality. The methodologies used to assess effectiveness varied, with some studies focusing on silt load and emission reductions, and others examining ambient air quality impacts.

Several factors influence the effectiveness of street sweeping, including initial silt load, rain, humidity, frequency of street sweeping, and the sweeping technology used. The frequency of street sweeping is particularly important, with studies suggesting that more frequent sweeping leads to better air quality outcomes. Optimal frequency can vary depending on local conditions, but a few studies showed that repeated nightly cleanings produced beneficial results. Notably, the type of street cleaning technology used plays a crucial role in reducing road dust emissions. Regenerative air sweepers, and combinations of sweeping and washing, generally outperform other methods, though the duration of their impact on emissions varied. On the other hand, mechanical sweepers often had little to no positive effect on PM concentrations.

There is a lack of studies providing quantitative estimates of the benefits of street sweeping when it comes to reducing road dust PM emissions. Additional research is necessary to better understand the impact of street sweeping on air quality, particularly through the sharing of experiences across different urban environments. Increasing the number of observations and conducting long-term studies will help create a more comprehensive assessment of the effectiveness of street cleaning. Future studies should aim to sample conditions representative of the communities intended to benefit from street sweeping measures, considering the many local variables that influence effectiveness.

2. Background

2.1 Brief History

Street sweeping in urban areas is a common practice; its primary goals include removing material such as dirt, vegetation, and other debris from roadways. Street sweeping was primarily designed for aesthetic, safety, public health, and environmental reasons. Early methods were manual, relying on human labor to clean streets. The history of street sweeping can be traced back over 200 years, with Benjamin Franklin mentioning in his autobiography the hiring of a man to sweep a paved market area in Philadelphia (Calvillo et al., 2015).

New York City was among the first cities to incorporate street sweeping into governmental policies; street sweeping in New York City was initially managed by the police department until it became its own administrative branch in 1881. The efforts of the street sweeping appeared to produce a decline in sickness, with declines in diarrheal diseases and the death rate (from 26.8 per 1,000 from 1882 to 1894, to 19.6 per 1,000 in 1897). New York City accordingly became a model for other cities throughout the United States (Calvillo et al., 2015).

Over time, technological advancements have transformed street sweeping from manual labor to a mechanized and automated process. Modern street sweepers now incorporate advanced features such as vacuum systems, regenerative air technology, and high-efficiency particulate air (HEPA) filters, enhancing their capability to capture finer particulates.

With improvements in technology, the use of street sweepers has moved beyond just aesthetics and public health. Street sweeping has been used as a mechanism to reduce the amount of toxics substances entering waterways. The 1968 Federal Water Pollution Control Act Amendments[3] were enacted and regulatory requirements included pollutants from point and nonpoint sources (Schilling, 2005). In 1978, the U.S. EPA launched the Nationwide Urban Runoff Program, which included studies of the effectiveness of street sweeping and washing in reducing runoff impacts on water quality (Calvillo et al., 2015). The studies revealed that street sweeping was not very effective at removing pollutant loads but effective at removing litter and debris (Yee, 2005). Now street sweeping has been implemented as a best management practice (BMP) for stormwater pollution control,[4] and many municipalities conduct street sweeping to meet regulatory requirements and improve water quality (Calvillo et al.,

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[3] The current federal statute is the Clean Water Act of 1987, as amended.

[4] For example, see the **Federal Highway Administration (FHWA) Fact Sheet on Street Sweepers and Stormwater Best Management Practices in an Ultra-Urban Setting** (https://www.environment.fhwa.dot.gov/env_topics/water/ultraurban_bmp_rpt/3fs16.aspx).

2015). In California, municipal separate storm sewer systems (MS4s) permits may require sweeping programs to reduce pollutant runoff.[5] Street sweeping is also a Caltrans BMP for preventing water pollution during construction activities on the state highway system,[6] and the State Water Resources Control Board construction general permit calls for vacuuming or sweeping to remove sediment or other construction activity-related materials that are deposited on the roads.[7]

More recently, street sweeping has been identified as a management practice to reduce the amount of fugitive dust that may be re-entrained into the atmosphere by vehicle traffic. However, these management practices are less studied than the improvements from street cleaning on water quality. Even so, multiple cities and agencies—including the Denver Regional Council of Governments, Maricopa Association of Governments (MAG), Government of Catalonia, Spain and the city of Toronto, Canada (Colorado Department of Public Health and Environment, 2001, 2005; Maricopa Association of Governments, 2022; Amato et al., 2010b; Morgan, 2007)—regularly use street sweeping to improve air quality.

2.2 Road Dust

The term “road dust” commonly refers to any small solid particle or fine silt on the road surface, including PM_{10} and $PM_{2.5}$, as well as larger particles, that can be entrained into the air from traffic or wind.[8] Larger particles may be broken down by vehicles until they are able to become airborne (Piscitello et al., 2021). Road dust may be generated by traffic or transported and deposited from near- or long-range sources (Fussell et al., 2022) that are either organic or inorganic. A major component of road dust originates from particles related to brake wear, road surface wear, and tire wear. Road dust is also known to contain various toxic particles (Calvillo et al., 2015), including metal(loid)s, organic pollutants, black carbon, PAHs and microparticles (Polukarova et al., 2020; Lin et al., 2023; Das & Wiseman, 2024).

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[5] For example, **the Los Angeles Regional Water Quality Control Board's Regional Phase I MS4 NPDES permit** (https://www.waterboards.ca.gov/losangeles/water_issues/programs/stormwater/municipal/public_docs/2022/1_Order(ACC-RPSignature).pdf) requires street sweeping of curbed streets at frequencies based on priority levels. The permit specifies that Priority A streets must be swept at least twice per month, Priority B streets at least once per month, and Priority C streets at least once per year. This requirement is part of the broader stormwater management efforts mandated by the State Water Resources Control Board to control pollutants in urban runoff and protect water quality.

[6] See the **Caltrans Construction Site Best Management Practices (BMP) Manual**, CTSW-RT-24-425.11.1 (https://dot.ca.gov/-/media/dot-media/programs/construction/documents/environmental-compliance/construction-site-bmps_final-march-2024_a11y.pdf).

[7] See the **State Water Resources Control Board Construction General Permit Fact Sheet** (https://www.waterboards.ca.gov/water_issues/programs/stormwater/docs/constpermits/wqo_2009_0009_complete.pdf).

[8] In the air quality context, road dust refers to the suspension of silt-sized material equal to or less than 75 micrometers in physical diameter. Most air quality analyses focus on $PM_{2.5}$ and PM_{10} since these pollutants are regulated through the NAAQS, but road dust may also include larger particles.

The amount, size, and composition of road dust on a given road surface can differ greatly based on location and environment (Calvillo et al., 2015). The localized composition of road dust can be influenced by winter traction sanding, building sites, and wind-blown dust from bare soils and traffic from connecting unpaved roads (Fussell et al., 2022). For instance, in colder regions wear from tire studs has been shown to be a dominant constituent of road dust emissions; in urban environments, studies have shown that road dust emissions are high in tire and brake wear (Piscitello et al., 2021). Across multiple studies that spanned Massachusetts and Florida, USA; Xincheng, China; Brisbane, Australia; and Jonkoping and Luea, Sweden, the most commonly examined metals in road dust included aluminum, cadmium, chromium, copper, lead, nickel, and zinc (Calvillo et al., 2015). The metals come from a large variety of sources, and Calvillo et al. (2015) states the following common sources:

- Aluminum: Primarily from local soils
- Cadmium: Vehicle exhaust, tire wear, and industrial emissions
- Chromium: Mainly associated with brake dust
- Copper: Brake linings, tires, motor vehicle alloys, and weathered pavement
- Lead: Vehicle exhaust, tire wear, and industrial emissions
- Nickel: Gasoline, oil, asphalt, vehicle exhaust, and weathering of asphalt and concrete
- Zinc: Vehicle exhaust, tires, vehicle body wear, fluid leakage from vehicles, weathered steel structures, and weathering of pavement

2.2.1 Resuspension of Road Dust

Resuspension of road dust is a complex process dependent on multiple factors including silt load, road surface macro texture, humidity, traffic density, composition, and vehicle speed (Fussell et al., 2022; Fitz et al., 2021; Amato et al., 2010b). Road dust PM emission rates are affected by vehicle mass, vehicle aerodynamic turbulence (Venkatram, 2000), local dust levels, precipitation, traffic volume, vehicle speed, and road surface characteristics (e.g., pavement condition, shoulder type, and pavement microtexture[9] and macrotexture[10]). Sweeping practices and the use of salt, anti-icing agents, sand and road surface treatments for traction also affects resuspension.

According to EPA AP-42 Section 13.2.1 Paved Roads and technical support (U.S. Environmental Protection Agency, 2011), the theory of resuspension suggests that loose material on the road surface becomes airborne due to vehicle tire interaction and traffic-

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[9] Based on ASTM E 867, pavement microtexture refers to deviations of a pavement surface with characteristic dimensions of wavelength and amplitude < 0.5 mm.

[10] Based on ASTM E 867, pavement macrotexture refers to deviations of a pavement surface with characteristic dimensions and amplitude from 0.5 mm up to a value that no longer affects tire-pavement interaction.

induced turbulence.[11] Emissions depend on factors such as the average weight of vehicles and silt loading (the amount of suspendible material on the roadway). Silt loading is replenished by various sources, including pavement wear, track-out from unpaved areas, windblown dust, and deposition from nearby activities. The AP-42 method assumes an equilibrium between the material resuspended by vehicles and the material deposited on the road surface. This balance can be disrupted by changes in silt loading caused by weather (e.g., rain or windborne dust), spillage of new material, or removal of existing material. **Figure 1** provides a conceptual illustration of the road dust deposition and removal process.

