ABSTRACT

Street Dust: Implications for Stormwater and Air Quality,
and Management through Street Sweeping

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Street dust represents a source of dual potential risk to stormwater and air quality. It has been well-documented that washing of this material to local watersheds can degrade water quality. Studies have also demonstrated that as much as 85% of ambient particulate matter (PM_{10}), exposure to which is associated with several health effects, can arise from resuspension of accumulated street dust. The objectives of this study were to: (1) Critically review the available literature regarding street dust and potential impacts on stormwater and air quality, (2) Develop an understanding of available street sweeping technologies and their relative efficacy, (3) Extrapolate the relative efficacy of multiple street sweeping technologies to the context of environmental/ecological and human health risk, and (4) Provide recommendations for future research studies.

Street Dust: Implications for Stormwater and Air Quality,
and Management through Street Sweeping

by

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A Thesis

Approved by the Department of Environmental Science

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CHAPTER ONE

Street Dust: Implications for Stormwater and Air Quality, and Management through Street Sweeping

Introduction

Street dust is composed of particles that arise from motor vehicles (e.g., tire debris, emission-related particulates), local soils, and road pavement (Yeung et al. 2003). These materials are associated with larger debris, including discarded trash and biological material (e.g., leaves, twigs; Fig. 1). The nature and composition of street dust and associated materials is expected to vary widely based on local climate, geology, population and traffic density, infrastructure, and other factors. Street dust and the high levels of organic and inorganic contaminants associated therewith represent a source of dual potential risk to stormwater and air quality. Runoff of street dust to local watersheds can degrade water quality and impact sediment (Buckler and Granato 1999; Sartor and Boyd 1972; Walker et al. 1999). It is also clear that many contaminants exist at higher concentrations in the smallest particles, which represent an important management component of stormwater (Breault et al. 2005; Herngren et al. 2006; Zhao et al. 2009a). Further, studies have indicated that as much as 85% of ambient particulate matter (PM_{10}), exposure to which is associated with several adverse health effects, can arise from accumulated street dust (Amato et al. 2010a).

To manage street dust and the hazards associated therewith, most large municipalities coordinate the sweeping of streets on a regular basis. Street cleaning is considered a best management practice (BMP) for stormwater by the U.S. Environmental

Protection Agency (EPA). A number of different strategies and technologies are available to achieve effective street cleaning, including flushing, mechanical broom, vacuum and regenerative air systems. The mass of materials diverted from stormwater runoff by street cleaning can be significant. For example, more than 2,000 tons of materials per year are removed by street cleaning in the City of Waco, Texas, USA, which correspondingly has maintained a model compliance record for stormwater management (City of Waco Utilities, personal communication, 2011). Aside from stormwater management, the importance of street cleaning is increasingly studied to determine its utility in improving ambient air quality (Amato et al. 2010a, b).

Figure 1. Photo of street sweeping material following collection.

The purpose of this study was to critically review available data on the efficacy of various street cleaning technologies and practices for assessment and management of stormwater and air quality. As such, I examined the available literature that addressed street dust and potential impacts on stormwater and air quality, and extrapolated the relative efficacy of multiple street sweeping technologies to the context of environmental/ecological and human health risk. During this exercise, 1,187 journal articles from the peer reviewed literature were compiled by search for phrases that contained the following terms: "street dust," "road dust," "urban dust," "roadway sediments," and similar search terms. Of these, 89 papers contained the phrases "street sweeping," "street cleaning," "road sweeping," or "road cleaning." Only two journal articles provided details relating to the varying efficacy of multiple sweeping technologies on gathering street dust (Amato et al. 2010a; Tobin and Brinkmann 2002). The authors of many studies failed to sufficiently describe the specific street cleaning apparatus they used. Several government documents from the United States and Canada, however, attempted to assess comparative efficacy of street cleaning across the available technologies. To date, no published journal articles or government reports have characterized comparative margins of safety and/or relative risk to human health and the environment for managing street dust, in the context of multiple modern street sweeping technologies and strategies. In Table 1 I summarize the available literature in which street cleaning technologies and constituents have been measured.

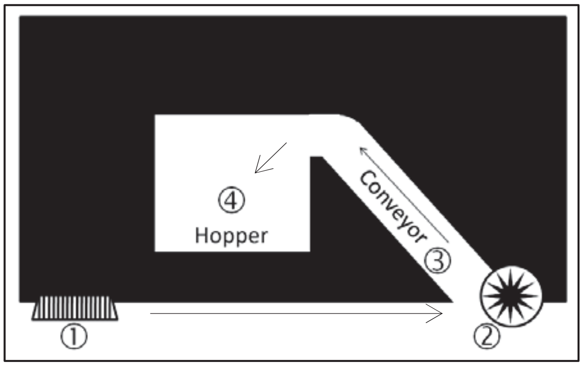
Most modern street sweepers fall into one of three categories: mechanical, vacuum, and regenerative air (Fig. 2). The majority (about 41%) of sweepers in the United States are mechanical broom sweepers, which remove debris with a large rotary

Table 1. A summary of published scientific studies of street cleaning.