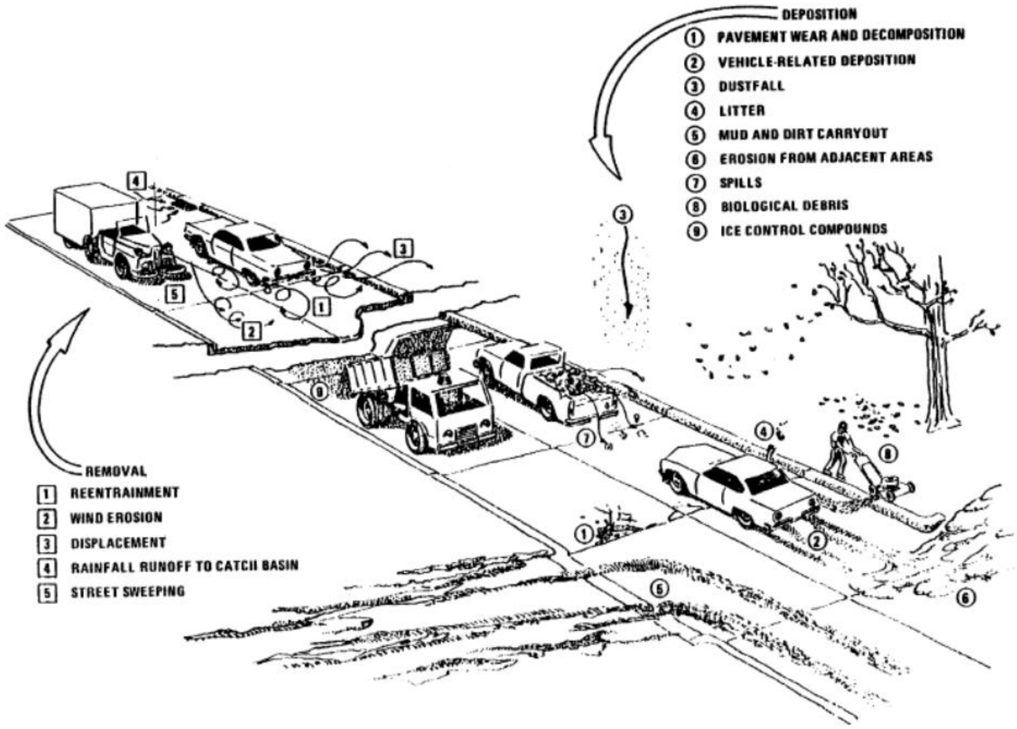

Figure 1. Road sediment deposition and removal processes (Figure and caption from EPA AP-42 Paved Roads 13.2.1).

In 2003, EPA opted to add resuspended road dust emissions as a separate calculation for traffic emissions (EPA, 2011). Now, particulate emissions from vehicle exhaust, brake wear, and tire wear are estimated separately in EPA's MOtor Vehicle Emission Simulator (MOVES) model and subtracted from the road dust emissions calculation in AP-42. This adoption was designed to eliminate double counting of emissions. On the other hand, the European Environment Agency (EEA) does not provide explicit

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[11] The ambient wind may also contribute to road dust emissions, and it plays a role in replenishing the surface silt load, but it is assumed that vehicles traversing the roadway are the dominant mechanism for resuspension. The ambient wind plays a significant role in determining the local and regional air quality impact from road dust emissions.

estimates of resuspended road dust emissions; instead, the road dust emissions are included implicitly as part of EEA's emission factors for brake wear, tire wear, and road surface wear.

According to EPA AP-42, the quantity of particulate emissions from the resuspension of loose material on the road surface due to vehicle travel on a dry, paved road may be estimated using the following empirical expression:

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

where E = particulate emission factor (having units matching the units of k),

k = particle size multiplier for particle size range and units of interest,

sL = road surface silt loading (g/m^2), and

W = average weight (tons) of vehicles traveling on the road.

The silt loading (sL) term refers to the mass of silt-sized material (i.e., equal to or less than 75 micrometers in physical diameter per unit area of the travel surface) and is the product of the silt fraction and the total loading. The total road surface dust loading refers to loose material that can be collected by broom sweeping and vacuuming of the paved road. To determine the silt content within this collected material, researchers commonly use the ASTM-C-136 method. This method involves passing the dry, loose surface dust through a 200-mesh screen (with a mesh opening size of approximately 75 µm) and measuring the proportion that successfully passes through, thereby quantifying the silt fraction of the road dust. Details of the sampling and analysis of silt loading can be found in AP-42 Appendices C.1 and C.2. The particle size multiplier (k) is specific to the aerodynamic diameter (e.g., $PM_{2.5}$ or PM_{10}). Suggested default values for k may be found in Table 13.2.1-1, and for sL in Section 13.2.1.3 (wintertime sL values with contributions from anti-skid abrasives may be found in Table 13.2.1 -2.) within AP-42 13.2.1 Paved Roads and the California Air Resources Board Miscellaneous Process Methodologies Section 7.9 Paved Road Dust.[12] The appropriate default values are used in the Caltrans CT-EMFAC tool.

Based on this theory and calculations, silt loading is directly related to the PM road dust emissions factor. Therefore, street sweeping measures could decrease PM road dust emissions by decreasing the silt loading on road surfaces. However, the real-world air quality benefits from street sweeping depend on local factors, including, but not limited to, the type of sweeping equipment used, the frequency of street sweeping, and the rate of silt load replenishment from various sources.

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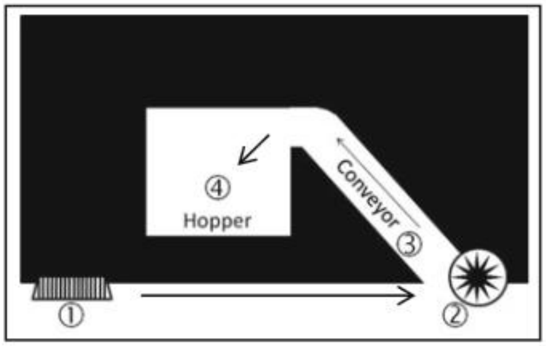
[12] See **CARB Miscellaneous Process Methodologies Section 7.9 Paved Road Dust** (https://ww2.arb.ca.gov/carb-miscellaneous-process-methodologies-paved-road-dust).

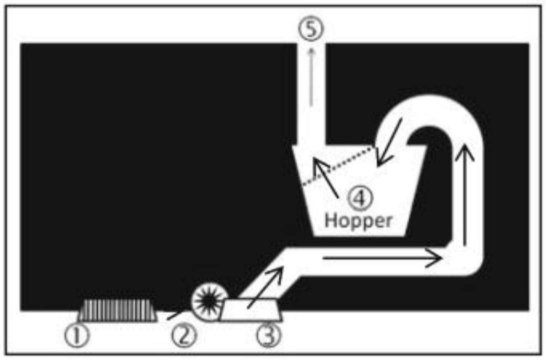
3. Types of Sweepers

Street sweeping may be performed a few different ways. However, most street sweeping uses some kind of vehicle sweeper. There are three common kinds of sweepers: mechanical broom sweepers, vacuum sweepers, and regenerative air sweepers. An explanation of each appears below. The three different kinds of sweepers are shown in **Figure 2**, and brief descriptions are provided in the same figure.



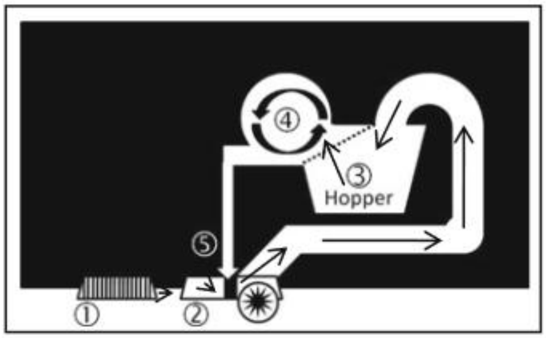
A. Mechanical Broom Sweepers

1. A rotating gutter broom directs dirt and debris from the curb into the path of a large rotating cylindrical broom.
2. The main broom flicks dirt and debris onto a conveyor.
3. The conveyor carries dirt and debris to a hopper.
4. The conveyor drops dirt and debris into a hopper.



B. Vacuum Sweepers

1. A rotating gutter broom directs dirt and debris from the curb into the path of the vacuum nozzle.
2. A windrow broom is often used to direct dirt debris into the path of the vacuum nozzle.
3. The debris-laden air stream is pulled into a hopper, at the opposite side of the suction inlet where the air loses velocity and the larger debris drops to the bottom.
4. Dirt and debris settle in hopper and lighter debris is blocked by a screen.
5. Air is exhausted from hopper.



C. Regenerative Air Sweepers

1. A rotating gutter broom directs dirt and debris from the curb into the path of the pick-up head.
2. Within the pick-up head, a blast of air dislodges and suspends dirt and debris. A broom within the pick-up head is sometimes used to dislodge stuck-on debris.
3. The debris-laden air stream is pulled into a hopper, at the opposite side of the suction inlet where the air loses velocity and the larger debris drops to the bottom.
4. Dirt passes through a centrifugal dust separator
5. Clean air returns to the blast orifice of the pick-up head.

Figure 2. Process flow diagrams for the three primary street sweeping technologies. Figure and caption from Calvillo et al., 2015.

3.1 Mechanical Broom Sweepers

Mechanical broom sweepers are the oldest type of street sweepers, dating back to the 19th century, and are still being produced today. They use a rotating cylindrical broom to push dirt and debris onto a conveyor, which then moves the material into a hopper for collection. These sweepers are particularly effective at picking up heavy materials such as coarse sand and gravel. However, they are less effective at removing finer particles and may leave debris in cracks and potholes. The abrasive action of the broom can also break down larger particles into smaller ones, potentially contributing to particulate pollution (Schilling, 2005).

In West Oakland's 2023 fleet record, 13 out of 17 sweepers are mechanical (see Appendix A. West Oakland Sweeper Inventory 2023). This preference is partly due to feedback from the West Oakland Public Works Supervisor, who reported challenges with using regenerative air sweepers in areas with substantial debris. Regenerative air sweepers can become clogged when there is a lot of debris on the road, leading to costly downtime and repairs. Consequently, mechanical sweepers, which are less sensitive to clogging, are favored in areas with high amounts of large debris (e.g., items larger than leaves). In some cases, regenerative air sweepers are used in tandem with mechanical sweepers, following behind to capture finer particles after the larger debris has been cleared by the mechanical sweeper.

3.2 Vacuum Sweepers

Vacuum sweepers operate similarly to household vacuum cleaners but on a much larger scale. They use an engine-powered fan to create suction, drawing debris into a hopper through a vacuum nozzle. A windrow broom typically moves dirt into the path of the vacuum nozzle. Vacuum sweepers are better at picking up finer materials than mechanical sweepers but less effective at picking up wet vegetation or large debris (Calvillo et al., 2015). However, the exhaust air from the vacuum can re-release fine particles into the air. New vacuum sweeping technologies can also include some type of filter or water system to reduce the amount of dust released from the vacuum (Calvillo et al., 2015).

3.3 Regenerative Air Sweepers

Regenerative air sweepers are like vacuum sweepers but were designed to redirect the exhaust air to improve the dust removal from pavement cracks using a closed-loop air system to clean surfaces. Unlike vacuum sweepers, the air in regenerative air sweepers is continuously recirculated, reducing the amount of dust emitted into the atmosphere. An engine powers a blower that pushes the air through a blast orifice across the width of a pick-up head. This air blast dislodges debris, which is then sucked into a hopper. These sweepers are effective at removing both coarse and fine particles, including those lodged in pavement cracks and potholes. They are considered more environmentally friendly due to their ability to limit dust emissions, remove large debris and small particles found in cracks, and clean a wider swathe of road compared with vacuum sweepers (Calvillo et al., 2015). However, regenerative air sweepers are less effective at removing wet vegetation or large road debris compared to mechanical sweepers (Calvillo et al., 2015).

3.4 Certified Sweepers

The South Coast Air Quality Management District (South Coast AQMD) developed a street sweeper testing protocol that certifies equipment based on two factors: its PM_{10} efficiency at removing typical urban street debris and its ability to limit PM_{10} entrainment during the sweeping process (Schilling, 2005). In the late 20th century, areas of southern California were in nonattainment for PM_{10}, including Orange County and parts of Los Angeles, Riverside, and San Bernardino counties. As a result, the South Coast AQMD was required to implement the best available control measures for fugitive dust sources, including agriculture, development sites, industry, and streets. It was identified that street sweeping could be used as a management tool to reduce the amount of fugitive dust on streets. PM_{10} certified street sweepers need to both reduce the amount of fugitive dust and not increase the amount of fugitive dust as a result of their action. In a study performed with the University of California – Riverside, College of Engineering - Center for Environmental Research and Technology (CE-CERT) for the Coachella Valley Association of Governments, street sweepers were tested in an artificial tunnel for road dust efficiency and PM_{10} entrainment. The study determined that street sweepers with vacuums sweepers equipped with adequate filters had the ability to reduce 80% of PM_{10} particles from re-entrainment or vented from the sweeper (Schilling, 2005); $PM_{2.5}$ and UFPs were not examined.

Since then, South Coast AQMD developed a test to ensure that street sweepers reduced urban street loadings and additionally limited the amount of PM_{10} entrained during the sweeping process. Passing such a test ensured that street sweepers were "PM_{10} Certified" (Appendix A to Rule 1186, Section 1.1 Purpose). South Coast AQMD has a list of prequalified sweeper manufactures available on their website.[13] A summary of the testing protocol is stated in Schilling (2005).

In 1997, South Coast AQMD enacted Rule 1186 requiring all local government agencies to use PM_{10}-efficient street sweepers, including private street sweepers contracted by

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[13] **South Coast Air Quality Management District, Certified Street Sweepers Under South Coast AQMD Rule 1186 (as of July 10, 2024)** (https://www.aqmd.gov/docs/default-source/rule-book/support-documents/rule-1186/certified-street-sweepers-equipment-list.pdf).

government agencies. According to Rule 1186, sweepers must achieve 80% pick-up efficiency on a test track and limit entrained PM_{10} particles to no more than 200 mg/m³ based on ambient air monitoring. Further, South Coast AQMD implemented rule 1186.1 requiring government agencies and private sweeper contractors to acquire alternative-fuel or less-polluting sweepers when purchasing or leasing sweeper vehicles (South Coast Air Quality Management District, 2009). Since then, other jurisdictions have adopted requirements for PM_{10}-efficient sweepers, many using the South Coast AQMD list of approved sweepers. In 2004, San Joaquin Valley Air Pollution Control District adopted a rule requiring all purchases of street sweeper equipment must be PM_{10}-efficient street sweepers (Rule 8061). Today, most manufacturers of street sweepers in the United States and Europe have achieved PM_{10} certification, as defined by South Coast AQMD (Schilling, 2005).

However, there are some concerns about the South Coast AQMD testing procedure given that it does not require that the size of particles removed by the sweeper are measured (Calvillo et al., 2015). Other regions have developed their own testing protocols. For example, the city of Toronto requires their own certification testing protocol (**Section 5.3**) (City of Toronto, 2005), and Europe created its own certification test in 2015 to test the PM_{10}/$PM_{2.5}$ efficiency of street sweepers (Fussell et al., 2022). The European standard, DIN EN15429-3:2015, provides a method for assessing the efficiency of road sweepings in removing and capturing PM_{10} and $PM_{2.5}$ from urban road surfaces. It also evaluates their ability to minimize airborne and entrained PM_{10} and $PM_{2.5}$ during sweeping (GlobalSpec). This standard applies to a variety of street sweepers, including truck-mounted, self-propelled, towed, and attached sweeping equipment. The use of dust suppression water is allowed during testing; however, sweepers with flushing machines or equipped with front-mounted spray bars that are not part of a dust suppression system are excluded from the test's scope (GlobalSpec).

3.5 High-Efficiency Sweepers

The term "high-efficiency sweepers" refer to sweepers (mechanical, vacuum, or regenerative air) that are modified to control the loss of fugitive dust smaller than 60 μm in diameter with filters (Calvillo et al., 2015).

3.6 Street Washing

Street washing, also known as water flushing, involves the periodic application of water under high or low pressure to a roadway. Street washing can be performed either in conjunction with street sweeping or as a separate operation. For the purposes of this report, street sweeping in combination of street washing is reviewed, but we do not review stand-alone street washing.

3.7 Caltrans Current Street Sweeper Fleet

Caltrans currently has eight sweepers that are either sweep/wash or sweep/vacuum. Some equipment uses water to aid in material collection and minimize dust generated by the equipment. Street sweeping may be conducted during dry periods, just before or after rainfall, and even during light rain when necessary. Street sweeping operations may be conducted during the rainy season, depending on various factors, including if there is no standing or running water that could affect equipment performance. Routine sweeping is also performed in mountain areas during winter to collect sand from roadways. Additionally, emergency situations, such as debris spills on highways, may require sweeping in the rain to ensure road safety and cleanliness (Caltrans Division of Environmental Analysis, personal communication, September 19, 2025 and October 15, 2024).

4. Effectiveness of Street Sweeping on Reducing Entrained Dust Emissions

The effectiveness of street sweeping at reducing road dust PM emissions and improving air quality is found to be inconsistent in the literature. Determining the effectiveness of street sweeping is done in different ways. As noted by AIRUSE (2013), there are two common ways to identify the effectiveness of street sweeping: (1) reduction of PM road dust emissions, and (2) reduction of ambient air PM concentrations near a road. The emissions reduction method measures the direct impact of street sweeping on road dust emissions, focusing on the immediate decrease in surface silt loading that can be lifted from the road surface and suspended into the atmosphere. In contrast, the ambient air PM concentration method assesses the overall air quality near the road, which is influenced by multiple factors beyond just street sweeping. While the emissions reduction approach provides a more direct measure of sweeping effectiveness, the ambient air method offers a broader view of air quality impacts.

Many studies have determined road dust emissions rates by using road dust or silt load measurements. Those rates are then used to infer (i.e., not directly measure) subsequent air quality impacts. Inferring potential impacts on subsequent road dust emission rates is easier, since the EPA AP-42 method for estimating PM road dust emission rates is a function of silt loading (i.e., the fugitive dust emission rate increases with increased silt loading). Inferring subsequent air quality impacts is challenging and requires modeling, additional measurements, or both. There have been fewer comprehensive studies focused on ambient air quality impacts than silt load or emission reduction.

Multiple factors must be considered when comparing studies. Those factors include the local climate, meteorological conditions, type of sweeper, measurement methods, and the frequency of measurements. Many studies have focused solely on the short-term impacts of individual sweeping events, without considering the potential cumulative impact of regular and repeated cleanings. As a result, these studies may not capture how ongoing street sweeping could reduce the overall buildup of road dust and potentially improve near-road PM concentrations over time. Furthermore, different methods introduce uncontrolled factors and leave gaps within the analysis of the effectiveness of street sweeping. Only a few studies have performed both kinds of measurements using silt loading and ambient PM measurements; those investigations include Chang et al. (2005), Amato et al. (2009), and Buckley (2015).

This section presents the results of studies that quantify the effectiveness of street sweeping measures at reducing roadway sediment load, reducing PM_{10} and $PM_{2.5}$ road dust emissions, and reducing near-road PM concentrations. Limitations and gaps in the existing research are also summarized. The studies reviewed are limited to the last 30 years, with a focus on more recent studies. Unfortunately, there are few recent studies and not many studies are focused within California.

4.1 Emissions Reduction

Table 2 summarizes studies that focused on estimating the impact of street sweeping on roadway silt loadings and/or PM road dust emissions rates. Many of the studies collected road silt samples before and after sweeping. They then used silt load measurements to determine road dust emissions rates using, for example, the EPA AP-42 approach. However, many studies did not directly measure road dust emission rates. Some used an upwind/downwind measurement method to estimate PM emissions based on differences in PM concentrations measured upwind and downwind of the roadway. This measurement method is similar to that used to develop the AP-42 empirical equation describing emissions from paved roads. Upwind/downwind measurement studies must account for numerous confounding factors, including vehicle PM emissions from exhaust, brake and tire wear, meteorological conditions, traffic activity and vehicle fleet composition, and road surface conditions.

The studies that attempted to directly measure road dust emission rates often used a mobile emission rate system or other monitoring methods such as Light Detection and Ranging (LIDAR). Another commonly used method is the Testing Re-Entrained Kinetic Emissions from Roads (TRAKER) system, which uses a particle monitor mounted in front of a vehicle and behind its front tires to measure, in real time, the concentration of road dust suspended from the road surface (Kuhns et al., 2003).

Table 2. Summary of studies pertaining to street sweeping on road dust emissions using emission factors and/or silt loading.

Table Summary: This table provides a list of studies that investigated street sweeping and washing based on the efficiency of silt removal or emissions reductions.