Reference	Sweeper Technology					
	Standard			High Efficiency		
	Mechanical	Vacuum	Regen. Air	Mechanical	Vacuum	Regen. Air
Amato et al. 2009		x				
Amato et al. 2010a	x	x	x			
Amato et al. 2010b		x				
Bender and Terstreip 1984	x					
Bender et al. 1981	x					
Berretta et al. 2011	Unspecified					
Breault et al. 2005	x	x				
Brinkmann et al. 1999	x		x			
Brinkmann and Tobin 2001	x					
Bris et al. 1999						
Calabro 2010	x					
Chang et al. 2005						x
DeLuca et al. 2012						x
Duncan et al. 1985	x		x			
ETV 2011, 2012a, 2012b, 2012c				x		x
Gasperi et al. 2005						
German and Svensson 2001		x				
German and Svensson 2002		x				
Gertler et al. 2006	x					
Gromaire et al. 2000						
Jang et al. 2009	Unspecified					
Kang et al. 2009	x	x	x			
Kuhns et al. 2003	x	x				
Law et al. 2008		x				
Lee et al. 1959	x	x				
Norman and Johansson 2006	x					
Pitt 1979	x	x				
Pitt 1985	x		x			
Rochfort et al. 2007	x		x			x
Sartor and Boyd 1972	x	x	x			
Sartor and Gaboury 1984	x	x				
Schilling 2005a	x		x		x	
Seattle Public Utilities and Herrera EC 2009			x			
Selbig and Bannerman 2007	x	x	x			
Smith 2002	x					
Sorenson 2013	x	x				x
Sutherland and Jelen 1997	x		x		x	
Sutherland et al. 1998	x		x		x	
Sutherland 2009		x	x	x		x
Sutherland 2011	x	x	x	x	x	x
Tandon et al. 2008						
Terstriep et al. 1982	x					
Tobin and Brinkman 2002	x		x			
USEPA 1983	Unspecified					
Waschbusch 2003	x				x	
Weston Solutions 2010	x	x	x			
Wilber and Hunter 1979	Unspecified					
Wu et al. 2010		x				
Zarriello et al. 2002	x	x	x		x	

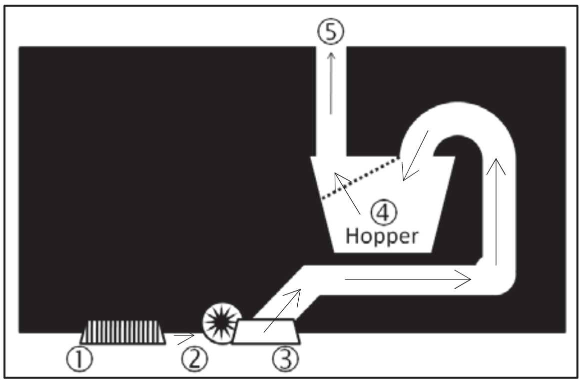
Table 1. A summary of published scientific studies of street cleaning. (continued)

Reference	Constituents Analyzed						
	Metals	Organics	Solids	Nutrients	Particle Size	PM_{10}	$PM_{2.5}$
Amato et al. 2009	x					x	
Amato et al. 2010a			x		x	x	
Amato et al. 2010b	x					x	
Bender and Terstreip 1984	x		x	x			
Bender et al. 1981	x		x	x			
Berretta et al. 2011			x	x			
Breault et al. 2005	x	x			x		
Brinkmann et al. 1999	x	x	x	x	x		
Brinkmann and Tobin 2001	x	x	x	x			
Bris et al. 1999	x	x	x				
Calabro 2010	x		x		x		
Chang et al. 2005						x	
DeLuca et al. 2012						x	
Duncan et al. 1985			x				
ETV 2011, 2012a, 2012b, 2012c						x	x
Gasperi et al. 2005		x					
German and Svensson 2001	x				x		
German and Svensson 2002	x				x		
Gertler et al. 2006						x	x
Gromaire et al. 2000	x		x				
Jang et al. 2009	x						
Kang et al. 2009	x		x			x	
Kuhns et al. 2003						x	
Law et al. 2008	x		x	x	x		
Lee et al. 1959							
Norman and Johansson 2006						x	
Pitt 1979	x	x	x	x	x	x	
Pitt 1985							
Rochfort et al. 2007	x	x	x	x	x		
Sartor and Boyd 1972	x	x	x	x	x		
Sartor and Gaboury 1984	x		x	x			
Schilling 2005a						x	
Seattle Public Utilities and Herrera EC 2009	x	x	x	x			
Selbig and Bannerman 2007	x		x	x	x		
Smith 2002	x	x	x	x	x		
Sorenson 2013	x		x	x	x		
Sutherland and Jelen 1997					x		
Sutherland et al. 1998	x	x	x	x	x		
Sutherland 2009					x		
Sutherland 2011						x	
Tandon et al. 2008	x			x		x	
Terstriep et al. 1982	x		x	x			
Tobin and Brinkman 2002	x	x		x	x		
USEPA 1983	x		x	x			
Waschbusch 2003	x		x	x			
Weston Solutions 2010	x	x	x	x	x		
Wilber and Hunter 1979	x		x				
Wu et al. 2010					x		
Zarriello et al. 2002	x		x	x			



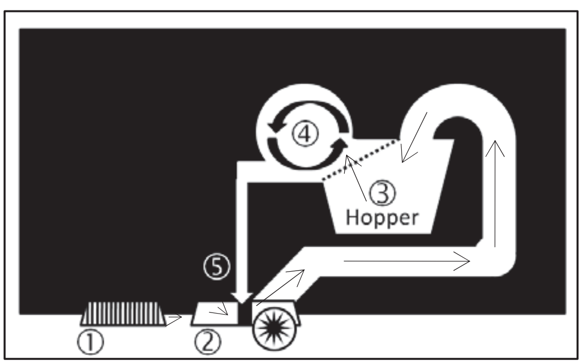
Mechanical Broom Sweepers:

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.



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.

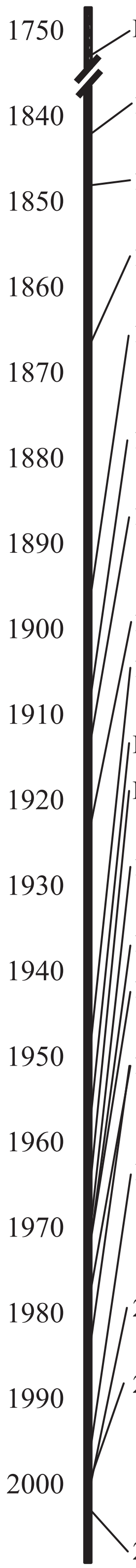


Regenerative Air Sweepers

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 three priamary street sweeping technologies.

brush at the rear of the sweeper that utilizes gutter brooms directing dirt and debris into its path (Schilling 2005a, b). Mechanical sweepers are effective at picking up wet vegetation, gravel and coarse sand but are less efficient at removing fine particles (Kang et al. 2009; Schilling 2005a). Vacuum street sweepers have gained popularity, because of their ability to remove fine dust more effectively than mechanical sweepers (Breault et al. 2005; Fleming 1978; Selbig and Bannerman 2007). They use gutter brooms and a rotary brush called a windrow boom to push dirt and debris toward the path of the suction nozzle (Fleming 1978; Sutherland 2011). Vacuum street sweepers can be compared to household vacuums, in that they suck in air with a fan, collect dust and debris, and then exhaust the air (Sutherland 2011). In general, these units have difficulty picking up wet vegetation and large road debris (Schilling 2005a). The newest street sweeping technology, regenerative air, is similar to a vacuum unit, in that it uses a fan called a blower to suck in dirt and debris from the street surface; rather than just a vacuum nozzle, it uses a pick-up head with a blast orifice, which directs a strong blast of air from the blower onto the street suspending dirt and debris with the pick-up head enclosure. The ambient air is then sucked into the hopper where larger volume forces the heavier dust and debris to fall. Some regenerative air sweepers use a centrifugal dust separator to remove the lighter dust (Schilling 2005a). Cleaned air is then returned to the blower, making it a closed-loop system with no air or dust exhausted to the atmosphere (Fleming 1978).



Pre-1790:	Benjamin Franklin starts street sweeping program in Philadelphia (Michaels 1977).
1843:	Joseph Whitworth invents the first mechanical sweeper which also incorporated means of collection and conveyance in Manchester, England (Richmann 1962).
1849:	An elevator-belt street sweeper patented in the United States. Patent #6699 (Kidwell-Ross 2012).
1868:	The first self propelled sweeper for railroads is patented in the United States. Patent #79606 (Kidwell-Ross 2012).
1895:	Colonel George E. Warring Jr. is appointed Commissioner of New York City Street Cleaning Department and establishes rigid standards for street cleaning (Soper 1909).
1911:	The first internal combustion engine powered sweeper was shown in the United States (Richmann 1962).
1914:	The first practical and commercially successful self-propelled mechanical sweeper was sold in Boise, Idaho. Invented by John M. Murphy (Richmann 1962).
1920s:	Vacuum sweepers appear (Richmann 1962).
1948:	The United States establishes the Federal Water Pollution Control Act (USEPA 2013a).
Late 1950s:	Johnston creates the first truck mounted sweeper (Johnston 2012).
Mid 1960s:	B.W. Young, founder of TYMCO, Inc. in Waco, Texas invented the regenerative air sweeper (TYMCO, Inc., personal communication, 2011).
1970:	TYMCO air flow surface cleaning apparatus and air cleaning apparatus are patented (US Patents 3512206 and 3545181) (USPTO .1970a, b)
1970:	The United States establishes the Clean Air Act (USEPA 2013d).
1972:	The United States establishes the Clean Water Act and The National Pollutant Discharge Elimination System (NPDES) (USEPA 2013a, b).
1978-1983:	EPA implements The National Urban Runoff Program (NURP) - The first comprehensive study of urban stormwater pollution across the United States (USEPA 1983)
1997:	South Coast Air Quality Management District (AQMD) in California adopts Rule 1186, requiring local governments within the AQMD to procure Rule 1186 PM 10 certified street sweepers for new equipment purchases or new street sweeping contracts made after January 1, 2000 (AQMD 2008).
2000:	TYMCO dustless regenerative air sweeper patented (US Patent 6161250) (USPTO 2000).
2000:	AQMD adopts Rule 1186.1, requiring certain public and private sweeper fleet operators to acquire alternative-fuel or otherwise less-polluting sweepers when purchasing or leasing these vehicles for sweeping operations undertaken by or for government entities in the jurisdiction of the AQMD after July 1, 2002 (AQMD 2009).
2003:	The Clean Roads to Clean Air program (CRCA) was initiated by the City of Toronto and tested street sweeper technology efficiency in removing fine particulate matter (PM 10 and PM 2.5) (Toronto 2008).