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Kantamaneni et al., 1996	Spokane, WA	Silt loading & Upwind/downwind	Used a tracer release and silt loading to measure PM_{10} emissions factors on four-lane commercia/residential paved road	Correlation between PM_{10} emission factor and the time passed after sweeping only for periods of low relative humidity (<30%)	• Regenerative air sweeper • Measurements were taken at varying days after sweeping (1 – 45 days)
Kuhns et al., 2003	Treasure Valley, ID	TRAKER	Used the mobile TRAKER vehicle to investigate sweeping impacts during the winter directly after sanding and during the summer where roads were not impacted by sanding	• Increase PM_{10} emissions immediately after sweeping by 40% • PM_{10} emissions were increased directly after sanding and sweeping; Approximately 8 hours after sanding and sweeping, emissions returned to pretreated levels	• Vacuum & mechanical sweeper • Frequency was not noted • Curb was present for one location in the wintertime sanding and sweeping test; both locations with curb and without curb saw an increase in emissions after sanding and sweeping

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Chang et al., 2005	Taipei, Taiwan	Silt load and upwind and downwind	Tested regenerative air vacuum sweeper with spray nozzles and street washing with silt loading and total suspended particles (TSP)	• Decrease silt load (by 23-91%) • Decrease in ambient TSP by up to 30%	• Regenerative air vacuum sweeper followed by street wash • Short-lived effect of decreased TSP • Used AP-42 method for silt collection at 3, 5, and 7 hours after cleaning event • Frequency was not of concern • Measurements were taken 0-9 hours after cleaning event
City of Toronto, 2005	Toronto, Canada	Silt load and LIDAR	Tested the efficiency of street sweeping within a controlled environment through silt loading. Also investigated entrainment of particles through LIDAR of mechanical and regenerative air sweepers	92% combined surface and air removal efficiency of PM_{10} and $PM_{2.5}$. with regenerative air sweepers	• Mechanical and regenerative air sweepers • Frequency was not noted
Gertler et al., 2006	Lake Tahoe Basin, NV	Upwind/downwind flux	Investigated emissions in springtime using an upwind and downwind method using a near-road flux tower	Increase in emission factors directly after sweeping for both PM_{10} (by 11%) and $PM_{2.5}$ (by 59%)	• Mechanical broom and water wash street sweeper • Measurements were taken after sweeping following a snow storm • Study did not mention location of drainage inlet

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Zhu et al., 2012	Lake Tahoe Basin, NV & CA	TRAKER	Reviewed one year of data or road dust emissions collected on mobile sampling platform (TRAKER)	• Sweeping ASAP could reduce winter emissions by 41% • Larger benefits in winter than summer after treatment was placed for wintertime storms	• Does not note type of sweeper • No requirements for PM_{10}-certified sweeper in the Lake Tahoe Basin • Two different sweeping frequency: ASAP after snow event versus once or twice during the winter season • Looked at cost effectiveness of street sweeping and found street sweeping is cost effective

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Amato et al., 2009	Barcelona, Spain	Silt load and upwind/ downwind	Investigated road dust samples and near-road monitors after routine street washing and street sweeping and washing	• Slight decrease in PM_{10} concentration downwind after washing • 94% decrease in silt load after 10 hours for one washing; 99% decrease in silt load after three washings • 93% decrease in silt load with mechanical sweeper before washing • 7-10% reduction in daily PM_{10} concentrations	• Mechanical sweeper before street washing and washing only • Street cleaning occurred eight times between April 7 and May 4, 2008; the cleaning schedule was inconsistent, with some cleanings happening only a few days apart and others on consecutive days • Study only took silt load measurements after 10 hours
Karanasiou et al., 2014	Madrid, Spain	Silt load	Took samples of silt load before and after washing in morning and night to compare with a reference site	No statistically significant difference in silt load 12 hours after sweeping and washing; silt load within 12 hours of the cleaning event were not measured	• Vacuum sweeper then washing • Background compared with a reference site • Multiple test were preformed from July 9-17, 2009 • Frequency was not of concern

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Buckley, 2015	Toronto, Canada	Silt load and near-road monitors	Compared mechanical and regenerative air sweepers in ambient conditions using air quality monitors and silt loading	66% silt removal efficiency for regenerative air sweepers after 1 sweep	• Mechanical and regenerative air sweepers • Regenerative air sweepers had a higher average entrainment efficiency compared with mechanical sweepers • Did not mention frequency
Fitz et al., 2021	Las Vegas, NV	Silt load and TRAKER	Tested silt using the AP-42 and TRAKER method for emission rates before and after sweeping on roads with native road dust; study went on to test emission rates with soil applied to the road	Increase in emissions rates from AP-42 and mobile TRAKER method after street sweeping with a PM_{10}-certified sweeper	• Used a PM_{10}-certified regenerative air sweeper • The study was performed on a closed off road over 5 days, with road traffic diverted for the period to perform tests; the study's main focus was to compare measurement methods

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Das and Wiseman, 2024	Toronto, Canada	Silt load	Investigated the use of regenerative air sweepers to efficiently remove road dust particles and metal(loids); used silt samples from four locations	• Reduction of <10 μm road dust particles by 76% • Reduction in concentrations of metal(loids) particles <2 mm	• Regenerative air sweeper • Frequency differed at each site • Authors were not able to interpret effects from frequency as traffic volumes, and asphalt surface conditions differ at each site

Overall, studies have reported inconsistent results. A few studies, including Kuhns et al. (2003), indicated that street sweeping resulted in no significant change in PM emissions. Kuhns et al. (2003) investigated vacuum and mechanical sweepers in the context of emissions. Karanasiou et al. (2014), on the other hand, investigated sweeping and washing, and also did not find a statistically significant difference in silt load.

Other studies found that emissions rates were higher directly after sweeping. Fitz et al. (2021) used the TRAKER and EPA AP-42 methods and found higher emissions rates directly after sweeping (i.e., within 35 minutes) with a regenerative air sweeper. The authors speculated that the sweeper was likely pulling debris from the interstitial surfaces of the pavement and redistributing that debris on the roadway; the exact place of the drainage outlet was not specified. Similarly, Gertler et al. (2006) found that street sweeping with a brush and water wash sweeper in Nevada increased the PM_{10} and $PM_{2.5}$ re-entrainment rate of the remaining road dust. Those authors used the upwind/downwind measurement method and did not state the location of drainage outlet.

A few studies noted reductions in silt load after sweeping. The city of Toronto performed two tests of the efficiency of silt removal using mechanical and regenerative air sweepers (City of Toronto, 2005; Buckley, 2015). In 2004, the test was performed within a controlled environment (i.e., an enclosed tunnel) to minimize confounding factors. Ten years later, the city performed a similar test. However, this time the test was conducted on a real street. In both studies, regenerative air sweepers outperformed mechanical sweepers in terms of sediment removal. The regenerative air sweepers exhibited 90% and 66% removal efficiencies in 2004 and 2014, respectively, while the mechanical sweepers exhibited 81-85% removal efficiencies in 2004 and a 26% removal efficiency in 2014. In another study in the Toronto area, Das and Wiseman (2024) found that regenerative air sweepers had high removal efficiencies; on average, they removed 76% of the total mass of particles less than 10 μm in diameter.

The combination of street washing after street sweeping has been shown to be effective at removing road dust. In Barcelona, on an urban road that received about 19,000 vehicles per day, Amato et al. (2009) observed a 93% decrease in dust load (PM_{10} fraction) after three nightly street sweep and wash cycles. On the same road, the authors also tested only street washing and found a 94% decrease of dust load 10 hours after one wash. Furthermore, the author performed three additional washing cycles within four days that increased the efficiency to 99%. The authors note that a rain event occurred on the third night and therefore postponed the third washing until the fourth night. The rain had some effect on the street silt load and decreased the PM_{10} concentration in the untreated section by 44%. Chang et al. (2005) also noted a decrease in silt load after a vacuum sweeper and street washing in samples taken 3, 5, and 7 hours after cleaning. However, Karanasiou et al. (2014) did not find a significant difference in silt load (PM fraction) after sweeping and washing. Those authors noted that measurements were taken in the morning roughly 9-12 hours after the road had been cleaned, on a road with consistent weekday traffic of around 32,000 vehicles per day and with ambient temperatures ranging from 21-43° C. Karanasiou et al. (2014) speculated that equilibrium between mobilization deposition and the moistening/resuspension process may have already been reached at the time of remeasurement. The temperature may influence when the moistening/resuspension process reaches equilibrium.

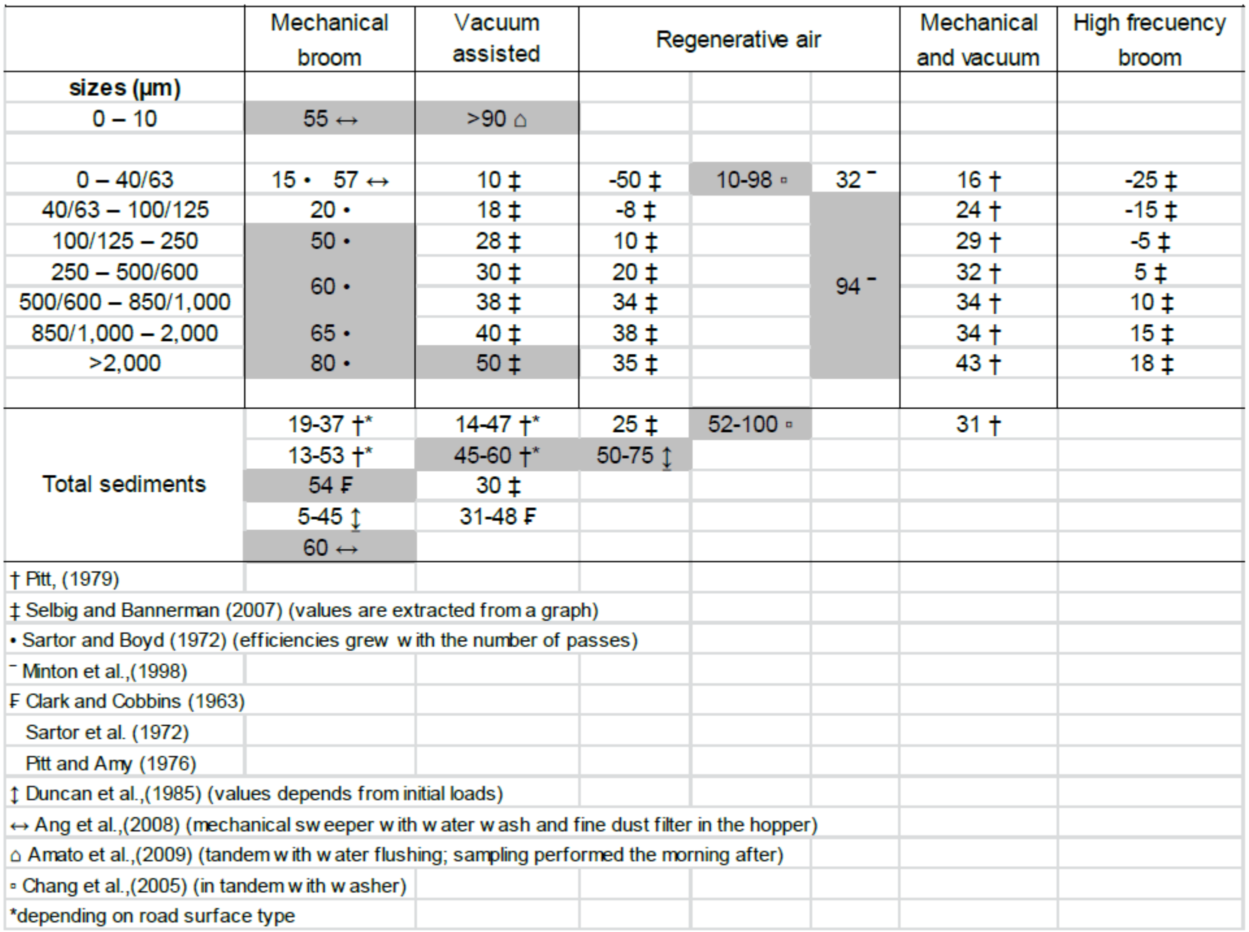
Local factors, especially relative humidity, can influence the efficiency of street sweeping on emissions and silt load. Kantamaneni et al. (1996) investigated emission rates in Spokane, Washington using a regenerative air sweeper and found a relationship between the road dust PM_{10} emission rate and relative humidity. When the relative humidity was less than 30%, there was a strong correlation between the time elapsed after street sweeping and the emissions factor. However, that correlation disappeared when the relative humidity was above 30%.