Figure 3. A timeline of technological development and regulation in street cleaning.

Street Cleaning, Sweeping and Mitigation

For hundreds of years street sweeping has been used as a means for municipalities to remove litter, dirt, horse droppings, and vegetation for aesthetic and sanitation purposes (Schilling 2005a; Fig. 3). Before the introduction of the mechanical sweeper, street sweeping was done manually, using a broom, shovel, and either push or horse-drawn carts (Schilling 2005a).

The earliest account of street cleaning in the United States may have appeared (Fleming 1978; Michaels 1977) in Benjamin Franklin's *Autobiography*. Franklin wrote about hiring a man to sweep a paved market area in Philadelphia over 200 years ago:

> This, for some time, gave an easy access to the market dryshod; but, the rest of the street not being paved, whenever a carriage came out of the mud upon this pavement, it shook off and left its dirt upon it, and it was soon cover'd with mire, which was not remov'd, the city as yet having no scavengers. After some inquiry, I found a poor, industrious man, who was willing to undertake keeping the pavement clean, by sweeping it twice a week, carrying off the dirt from before all the neighbour's doors, for the sum of six-pence per month, to be paid by each house (Michaels 1977, Fleming 1978).

New York's street cleaning practices in the late 1890s were the first to give the United States recognition and stature (Fleming 1978). Street cleaning in New York City was conducted by the police department, until it became its own administrative branch in 1881. Colonel George E. Waring Jr. was appointed as Commissioner of Streets in 1895 (Armstrong et al. 1976; Fleming 1978; Richmann 1962; Soper 1909). Drawing from his military experience as a volunteer in the Missouri Cavalry during the Civil War, Waring outfitted street sweeping workers with white uniforms and instilled a sense of pride, earning them the nickname "White Wings" (Armstrong et al. 1976). Waring's efforts appeared to produce a decline in sickness, to wit, declines in diarrheal diseases and death rate in New York City (from 26.8 per 1,000 from 1882 to 1894, to 19.6 per 1,000 in 1897) (Richmann 1962), and made New York City a model for other cities throughout the United States (Armstrong et al. 1976).

Street Cleaning Technologies

Manual. Manual cleaning is the oldest form of street cleaning in the U.S., and is still selectively practiced today. Though it has been largely replaced by modern methods, it retains several advantages, including low initial and maintenance cost of equipment; manual push brooms can reach into places inaccessible to mechanical sweepers such as parked cars, small alleyways, and busy city areas, no matter the time of day, level of traffic, or weather conditions (Fleming 1978).

Mechanical. The first mechanical sweepers were horse drawn with a rotary broom at the rear, which would push dirt from the center of the street to the curb. The dirt would then be pushed in piles, and then shoveled onto carts by workers (Richmann 1962). These horse drawn sweepers were used in New York City as early as 1882 (Armstrong et al. 1976). Because these early mechanical sweepers created a great deal of dust, tanks were added to sprinkle water on the street to suppress dust. Later, more powerful high capacity sprinkling wagons would follow the sweeper (Richmann 1962).

The first mechanical sweeper that integrated collection and conveyance was invented by Joseph Whitworth and was used in Manchester, England in 1843 (Richmann 1962). In the United States, the first elevator-belt mechanical street sweeper is widely credited as being patented by Charles B. Brooks in 1896; however, other sources cite his system as just one of many around the same time. There are over 300 US patents for street sweepers, prior to 1900; the earliest of which may be an elevator-belt sweeper patented in 1849 (Kidwell-Ross 2012).

Among those systems invented prior to 1900 was the first self-propelled sweeper patented in the United States in 1868, which was intended for cleaning railroad tracks. In 1891, a self-propelled steam powered sweeper designed to clean roads was also patented (Kidwell-Ross 2012). An electrically powered street sweeper was used in Berlin, Germany in the early 1900s (Soper 1909). In 1911, the first internal combustion-engine-powered sweeper was shown in the United States, but was not widely accepted because it lacked maneuverability, its pan-type shelf was only large enough to hold sweepings from one side of a single block, and its engine could not supply power to both the sweeping apparatus and provide mobility for the unit (Armstrong et al. 1976; Richmann 1962). The first practical and commercially successful self-propelled mechanical sweeper was sold in Boise, Idaho in 1914 and was invented by John M. Murphy in a partnership with American Tower and Tank Company, which would later become Elgin Sweeper Company (Armstrong et al. 1976; Fleming 1978; Richmann 1962).

Modern mechanical broom sweepers use a large rotary brush that is as wide as the sweeper, and which flicks dirt and debris on a conveyor that then carries dirt and debris to a hopper (Schilling 2005a; Sutherland 2011). A water spray is often used for dust suppression (Kang et al. 2009) and gutter brooms may be used to move dirt and debris from the gutter to the path of the brush (Schilling 2005a; Sutherland 2011). Mechanical sweepers are still the main type of sweeper used by municipalities, despite advances in other sweeper technologies (Sutherland 2011). According to a survey conducted in 2005, about 41% of municipalities in the United States and Canada still use traditional mechanical broom sweepers, rather than vacuum and regenerative air varieties (Schilling 2005a).

Mechanical sweepers are effective at picking up wet vegetation, coarse sand, and heavy material such as gravel, but are less efficient at removing finer particles (60 μm and smaller) left behind in cracks and uneven pavement. Such finer particles may contribute to stormwater pollution, because the rotary action of the broom breaks down large particles to smaller ones that are transported by surface runoff (Schilling 2005a; Sutherland 2011). Mechanical sweepers can also increase airborne dust in dry weather despite the use of water to suppress it (Sutherland 2011). Use of too much water, of course, turns street dirt to mud, making its removal difficult.

Flushing. Because early mechanical street sweepers created a great deal of airborne dust, on-board water systems were developed. Eventually, separate sprinkling wagons with greater capacity were developed to disperse water in the path of the street sweeper, although this method created mud, which would eventually dry and create dust. The need for more water capacity led to the development of the street flusher. Early flushers used gravity to discharge water. With the development of the gasoline engine, high pressure water pumps were added. The water was sprayed at high pressure, and an angle onto the street that created a "chisel" action, removing stuck-on dirt and debris, which could then be washed to the curb or introduced to the stormwater system (Richmann 1962).

Street flushing is no longer common practice in the United States, because dirt was only flushed to the gutters rather than being removed, and added to maintenance costs. The environmental implications of street dirt, accumulated in gutters, being washed into streams and reservoirs, also detracted from the utility of street flushing operations, as did the damage it caused to pavement (Richmann 1962). Although flushing is no longer a common practice in the United States, it remains so in other countries. Amato et al. (2009) evaluated the effectiveness of flushing as a street cleaning method in Spain, Chang et al. (2005) used a street washer in Taiwan, and Bris et al. (1999) assessed the effectiveness of a water jet cleaning procedure in France.

Vacuum. Vacuum sweepers were first used in the 1920s to remove fine dust left behind mechanical sweepers (Armstrong et al. 1976; Fleming 1978; Richmann 1962). The advantage of early vacuum sweepers were that they could operate in freezing weather without the use of water, but they were noisy and unreliable (Richmann 1962). In the early 1970s, several sweeper manufacturers reintroduced vacuum sweepers to the market, again to remove fine particulate matter not removed by mechanical sweepers (Armstrong et al. 1976).

Modern vacuum sweepers use an engine powered fan to create suction. Because most street dirt and debris is found within 36 inches (1 meter) of the curb line, vacuum sweepers are designed with the vacuum nozzle located in this area, typically on one side of the sweeper (Sutherland 2011) or on both sides with one suction nozzle operating at a time.

Most vacuum sweepers use gutter brooms and a rotary brush called a windrow boom to push dirt and debris into the path of the suction nozzle (Fleming 1978; Sutherland 2011). An inherent problem with the windrow broom is that it tends to brush dirt and debris into cracks and other irregularities found on pavement; while the vacuum nozzle does not typically cover the entire width of the sweeper (Sutherland 2011). The abrasive nature of the brooms used may also expose finer size particles for that can more easily be transported by surface runoff (Schilling 2005a).

Vacuum sweepers may use a filtration system or water for dust suppression (Breault et al. 2002; Fleming 1978; Zarriello et al. 2002). Used air is exhausted from the sweeper, typically releasing a large amount of particulate matter into the atmosphere (Sutherland 2011). Vacuum sweepers are not as effective as mechanical sweepers when picking up wet vegetation or large debris (Schilling 2005a). Several studies have shown that vacuum sweepers are more effective than mechanical sweepers at picking up smaller particles. When comparing an Elgin Pelican (mechanical sweeper) to a Johnston 605 Series (vacuum sweeper), Breault et al. (2005) found that the vacuum sweeper was at least 1.6 to 10 times more efficient than the mechanical sweeper for removing all particle-size ranges. In addition, they found that removal efficiencies for particle sizes between 2 millimeters and 250 micrometers (or coarse sand) were at least 1.5 to 5 times greater for the vacuum, than the mechanical sweeper. Constituent concentrations of street dirt, collected from the surface, tended to increase with decreasing particle size.

When comparing an Elgin Pelican (mechanical sweeper) to an Elgin Crosswind (regenerative air sweeper) and an Elgin Whirlwind (vacuum sweeper), Selbig and Bannerman (2007) found that regenerative air and vacuum sweepers had similar pickup efficiencies of 25 and 30% compared to ~5% of street-dirt yield for the mechanical sweeper.