In the Lake Tahoe Basin, where roads receive wintertime sanding, street sweeping has been shown to be a cost-effective method for reducing PM_{10} emissions when performed after winter storms. Most street sweeping studies have focused on short-term impacts, but Zhu et al. (2012) conducted one of the few year-long studies investigating the impact of sweeping on wintertime and summertime emissions. Zhu et al. (2012) found that implementing an “as soon as possible” (ASAP) sweeping practice—meaning deploying sweepers as soon as possible after a snow storm—reduced wintertime emissions averages by 41% compared with a reference site. Street sweeping also reduced summer emissions, although the effect was less significant compared with winter emissions. Furthermore, Zhu et al. (2012) noted that the strongest predictor of emissions on roads was whether sweeping occurred when the roads are dry after a winter storm. The authors do not note if all ASAP sweepings in the study happened when roads are completely dry after a winter storm or not. The wetness of the road may temporarily suppress dust resuspension and impede the effectiveness of removing small particles due to the adherence of particles to the road surface.

Finally, the efficiency of silt removal by street sweeping extends beyond air quality concerns as particle sizes increase. While this report primarily focuses on studies investigating airborne particles, AIRUSE (2013) provided an important comparison by examining studies related to the removal of larger particles (**Table 3**). Sweepers were generally better at picking up larger debris than smaller debris. Many of the studies noted in Table 3 were not investigated in detail in this literature review as our focus was on airborne particles.

Table 3. Summary of quantitative efficiency estimates (%) for total size-fractionated sediments. Size bins are in ranges given differences between different studies. Efficiencies ≥50% are shaded grey. (Figure and caption from AIRUSE, 2013.) Column 1 represents the size distribution in µm. Columns 2-8 represent the efficiency estimates in percentages.

Table Summary: The table displays sweeping vehicle efficiencies for different particles size bins. Generally, efficiency improves as particle size increases.



	Mechanical broom	Vacuum assisted	Regenerative air			Mechanical and vacuum	High frecuency broom
sizes (µm)							
0 – 10	55 ↔	>90 ⌂					
0 – 40/63	15 • 57 ↔	10 ‡	-50 ‡	10-98 ▫	32 ¯	16 †	-25 ‡
40/63 – 100/125	20 •	18 ‡	-8 ‡		94 ¯	24 †	-15 ‡
100/125 – 250	50 •	28 ‡	10 ‡			29 †	-5 ‡
250 – 500/600	60 •	30 ‡	20 ‡			32 †	5 ‡
500/600 – 850/1,000		38 ‡	34 ‡			34 †	10 ‡
850/1,000 – 2,000	65 •	40 ‡	38 ‡			34 †	15 ‡
>2,000	80 •	50 ‡	35 ‡			43 †	18 ‡
Total sediments	19-37 †*	14-47 †*	25 ‡	52-100 ▫		31 †	
	13-53 †*	45-60 †*	50-75 ↨				
	54 ₣	30 ‡					
	5-45 ↨	31-48 ₣					
	60 ↔						

† Pitt, (1979)
‡ Selbig and Bannerman (2007) (values are extracted from a graph)
• Sartor and Boyd (1972) (efficiencies grew with the number of passes)
¯ Minton et al.,(1998)
₣ Clark and Cobbins (1963)
Sartor et al. (1972)
Pitt and Amy (1976)
↨ Duncan et al.,(1985) (values depends from initial loads)
↔ Ang et al.,(2008) (mechanical sweeper with water wash and fine dust filter in the hopper)
⌂ Amato et al.,(2009) (tandem with water flushing; sampling performed the morning after)
▫ Chang et al.,(2005) (in tandem with washer)
*depending on road surface type

4.2 Ambient PM Concentrations

Table 4 summarizes studies that focused on direct measurements of the impact of street sweeping on near-road PM concentrations. These studies used ambient air measurements from nearby monitoring towers or roadside monitors. Studies vary in their monitoring approaches. Some use existing local monitoring networks positioned near the tested roads. Others place monitors specifically for the study, with distances ranging from as close as 1.5 m to 6 m from the road. The height of monitors also differs across studies, with some using multiple heights ranging from 0.5 to 9.8 m above ground. Notably, some studies do not specify the exact height or distance of their monitors from the road.

Using ambient PM measurements to quantify the impact of street sweeping on near-road PM concentrations is difficult due to a variety of uncontrolled factors, including meteorology and nearby source variability. Accurately assessing air quality benefits necessitates making comparisons with control sites and control periods (i.e., places and times unaffected by cleaning activities) (AIRUSE, 2013).

Overall, these studies reported inconsistent results, and it is difficult to draw definitive conclusions regarding the benefit of street sweeping on near-road PM concentrations. Two studies—Norman and Johansson (2006) and Bogacki et al. (2018)—noted an increase in ambient PM measurements during or directly after sweeping. Those studies both used mechanical sweepers. Other studies did not find a statistically significant relationship between street sweeping and atmospheric PM concentrations, regardless of sweeper technology or the frequency of sweeping. For example, Keuken et al. (2010) found that near-road hourly PM concentrations over a 21-wk period in Amsterdam, the Netherlands, did not change on days with sweeping and/or washing compared with days with no sweeping and/or washing.

A few studies concluded that street sweeping performed alone or in combination with street washing reduced near-road PM concentrations. There was a decrease in ambient PM_{10} and $PM_{2.5}$ levels in Toronto after streets were swept with a regenerative air sweeper (Buckley, 2015). Lin et al. (2023) also found a decrease in UFPs and $PM_{2.5}$ after street sweeping. Furthermore, Lin et al. observed an even greater short-term decrease in UFP when street sweeping was combined with washing. Lin et al., (2023) further investigated street washing on roads with and without drainage ditches and found that street washing was less effective on road sections without drainage ditches. In these areas, road dust was more likely to become airborne again as the road surface dried.

A few studies only noted a decrease in PM concentrations for a short period time (a few hours to one day) after street sweeping and washing; others found longer-lasting impacts of sweeping that extended from days to entire seasons. Karanasiou et al. (2011) only saw a decrease in PM_{10} concentrations in the morning hours after nightly street cleaning. Amato et al. (2010a) found that there was only a slight decrease in ambient PM_{10} between 12:00 and 18:00 local time after night street sweeping and washing. The authors noted there was an increase in PM_{10} concentrations in the morning and evening hours; however, the study determined this was likely due to either atmospheric stagnation or higher road traffic emissions. Therefore, the authors only decided to compare the time frame from 12:00 to 18:00 local time, when the study area was less affected by worsening urban and regional pollution. Kryłów and Generowicz (2019) studied the impacts of mechanical PM_{10}-certified sweeping and street washing and found a 17.3% decrease in PM_{10} concentration and a 15.4% decrease in $PM_{2.5}$

concentration that lasted up to three days after sweeping. The magnitude and duration of the benefit was influenced by meteorological conditions and traffic volumes. Amato et al. (2009) concluded that street sweeping followed by street washing reduced near-road PM_{10} concentrations by 7-10% for 24 hours following cleaning.

Table 4. Summary of studies of the effect of street sweeping on road dust emissions using ambient air measurements.

Table Summary: This table lists studies that investigated the effects of street sweeping and washing on ambient air.

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Norman and Johansson, 2006	Stockholm, Sweden	Nearby monitoring network	Investigated the impact of intense springtime sweeping on PM_{10} emissions from studded tires. For 8 days in March 2003 and 12 days in April 2003, the street was cleaned by a mechanical street sweeper	• No statistically significant reduction in PM_{10} • Increase in PM_{10} on days with sweeping	• Mechanical sweeper • Swept every night for 8 days in March and 12 days in April
Chang et al., 2005	Taipei, Taiwan	Silt load and upwind/ downwind	Tested regenerative air vacuum sweeper with spray nozzles and street washing with silt loading and TSPs	• Decrease silt load (by 23-91%) • Decrease in ambient TSPs of up to 30%	• Regenerative air vacuum sweeper with street wash performed after • Short-lived effect of decreased TSPs • Used AP-42 method for silt collection at 3,5 and 7 hours after cleaning event (U.S. Environmental Protection Agency, 1995) • Frequency was not of concern • Measurements 0-9 hours after cleaning event

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Amato et al., 2009	Barcelona, Spain	Silt load & upwind/ downwind	Investigated road dust samples and near-road monitors after routine street washing and street sweeping and washing	• Slight decrease in PM_{10} concentration downwind after washing • 7-10% reduction in daily PM_{10} levels • 93% decrease in silt load with mechanical sweeper before washing • 94% decrease in silt load after 10 hours for one washing; 99% decrease in silt load after three washings	• Two cleaning methods: (1) mechanical sweeper before street washing, and (2) washing only • Street cleaning occurred eight times between April 7 and May 4; the cleaning schedule was inconsistent, with some cleanings happening only a few days apart and others consecutive days • Study only took silt load measurements after 10 hours
Amato et al., 2010a	Barcelona, Spain	Near-road monitoring	Investigated street cleaning of vacuum sweeper followed by street washing using near-road sites and urban background sites	• Slight reduction in PM_{10} from 12:00 to 18:00 after night cleanings; decrease of 4.7 µg m^{-3} downwind • No significant difference in daily averages	• Vacuum and washing • Background was a mean of three urban sites nearby • Street cleaning every night for one week (23:00 - 2:00)

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Keuken et al., 2010	Amsterdam, the Netherlands	Near-road monitoring	Compared daily average concentration of coarse fraction of PM on days with and without sweeping and on days with and without washing	No significant difference in coarse fraction of PM between days on and following sweeping and days with washing and weeks with no street cleaning	• Every other week from July to November, the street was vacuum swept on Tuesdays, followed by washing on Wednesdays from July • Found that only heavy rainfall (> 2mm per hour) reduced road dust emissions • Based on coarse fraction $PM_{2.5-10}$ (difference between PM_{10} and $PM_{2.5}$) • Background concentration was determined from weeks that did not have street cleaning
Karanasiou et al., 2011	Madrid, Spain	Near-road monitoring compared with a reference site	Examined nightly sweeping and washing over a month with continuous monitoring.	• Reduction in PM_{10} concentrations noticeable during the morning hours • Daily PM_{10} levels 2-15% higher for unwashed conditions	• Mechanical sweeper followed by washing • Street washing nightly for one month • Reduction persisted for only the following morning • Washed daily for one week at 23:00 LST

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Buckley, 2015	Toronto, Canada	Silt load & near-road monitors	Compared mechanical and regenerative air sweepers in ambient conditions using air quality monitors and silt loading	• 66% silt removal efficiency for regenerative air sweepers • 36% decrease in ambient PM_{10} concentration and 39% decrease in $PM_{2.5}$ concentration on average	• Mechanical and regenerative air sweepers • Regenerative air sweepers had higher average entrainment efficiency compared than mechanical sweepers • Did not mention frequency
Bogacki et al., 2018	Krakow, Poland	Near-road monitoring site and comparisons with modeled concentrations from silt loading	Compared direct measurements with modeled PM_{10} and $PM_{2.5}$ concentrations. For the modeled concentrations, samples of road dust were taken (in accordance with U.S. EPA guidelines) and used for emissions rates for the CALINE4 model	• Found that mechanical sweeping increased PM_{10} for up to 3 hours after sweeping, and then returned to pre-cleaning concentrations • Smaller increase for $PM_{2.5}$	• Mechanical sweeper • The sweeper did not have a PM_{10} filter • Only investigated one sweeping event
Krylow and Generowicz 2019	Cracow, Poland	Near-road monitor network	Investigated the impacts of street sweeping and washing	• Reductions in PM_{10} (17.3% on average) and $PM_{2.5}$ (15.4% on average) persisted for three days • Largest decreases in PM_{10} and $PM_{2.5}$ occurred within 48 hours of sweeping and washing	• PM_{10}-certified sweeper • Used both street sweeping and washing • Street cleaning done overnight from 22:00 to 5:00 LST with multiple cycles for 3 nights in a row

Study	Location	Measurement Type	Study Description	Potential Effectiveness	Sweeper Type and Notes
Lin et al., 2023	Chiayi, Taiwan	Mobile monitoring	Investigated three different cleaning methods: sweeping, sweeping before washing and washing before sweeping	• Decrease in UFP concentrations with all three methods • Sweeping before washing reduced UFPs by 42% • $PM_{2.5}$ decreased only after sweeping	• No information on type of sweeper • One cleaning was performed

4.3 Comparative Benefits of Street Sweeping Technologies

Only a few studies have compared street sweeping technologies (e.g., Lin et al., 2023; City of Toronto, 2005; Buckley, 2015; and Kuhns et al., 2003). Most studies considered only one type of sweeper technology. Some of the studies involved street washing. Although direct comparative studies are limited, the studies reviewed here were used to gain insights into differences in the effectiveness of different street sweeper technologies and the effectiveness of washing during or after sweeping.

Table 5 provides an overview of the effects of different street sweeping methods on PM levels, highlighting the impact of various sweeper types—regenerative, vacuum, mechanical, and sweeping and washing—on particulate matter levels. Table 5 includes data on reductions in silt load and ambient air concentrations, categorized as increases or decreases in PM levels across different studies and locations. An increase in emissions, silt load or PM concentrations would lead to a negative impact on air quality, while a decrease would indicate an improvement in air quality. While this format provides a quick comparison, it's crucial to consider that the specific contexts, methodologies, and local factors in each study can significantly influence the results.

Table 5. Summary of the effects of different street sweeping methods on PM Levels. This table includes simplified findings on reductions in silt load and ambient air concentrations, categorized by sweeper type (regenerative, vacuum, mechanical, and sweeping and washing) from various studies. The types of measurements are labeled as (sL) for silt loading, (Em) for emissions and (PM) for ambient PM concentrations.

Table Summary: This table lists simplified effects of different sweeper types on PM levels.

Source	Location	Regenerative	Vacuum	Mechanical	Sweeping and Washing
Kantameneni et al. (1996)	Spokane, Washington	Unclear	--	--	--
Kuhns et al. (2003)	Treasure Valley, Idaho	--	40% increase (Em)	40% increase (Em)	--
Toronto, CA (2005)	Toronto, Canada	90% decrease (sL)	80-90% decrease (sL)	81-85% decrease (sL)	--
Change et al. (2005)	Taipei County, Taiwan	--	--	--	23-91% decrease (sL)

Source	Location	Regenerative	Vacuum	Mechanical	Sweeping and Washing
Gertler et al. (2006)	Lake Tahoe, Nevada	--	--	--	Increased 11% for PM_{10} and increased 59% for $PM_{2.5}$ (Em)
Norman & Johansson (2006)	Stockholm, Sweden	--	--	Increase (PM)	--
Amato et al. (2009)	Barcelona, Spain	--	--	--	7% decrease (PM) & 93% decrease (sL)
Keuken et al. (2010)	Amsterdam, Netherlands	--	No significant difference (PM)	--	No significant difference (PM)
Amato et al. (2010a)	Barcelona, Spain	--	--	--	10% decrease (PM)
Karanasiou et al . (2011)	Madrid, Spain	--	--	--	2-15% decrease
Zhu et al. (2012)	Lake Tahoe Basin, Nevada and California	41 % decrease[a]	41 % decrease[a]	41 % decrease[a]	--
Karanasiou et al . (2014)	Madrid, Spain	--	--	--	Not statistically significant (sL)
Toronto	Toronto, Canada	66% decrease (sL)	--	26% decrease (sL)	--
Bogacki et al. (2018)	Krakow, Poland	--	--	Increase for PM_{10} & $PM_{2.5}$ (PM)	--
Krylow and Generowicz (2019)	Cracow, Poland	--	--	--	17.3% decrease for PM_{10} and 15.4% decrease for $PM_{2.5}$ (PM)
Fitz et al. (2020)	Las Vegas, Nevada	Increase (Em & sL)	--	--	--
Lin et al. (2023)	Chiayi City, Taiwan	--	--	--	42% decrease for UFPs (PM)
Das and Wiseman (2024)	Toronto, Canada	76% reduction (sL)	--	--	--

[a] Zhu et al. (2012) did not report the type of sweeper used.

4.3.1 Sweeping

While the results are mixed overall, there is some indication that emissions reductions and ambient air quality after sweeping both depend on the sweeping technology. Regenerative air sweeper and sweeping and washing outperformed mechanical sweepers in terms of entrainment and removal of $PM_{2.5}$ and PM_{10} particles. Multiple studies have shown that mechanical sweepers increase airborne dust during and immediately after a sweeping event (Calvillo et al., 2015; Norman & Johansson, 2006; Bogacki et al., 2018). Mechanical sweepers are relatively efficient at removing larger debris from roadways but are less efficient at removing smaller particles, including PM_{10} and $PM_{2.5}$, that may become entrained in the atmosphere (Schilling, 2005). Bogacki et al. (2018) measured the impact of mechanical street cleaning on PM_{10} and $PM_{2.5}$ 1-hour concentrations. Directly after street sweeping, there was rapid increase in PM_{10} ambient concentrations. That trend was confirmed by the model. There was a smaller effect on $PM_{2.5}$. After 3 hours, the peak from street sweeping diminished.

Similarly, Norman and Johansson (2006) noted that mechanical sweeping did not statistically reduce ambient PM_{10} concentrations in Stockholm, Sweden. Those authors found increased PM_{10} concentrations on days of sweeping. Furthermore, mechanical sweepers were shown to increase nearby PM_{10} and $PM_{2.5}$ concentrations, even when a water wash system was used. In Nevada, local protocols call for sweeping within four days after the roads are cleared and dried following a winter storm event to remove winter roadway abrasives that may decrease air quality. Gertler et al. (2006) investigated the short-term emissions impact of a brush and water sweeper after a storm event. The results revealed an increase in the PM_{10} emission factor (from 660 to 735 mg km^{-1}) and a larger increase in the $PM_{2.5}$ factor (from 133 to 211 mg km^{-1}) after sweeping.

Vacuum sweepers have similar effects as mechanical sweepers. We focused on only one study that investigated vacuum sweepers. Kuhn et al. (2003) studied the short-term impacts of both mechanical and vacuum sweepers. These authors noted an increase in the PM_{10} emission potential by up 40% immediately after sweeping. Eight hours after sweeping, the emission potential returned to within 15% of its pretreatment level.

Regenerative air sweepers exhibit greater potential for reducing road dust PM emissions and near-road PM concentrations. However, the studies we selected still noted inconsistent results. The city of Toronto compared a mechanical sweeper with a newer regenerative air sweeper in two studies that focused on both silt load and PM entrainment (City of Toronto, 2005; Buckley, 2015). The first study was performed in 2004 in a controlled environment (i.e., an enclosed tunnel) and tested several different mechanical vacuum-assisted and regenerative air sweepers. The goals of the test were to determine how well material was removed from a test track surface, the degree to which material was disturbed and deposited elsewhere, and how material became airborne. The test measured the silt load and the entrainment of PM via LIDAR. The investigation revealed that regenerative air sweepers achieved significant PM_{10} and $PM_{2.5}$ removal rates; these sweepers performed the best across all three key criteria categories (City of Toronto, 2005). Regenerative air technology has the potential to achieve surface removal efficiencies greater than 90%; this technology was also associated with the lowest PM_{10} and $PM_{2.5}$ air contamination concentrations.

In 2014, the city of Toronto performed a similar test on a city street (Buckley, 2015). The study involved ambient air quality monitoring before and after street sweeping on a city street, using both mechanical and regenerative air sweepers. Air quality was continuously measured at different heights for 48 hours each week for three consecutive weeks. Furthermore, silt loading was tested before and after the mechanical and regenerative air sweepers cleaned the street. The regenerative air sweeper outperformed the mechanical air sweeper in terms of removal efficiency (66% for silt) and reductions in average PM_{10} and $PM_{2.5}$ ambient air concentrations (36% and 39%, respectively). Additionally, the ambient air was measured during the test to determine the entrainment efficiency improvement; the regenerative air sweeper was 77-96% more efficient than the mechanical sweeper (Buckley, 2015).

Das and Wiseman (2024) further investigated the impact of regenerative air street sweepers on metal(oid)s and particles with diameters less than 10 μm in Toronto. They found that a regenerative air street sweeper reduced the total mass of <10 μm road dust particles by 76%, on average, and reduced the concentrations of metal(oid)s smaller than 2 mm in road silt particles.