Regenerative air. Regenerative air sweepers were invented by road construction contractor B.W. Young of Young Brothers Construction Company in Waco, TX during the mid-1960s. These units were designed to sweep dirt from pavement cracks to achieve better bonding of Slurry Seal, another of his inventions. Slurry Seal is a mixture of emulsified asphalt and sand, which repairs broken pavement and restores asphalt roads, and is applied with a truck-mounted Slurry Seal Machine. B.W. Young formed TYMCO, Inc. in the late 1960s, to focus on his regenerative air sweeper (TYMCO 2012a).

Regenerative air sweepers use an engine to power a blower fan, which pushes air forward through a blast orifice across the entire width of a pick-up head onto the street surface and into cracks in the street (Fleming 1978; Schilling 2005a; Sutherland 2011). The pick-up head extends across the entire width of the sweeper and uses rubber curtains on the front and back to create a seal on the road surface (Fleming 1978). The blast of air forces dirt and debris to become suspended (TYMCO 2012b). The debris-laden air is then sucked in the sweeper by a suction inlet to a hopper. The larger volume of space slows the air, allowing heavier debris to fall. Lighter debris such as paper, plastic bags and leaves is trapped by a screen, while the lighter particulates are removed by a centrifugal dust separator (Fleming 1978). The cleaned air then returns to the blower to restart the process. This closed-loop system prevents air from being exhausted into the atmosphere (Fleming 1978). Regenerative air sweepers are commonly grouped with vacuum sweepers (Brinkmann and Tobin 2001; Duncan et al. 1985). Like all sweeper types, gutter brooms may be used to direct dirt and debris to the path of a pick-up head and a water spray mist may be used throughout the entire process for dust suppression (Sutherland 2011). Some pick-up heads may also contain a rotary brush to assist in dislodging stuck-on dirt and debris (Elgin 2012a; TYMCO 2012c).

Regenerative air sweepers are considered to be more environmentally friendly than mechanical and vacuum sweepers, because of their ability to sweep a wider path than vacuum sweepers, remove gross pollutants (trash, road debris, vegetation) as well as small and coarse particles found in cracks and uneven pavement, and they do not exhaust air to the atmosphere (Schilling 2005a; Sutherland 2011).

Uneven pavement may create fugitive dust losses from the pick-up head, but this loss is much less than from a typical vacuum sweeper (Sutherland 2011). Regenerative air sweepers generally do not remove wet vegetation or large road debris as well as mechanical sweepers do; moreover, like all sweeper types, gutter brooms and the pick-up head broom may expose finer size particles for easy transport in stormwater (Schilling 2005a).

High-efficiency sweepers. High-efficiency sweepers are sweepers of any of the three main types (mechanical, vacuum, or regenerative air) that are modified to control fugitive dust smaller than 60μm with the use of media particulate filters (Sutherland 2011). Most high-efficiency sweepers have the ability to suppress dust without using water (Sutherland 2011).

Roger C. Sutherland is a water resources engineer and former president of Pacific Water Resources. Pacific Water Resources is a water resources engineering consulting firm located in Beaverton, Oregon, and is now merged with AMEC Earth and Environmental. Sutherland credits himself for coining the term "high-efficiency" in 1997, when describing what he thought was the first sweeper to use a filtration system, and not exhaust particles greater than 2.5 μm (Sutherland 2011). The device he described as being "high efficiency" was a vacuum sweeper developed in 1995 by EnviroWhirl Technologies in Centralia, IL.They were acquired by Schwarze Industries in 1999, and utilized this technology in their former EV-series models (Sutherland 2011).

In a computerized simulation comparing the EnviroWhirl sweeper with an Elgin Crosswind (regenerative air) and 1988 Mobil (mechanical), the EnviroWhirl showed mean reduction in total suspended solids (TSS) of greater than 80%, followed by about 70% for the Crosswind, and 20-30% for the Mobil (Sutherland and Jelen 1997). Though the EV-series performed well in test conditions mentioned above and was useful for waterless applications such as toxic and hazardous material cleanup, its high purchase cost and limited maximum transit speed of 25 mph hindered it from being accepted by the municipal market. The EV-series has since been discontinued (Sutherland 2011).

Although Sutherland thought the EnviroWhirl sweeper to be the first of its kind, the first sweeper which may be considered "high-efficiency" by his definition was developed by TYMCO in 1984 in their Model 600DC, the predecessor to their Model DST-6 (introduced in 2000) (TYMCO Inc. 2011, personal communication). The Model 600DC uses media filters inside its hopper to control $PM_{2.5}$ emissions (TYMCO Inc. 2011, personal communication). TYMCO's DST-6 and DST-4 models clean all of the air by employing a centrifugal dust separator. After passing through the centrifugal dust separator, a small percentage of the air is exhausted to atmosphere after it is diverted to an external module containing filter cartridges, which remove 99.999% of particles less than 0.5 μm. This causes an in increase in suction around the pick-up head, thereby reducing fugitive emissions (Sutherland 2011; TYMCO, Inc. 2011, personal communication, 2012d).

Several sweeper models as early as the late 1970s have used media filters; however may not be considered "high-efficiency" because they were not designed to capture particulates smaller than 60 μm. FMC, for example, used media filters in their

Model 72 and Model 74, introduced in 1978. These sweepers, however were not commercially successful because water could saturate the filters and cause a loss of suction (TYMCO Inc. 2011, personal communication).