However, Fitz et al. (2021) found no improvement in silt load using a regeneration PM_{10}-certified air sweeper. These authors in fact noted increased emissions factors after sweeping using the EPA AP-42 and mobile TRAKER method. Fitz et al. (2021) attributed this finding to the sweeper pulling debris from the interstitial surface of the road then redistributing the debris to areas that are not generally impacted by the vehicle's wheels.

4.3.2 Sweeping and Washing

Some of the studies that we reviewed found positive impacts in the short term from sweeping and washing; others did not observe significant differences. Washing may have a temporary effect due to the wet road surface, which can inhibit resuspension (AIRUSE, 2013), making it difficult to draw definitive conclusions about its benefits. This phenomenon has also been observed with heavy rainfall and extended periods of road wetness. Keuken et al. (2010) concluded that only high-intensity rainfall (i.e., more than 2 mm of rainfall per hour) was associated with a lower PM coarse fraction concentration. That finding is likely due to the total duration of road wetness, the authors noted.

Karanasiou et al. (2011) noted a reduction in PM_{10} immediately after street washing. However, that effect was short lived and persisted for only 3-5 hours. Karanasiou et al. (2012) did not find a significant effect on $PM_{2.5}$ within the same time frame.

Chang et al. (2005) investigated a combination of modified regenerative air vacuum sweepers and washers in Taiwan in terms of both silt loading and ambient measurements. These authors concluded that the process was effective at removing road dust and decreasing TSPs. However, the decrease in TSPs was short lived, and ambient concentrations returned to baseline values within 3-4 hours. The combination of modified regenerative air vacuum sweepers and washers was able to decrease the concentration of road sediments smaller than 297 µm and road silt particles less than 75 µm. Chang et al. (2005) found that the efficiency of street sweeping and washing was a function of the silt load and did not correlate with either traffic volume or wind velocity. Therefore, reduction efficiency of TSP can be determined by measuring the silt load on the road before and after street sweeping and washing.

Amato et al. (2009) examined the effects of eight nights of sweeping and washing over the course of one month in Barcelona, Spain. These authors focused on washing only and vacuum-assisted mechanical sweepers followed by manual washing. The results revealed that after washing only, PM_{10} concentrations decreased by 7-10% and road dust concentrations decreased by 94% 24 hours. After 3 nightly washings over 4 days, the authors noted a decrease in road dust by 99%. Vacuum-assisted machinal sweepers followed by washing saw similar results, with a 93% decrease in silt load. Amato et al. (2010a) used a similar approach of sweeping and washing and noted only a decrease from 12:00-18:00 local time after night cleaning. The authors noted that the maximum emission benefit by street cleaning was calculated to be equivalent to less than 1% of the total exhaust daily emissions in all of Barcelona.

Lin et al. (2023) investigated multiple methods, including street sweeping, sweeping before washing, and washing before sweeping. The study did not state the type of sweeper used. The team obtained measurements 1 hour, 1 day, and 2 days after street cleaning. Lin et al. (2023) found that all three methods decrease PAHs and UFPs. Sweeping before washing had the greatest impact on UFPs (i.e., a decrease of 42%). The mass concentration of $PM_{2.5}$ only decreased during sweeping. Concentrations at both the reference and measured sites fell significantly in the following days; both sites had the same decrease in concentration and, therefore, the decrease was not attributed to street cleaning. The authors did not investigate a reason for the decrease in background concentration.

4.4 Frequency

Most of the studies reviewed did not prioritize evaluating street sweeping frequency. Instead, they focused on short-term measurements taken within hours to days after sweeping events. This narrow focus may overlook the cumulative effects of repeated street sweeping efforts, including how these efforts interact over time and how larger particles left behind could eventually breakdown overtime into smaller, more easily airborne particulate matter.

Zhu et al. (2012) conducted one of the few studies examining seasonal variations in PM emissions, comparing two different sweeping frequencies: (1) sweeping as soon as possible (ASAP) after a snow event, and (2) sweeping only once or twice per winter season. The study found that higher sweeping frequency reduced winter PM emissions by 41%, with benefits that extended into the summer. This suggests that seasonal sweeping frequencies may have long-term benefits on emissions.

Other research supports the idea that more frequent street cleaning yields greater air quality benefits. Kryłów and Generowicz (2019) demonstrated that intensive overnight sweeping combined with street washing, repeated over three consecutive nights, reduced PM_{10} concentrations on average by 17.3%, and $PM_{2.5}$ concentrations by 15.4%. Similarly, Amato et al. (2009) showed that three repeated washes over four days led to significant improvements: an initial street wash reduced silt load by 94%, and a third cleaning within the four-day span further decreased silt load to 99%.

Conversely, less frequent sweeping proved less effective. Keuken et al. (2010) investigated the impact of biweekly street cleanings (brushing and vacuuming on Tuesdays, followed by washing on Wednesdays) in Amsterdam over a 21-wk period from July to November. They found no significant differences in $PM_{2.5\text{-}10}$ daily averages on or after the sweeping and washing days compared to weeks without any street cleaning.

4.5 Limitations and Research Gaps

The literature pertaining to street sweeping and its impacts on PM road dust emissions and near-road concentrations has several potential limitations and research gaps. One major challenge is the difficulty of isolating the effects of street sweeping due to the numerous sources of PM in both urban and nonurban environments. To accurately measure these impacts, a controlled environment is necessary. Some studies, such as those conducted in tunnels (e.g., City of Toronto, 2005), have attempted to create such conditions. However, these controlled settings may not accurately reflect real-life scenarios, in which factors such as wind, traffic, and humidity significantly influence the effectiveness of street sweeping.

Another limitation is that the available literature often does not note details about roadways, traffic sources, curbs, and drainage ditches, all of which can influence road dust emissions. Additionally, a few studies do not specify the type of sweeper used. Furthermore, studies often make use of different methods and can refer to the same process or instrument by different names. For instance, Amato et al. (2009) and Karanasiou et al. (2011) used the term “mechanical sweeper” but then referred to “aim of vacuuming coarser deposited particles,” which implied the use of a vacuum sweeper.

Moreover, there is a paucity of studies examining the long-term impacts of street sweeping and washing in both urban and non-urban environments and how their frequency affects the measurements. Isolating ambient air measurements specifically attributable to street sweeping for long-term assessments is particularly challenging. The studies reviewed here exhibit a wide variation in frequencies of street sweeping and washing, which makes it difficult to interpret their findings collectively. Additionally, many of the studies were conducted in different climates and used various street cleaning methods.

We were unable to find any studies investigating the potential for street sweeping to remove larger particles that could become smaller suspendible particles. This process could potentially reduce the total amount of PM_{10} available for emissions in the long term. This conjecture was raised in several studies, including Amato et al. (2010b) and Kuhns et al. (2003). This variability complicates the comparison of results and underscores the need for more standardized, long-term research that accounts for real-world variables while maintaining scientific rigor.

5. Regulations & Current Government Practices

Many municipalities and local governments have already implemented street sweeping and cleaning practices for either water quality or air quality concerns (or both). For instance, the Tahoe Lake Basin has implemented local protocols for ASAP street sweeping after the drying of winter storms to minimize the detrimental air quality impacts of winter roadway abrasives (Gertler et al., 2006). In the past, multiple sites across the western United States have added street sweeping in their SIPs to address PM_{10} NAAQS nonattainment, including El Paso, TX, Clark County, NV, the South Coast Air Basin in California, and Maricopa and West Pinal counties in Arizona. Governments in Canada have also conducted scientific investigations and implemented regulations to address PM road dust. Some examples are discussed below.

5.1 California

In California, street sweeping is used as a control measure for PM emissions in some regions. For example, the South Coast AQMD uses street sweeping for PM control in the South Coast Air Basin. The Basin has been designated by the EPA as an attainment area for the 24-hour average PM_{10} NAAQS, but it is still required to submit a maintenance plan. The Final 2021 PM_{10} Maintenance Plan for the Basin references several rules that involve the use of street sweeping to reduce PM_{10} road dust emissions (South Coast Air Quality Management District, 2021). For example, rule 1168 requires governmental agencies to procure and use certified street sweepers for routine street sweeping activities, while rules 1157 and 1158 requires procurements of certified street sweepers to implement specific rule requirements.

In the South Coast Air Basin Attainment Plan for the 2012 Annual $PM_{2.5}$ NAAQS, the authors indicate that “mandating increased street sweeping frequencies has unknown impacts on $PM_{2.5}$ levels, and studies that examine the effect of street sweeping on ambient $PM_{2.5}$ levels are scarce.” They suggest a pilot project and a comprehensive atmospheric measurement campaign to assess the effectiveness of street sweeping in reducing $PM_{2.5}$ (South Coast Air Quality Management District, 2024).

The most recent Air Quality Management Plan issued by the South Coast AQMD in 2022 does not mention street sweeping (South Coast Air Quality Management District, 2022). However, the 2016 Air Quality Management Plan identified Best Control Measure (BCM) 03, which acknowledged that Rule 1168 did not set requirements for sweeping frequencies and suggested that further emission reductions could be achieved by defining sweeping frequency, potentially reviewed through local jurisdictions’ National Pollutant Discharge Elimination System (NPDES) permits (South Coast Air Quality Management District, 2017).

Several cities within South Coast AQMD's jurisdiction have specified street sweeping practices. For example, the City of Norco, CA, sweeps every residential and private streets once a month, and commercial/arterial streets once a week (City of Norco, California, 2024). The City of Brea, CA, conducts sweeping twice a month using a regenerative air system. (City of Brea, California, 2024).

The State Implementation Plans for other PM nonattainment and maintenance areas in California also reference rules that involve the use of street sweeping to reduce PM_{10} road dust emissions. For example, the Imperial County PM_{10} SIP (Imperial County Air Pollution Control District, 2018) references District Rule 803 which requires actions to prevent, reduce, or mitigate fugitive dust emissions generated from Track-Out of dust onto paved road surfaces. Many air districts in California have similar rules that apply to construction projects. Other Local Authorities

5.2 Other States

Outside of California, other local authorities have implemented street sweeping programs to mitigate PM emissions. The different approaches and frequencies may be tailored to local conditions. For example, multiple cities and counties across the western United States have added street sweeping in their SIPs to address PM_{10} NAAQS nonattainment, including El Paso, TX; Clark County, NV; and Maricopa and West Pinal counties in Arizona. Governments in Canada have also conducted scientific investigations and implemented regulations around street sweeping to address PM road dust. Some examples are discussed below.

In Arizona, PM_{10}-certified sweepers are used in nonattainment areas such as Maricopa and West Pinal counties (Maricopa Association of Governments, 2012: Maricopa Association of Governments, 2022). The Maricopa Association of Governments (MAG) 2012 Five Percent Plan for PM_{10} calls for sweeping of freeways every 7 days and ramps/frontage roads every 14 days. In Colorado, street sweeping is employed to reduce road dust from winter street sanding. Streets are swept within 4 days of snowstorms, leading to PM_{10} reductions ranging from 20-75% (Denver Regional Council of Governments, 2018). In Toronto, Canada, the Clean Streets to Clean Air initiative tested street sweepers' effectiveness in reducing PM_{10} and $PM_{2.5}$ concentrations. By adopting advanced sweeper technologies, Toronto suggests regenerative air sweepers could reduce fine PM concentrations by 27% (Buckley, 2015).

6. Estimating Emission Reductions from Street Sweeping

Although the scientific literature reports conflicting results regarding the effectiveness of street sweeping at reducing PM road dust emissions, some agencies have determined that the available evidence is sufficient to develop calculation approaches that are suitable for estimating emission reductions in certain regulatory contexts, including SIP development, regional transportation conformity, and Congestion Mitigation for Air Quality Improvement (CMAQ) accounting. The Federal Highway Administration offers a dust mitigation tool within the CMAQ Emissions Calculator Toolkit that can be used to estimate fugitive dust emission reductions from street sweeping projects[14]. Examples of two other calculation approaches are provided in the electronic appendix that is provided with this document:

- Method 1: Emission Control Efficiency
- Method 2: Silt Load Control Efficiency

The first method, Method 1: Emission Control Efficiency, is designed by the Arizona Department of Transportation (ADOT) for their CMAQ guidelines (Arizona Department of Transportation, 2017). This method involves estimating the reduction in emissions from street sweeping using a known emission control efficiency value. This value is applied to an emission factor or baseline measurement to quantify the reduction in particulate matter.

The second method, Method 2: Silt Load Control Efficiency, follows MAG's Methodologies for Evaluating CMAQ projects (Maricopa Association of Governments ,

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[14] **Dust Mitigation Tool from CMAQ Emissions Calculator Toolkit** (https://www.fhwa.dot.gov/environment/air_quality/cmaq/toolkit/index.cfm#sect1b)

2011). The method was developed for quantifying emission benefits and cost-effectiveness for proposed CMAQ projects. This method calculates the effectiveness of street sweeping by assessing the reduction in silt load on road surfaces. A known silt load control efficiency is applied to calculate the emission factor using the AP-42 paved road dust equation. This calculation allows for the reduction in silt load as a function of days after sweeping. Furthermore, the calculations have different strategies for emissions reductions. A user can determine the best strategy by using local inputs.

The control efficiency or effectiveness is the key parameter that must be determined for accurate calculations. When estimating emission reductions from street sweeping control measures, it is important to account for factors such as climate, initial silt load, cleaning technology and frequency. Since the EPA AP-42 paved road dust emissions factor depends on silt loading, a common way to estimate the emission reduction from street sweeping is to use the silt loading efficiency of the sweeper technology. The preferred method to evaluate controls is measuring local silt loading before and after street sweeping (EPA AP-42 Paved Roads). Localized measurement studies may be necessary given the role of local conditions and climate on road dust PM emission rates. The silt load efficiency can then be applied to the AP-42 emission factor calculation to calculate final emissions from swept paved roads.

7. Conclusions

A comprehensive review of literature on street sweeping as a dust control measure highlights the potential of this practice to reduce road dust PM emissions, although its effectiveness varies widely across studies. Several factors, including sweeper type, cleaning frequency, local climate, road conditions, and seasonality, impact the results, making comparisons challenging and often yielding only short-term air quality improvements. Regenerative air sweepers generally perform better than mechanical sweepers in reducing silt loads and emissions, particularly when combined with street washing. However, the benefits to near-road air quality are typically temporary, suggesting that dust suppression immediately following cleaning may be the primary benefit, and that continued street sweeping is needed to maintain air quality benefits.

The literature also reveals limitations in the available data. Most studies focus on PM_{10} benefits, with only a few quantifying $PM_{2.5}$ benefits. While studies indicate potential reductions in silt load (23–94%) and PM emissions (up to 41% in winter), quantifying long-term air quality benefits of street sweeping remains difficult due to diverse methodologies and limited data on deposition rates and resuspension. The frequency of the street cleanings also varied within the studies, but in general, more frequent cleanings showed improved results. For practical implementation, local conditions such as humidity, precipitation, and specific roadway characteristics should be considered when assessing the feasibility of street sweeping for dust control.

The inconsistencies in results highlight the need for a more uniform approach to studying the effectiveness of street cleaning while accounting for numerous confounding factors. Furthermore, some studies lack details about cleaning methodologies and the equipment used, which additionally complicates meaningful comparisons across studies. Future research should focus on consistent methodologies and include long-term studies to better understand the sustained impact of street sweeping across various environments. Localized testing is necessary to quantify effectiveness under site-specific conditions, helping communities optimize street sweeping schedules for dust control.

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Appendix A. West Oakland Sweeper Inventory 2023

Table A-1. West Oakland Sweeper Inventory from 2023. Received directly from City of Oakland, Public Works Department via email.

Table Summary: This table lists the West Oakland Sweeper Inventory, which was obtained directly from the City of Oakland's Public Works Department via email.

Equipment ID	VIN	Model Year	Manufacturer ID	VIN Decode Make	Model ID	Equipment Description	VIN Decode Fuel	VIN Decode GVW
7160	1FVACXDT4DHFA3968	2013	TMC	FREIGHTLINER	500X	500X SWEEPER ON FREIGHTLINER M2 CHASSIS	Diesel	Class 7: 26;001 - 33;000 lb
7164	1FVAC4DX3DHFD1164	2013	FRI	FREIGHTLINER	M2-106	FRI M2-106 CNG W/ ELGIN BROOM BEAR BODY	Natural Gas	Class 7: 26;001 - 33;000 lb
7165	1FVAC4DX5DHFD1165	2013	FRI	FREIGHTLINER	M2-106	FRI M2-106 CNG W/ ELGIN BROOM BEAR BODY	Natural Gas	Class 7: 26;001 - 33;000 lb
7166	1FVAC4DX7DHFD1166	2013	FRI	FREIGHTLINER	M2-106	FRI M2-106 CNG W/ ELGIN BROOM BEAR BODY	Natural Gas	Class 7: 26;001 - 33;000 lb
7167	1FVAC4DX9DHFD1167	2013	FRI	FREIGHTLINER	M2-106	FRI M2-106 CNG W/ ELGIN BROOM BEAR BODY	Natural Gas	Class 7: 26;001 - 33;000 lb
7168	1FVAC4DX0DHFD1168	2013	FRI	FREIGHTLINER	M2-106	FRI M2-106 CNG W/ ELGIN BROOM BEAR BODY	Natural Gas	Class 7: 26;001 - 33;000 lb

Equipment ID	VIN	Model Year	Manufacturer ID	VIN Decode Make	Model ID	Equipment Description	VIN Decode Fuel	VIN Decode GVW
7170	1FVAC4DX9EHFX9614	2014	FRI	FREIGHTLINER	M2-106	FRI M2-106 CNG W/ ELGIN BROOM BEAR BODY	Natural Gas	Class 7: 26;001 - 33;000 lb
7171	1FVAC4DX0EHFX9615	2014	FRI	FREIGHTLINER	M2-106	FRI M2-106 CNG W/ ELGIN BROOM BEAR BODY	Natural Gas	Class 7: 26;001 - 33;000 lb
7172	1FVAC4DX8EHFY9244	2014	FRI	FREIGHTLINER	M2-106	FRI M2-106 CNG W/ ELGIN BROOM BEAR BODY	Natural Gas	Class 7: 26;001 - 33;000 lb
7173	1FVACXDT2FHGA5725	2014	TMC	FREIGHTLINER	500X	500X SWEEPER ON FREIGHTLINER M2 CHASSIS	Diesel	Class 7: 26;001 - 33;000 lb
7174	1FVACXDT4FHGA5726	2014	TMC	FREIGHTLINER	500X	500X SWEEPER ON FREIGHTLINER M2 CHASSIS	Diesel	Class 7: 26;001 - 33;000 lb
7175	1FVACXDT4FHGA5727	2014	TMC	FREIGHTLINER	500X	500X SWEEPER ON FREIGHTLINER M2 CHASSIS	Diesel	Class 7: 26;001 - 33;000 lb
7205	UN9CV20H1ND015328	2022	MHOG	MULTIHOG	CV350	SWEEPER/SCRUBBER SIDEWALK	Diesel	Class 5: 16;001 - 19;500 lb
7811	1FVAC4DX3JHJV5708	2018	ELG	FREIGHTLINER	2017 EBB CNG	2017 SWEEPER MECHANICAL BROOM BEAR CNG	Natural Gas	Class 7: 26;001 - 33;000 lb
7812	1FVAC4DX1JHJV5707	2018	ELG	FREIGHTLINER	2017 EBB CNG	2017 SWEEPER MECHANICAL BROOM BEAR CNG	Natural Gas	Class 7: 26;001 - 33;000 lb

Equipment ID	VIN	Model Year	Manufacturer ID	VIN Decode Make	Model ID	Equipment Description	VIN Decode Fuel	VIN Decode GVW
7813	1FVAC4DX1JHJV5710	2018	ELG	FREIGHTLINER	2017 EBB CNG	2017 SWEEPER MECHANICAL BROOM BEAR CNG	Natural Gas	Class 7: 26;001 - 33;000 lb
7814	1FVAC4DXXJHJV5706	2018	ELG	FREIGHTLINER	2017 EBB CNG	2017 SWEEPER MECHANICAL BROOM BEAR CNG	Natural Gas	Class 7: 26;001 - 33;000 lb
7815	1FVAC4DX5JHJV5709	2018	ELG	FREIGHTLINER	2017 EBB CNG	2017 SWEEPER MECHANICAL BROOM BEAR CNG	Natural Gas	Class 7: 26;001 - 33;000 lb

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18. Abstract:

This document provides a review and synthesis of the effectiveness of street sweeping as a control measure for reducing road dust PM. The review covers 18 studies with a focus on the

impact of street sweeping, both independently and in combination with street washing. Street sweeping is a common practice employed by local authorities for aesthetic, safety, and public health purposes, with recent applications in controlling fugitive dust emissions and improving air quality. Despite its widespread use, street sweeping as a control measure for reducing road dust PM emissions has produced inconsistent results, with outcomes influenced by factors such as initial silt load, climate conditions, frequency of sweeping, and technology used.