Elgin Sweeper Company has three models that may be called “high-efficiency” sweepers: the Waterless Eagle and Waterless Pelican (mechanical) and the Crosswind NX, a (regenerative air), which is no longer listed on Elgin’s website (Elgin 2012b; Sutherland 2011). The waterless mechanical sweepers use a vacuum fan to siphon dust out of the hopper, shrouded gutter brooms, and a shrouded rotary broom. A filter in front of the fan traps dust and the cleaned air is exhausted (Sutherland 2011).

The Crosswind NX is similar to the TYMCO DST-6 in that it siphons air from the hopper to an outside container. Rather than filter cartridges, the Crosswind NX use a series of filter bags, which remove 99.997% of particles less than 0.5 µm (NAS 2012).

Schwarze Industries also has a high efficiency waterless model called the DXR, which uses a series of filter cartridges within the hopper, filtering 100% of the air before it enters the blower. The DXR also employs shrouded gutter brooms with suction tubes to capture fugitive dust (Sutherland 2011). The DXR is not currently featured on Schwarze’s website, and may be discontinued.

Street Cleaning Purposes and Strategy

A survey of several municipalities across the United States shows concern about the cleanliness and aesthetics of stormwater quality. In communities with populations greater than 250,000, 11% were concerned about stormwater quality, 36% were concerned about cleanliness, and 36% were concerned about both categories (Brinkmann and Tobin 2001). Furthermore, the same survey disclosed that few cities have done research to assess their street sweeping practices or efficiency of their street cleaning program. Only 7% of communities with populations of 5,000-25,000, 17% of communities with populations of 25,000-100,000, and 24% communities with populations greater than 250,000 had done so (Brinkmann and Tobin 2001).

As previously noted, the peer-reviewed literature lacks information that supports environmental management practices for street-sweeping. Regardless, these areas of professional practice have been addressed in the grey literature, and, several cities have implemented changes in street cleaning technologies as part of environmental management efforts. For example, the City of San Angelo, TX has implemented several changes to its street sweeping program to improve water quality of the North Concho River, including the use of 5 TYMCO Model 600 regenerative air sweepers, and using geospatial technology to record sweeping times and frequency for accountability and management purposes. These changes resulted in a pickup increase from 200-250 tons of material per year to 400-450 tons of material per year (Talend 2012). Similarly, the City of Tacoma, Washington replaced its fleet of mechanical sweepers with 4 TYMCO Model 500x regenerative air sweepers and uses geospatial technology to track sweeping implementation and to mark catch basins that require cleaning; these replacements reduced the solids entering Commencement Bay via the Foss Waterway by more than half (Talend 2012). The City of Hamilton, Ontario, Canada and cooperative industry groups reduced ambient PM_{10} from 114 $\mu g/m^3$ to 73 $\mu g/m^3$ by implementing several control measures, including street sweeping with TYMCO Model DST-6 high-efficiency regenerative air sweepers (DeLuca 2012).

The California Stormwater Quality Association lists several suggested protocols for street sweeping and cleaning (CSQA 2003). These protocols include sweeping monthly at a minimum, sweeping in dry weather, avoiding flushing, increasing sweeping frequency in high traffic areas, before the wet season, special problem areas, special events and high litter zones, maintaining equipment in good order, and replacing older technologies with newer ones, preferably regenerative air (CSQA 2003).

A simulated study by the U.S. Geological Survey suggested that solids and lead removal efficiency noticeably increased at frequencies less than 7 days (Zarriello et al. 2002). A Florida study disclosed that the optimum sweeping frequency for reducing street sediment for mechanical sweepers is once per week, the optimum frequency for reducing constituent loading in stormwater runoff is twice per week, and maintaining a frequent sweeping schedule is more important than storm intensity and duration in reducing sediment and pollutant loadings (Brinkmann and Tobin 2001). Notwithstanding these inputs, peer-reviewed empirical data supporting such management activities are not available.

Early Street Sweeper Studies

The earliest street sweeper studies were conducted by the U.S. Naval Radiological Defense Laboratory (NRDL) in the late 1950s and early 1960s to compare mechanical, vacuum, and flusher effectiveness at removing dry particulate matter (dry fallout material) from paved areas (Lee et al. 1959; Sartor and Boyd 1972). Sartor and Boyd (1972) reviewed the early studies by NRDL, along with other published data and information from street cleaning manufacturers, and performed an in situ evaluation of several U.S. cities, and controlled tests using a simulated street surface contaminant. The

NRDL data review showed that vacuum sweeping is more effective than mechanical sweeping for a given level of effort. The in situ evaluation indicated removal efficiencies ranging from 11-62% for various mechanical sweepers, and the controlled study showed removal efficiencies of 26.5-77.7% for a Mobil-TE-3 mechanical street sweeper, and 36.0-44.2% for a TYMCO Model 300 regenerative air parking lot sweeper (Sartor and Boyd 1972).

Axetell and Zell (1977) of PEDCo Environmental evaluated control measures for particulate air quality for EPA in Kansas City, Missouri and Cincinnati, Ohio. In Kansas City, flushing and mechanical sweeping were evaluated. Flushing was found to be most effective at controlling air particulates, with a reduction of air particulate concentrations by 8-18 $\mu g/m^3$ after adjustment for external differences, followed by mechanical sweeping, and no control measures. Particulate concentrations were higher than average on the day of flushing and sweeping, but were lower on the days following. In Cincinnati, flushing, mechanical sweeping, and vacuum sweeping were evaluated with contradictory results. Mechanical sweeping was considered to be the most effective for particulates, with concentrations averaging from 6-20 $\mu g/m^3$ less than the other methods tested. Flushing showed no significant reduction, although concentrations were 16 $\mu g/m^3$ lower on the days that flushing was practiced and 4 $\mu g/m^3$ lower on the day after flushing. Vacuum sweeping was found to be ineffective, with concentrations increasing by 5 $\mu g/m^3$ vs. no street cleaning (Axetell and Zell 1977). A vacuum sweeper was also evaluated in a suburb of Kansas City, and appeared to be effective at removing material from the street surface. However, study results showed no significant difference in air particulate levels compared to a nearby area that was not swept. This outcome may have resulted from low traffic density at the test site (Axetell and Zell 1977).

EPA established the Nationwide Urban Runoff Plan (NURP) in 1978. The program was a five year study designed to quantify the characteristics of urban runoff in different locations to determine differences and similarities, determine how much urban runoff contributes to water quality problems across the nation, and determine the effectiveness of management practices for controlling pollutants in urban runoff. Study results showed street sweeping to be largely ineffective, with constituent reductions never exceeding 50% in event mean concentrations (USEPA 1983).

Robert Pitt is credited for being the first to evaluate the effectiveness of street cleaning to achieve stormwater quality by performing monitoring activities in an EPA funded study in San Jose, CA (Sutherland 2011; Pitt 1979). Pitt determined that street sweepers were more effective at picking up larger size particles than smaller ones; smaller size particles tended to increase over time, and that pollutant concentrations tended to increase with decreasing particle size (Pitt 1979). Pitt also developed sampling procedures for evaluating street cleaning equipment in real-world conditions. The sampling technique utilizes an industrial vacuum cleaner with a stainless steel canister. Street dirt was vacuumed along a randomly selected test strip within a test area from the curb to the center of the street before and after sweeping (Pitt 1979). This sampling technique is popular amongst researchers (DiBlasi 2008; Selbig and Bannerman 2007), because of its random nature and ease, but drawbacks that have been pointed out by Sutherland (2011) include possible street dirt accumulation if sampling is not done immediately after street sweeping, and parked cars present at the time of sweeping may not be present at the time of sampling may inhibit measurements accuracy.

EPA tested the performance of a modified TYMCO Model 600 regenerative air sweeper, a standard TYMCO Model 600 regenerative air sweeper, and a Mobil mechanical sweeper. Modifications of the modified TYMCO Model 600 included partial hoods over the gutter brooms, venting the hoods to the hopper, and venting air out of the regenerative air system to increase suction with a low pressure drop venturi scrubber for dust suppression. Results of the study showed the modified TYMCO Model 600 was able to remove 80% of solids, followed by 70% and 20% for the standard Model 600 and Mobil sweepers respectively (Duncan et al. 1985).

Recent Sweeper Technology Comparison Studies

Though limited peer-reviewed information exists for comparisons of sweeping methods, several studies have attempted to compare efficacy for different types of sweeper technologies. Evaluating sweeper efficacy may prove difficult, because within the general sweeper technology categories of mechanical, vacuum and regenerative air, different manufacturers' sweeper models vary amongst the technology categories. In addition to differences amongst manufacturers, parameters in experimental designs may vary, including testing conditions, sweeping speed, human error and other factors. Despite such variabilities, which inherently introduce uncertainty in environmental assessment and management efforts, I examine these more recent studies below.

Sutherland and Jelen conducted a simulated model study, in which sweeper test data developed in the 1990s was compared to data from EPA's NURP studies of the late 1970s and early 1980s that disclosed sweeping to be largely ineffective (Sutherland and

Jelen 1997; USEPA 1983). The sweepers models compared included a ~1978 Mobil (mechanical) sweeper from Pitt (1985), a 1988 Mobil sweeper, a 1988 Mobil and a TYMCO regenerative air sweeper generically labeled as a vacuum, in tandem from HDR (1993), an Elgin Crosswind (regenerative air) sweeper from a test performed in 1995, and an EnviroWhirl (high efficiency vacuum) tested in two separate studies by Sutherland and Jelen in 1995. When comparing residuals left on the street, the NURP era mechanical sweeper left the most residuals, followed by the newer mechanical sweeper, the sweepers in tandem, the regenerative air sweeper, and the EnviroWhirl sweepers. Though the EnviroWhirl sweeper showed no residuals left on the street for any of the particle size groups examined, its efficiencies fell short of 100% for all particle sizes. Contrary to these results, 100% efficiencies were achieved for the newer mechanical sweeper in the lower particle size ranges <63-125 μm, and for the regenerative air sweeper in the 250-2000 μm particle size ranges (Sutherland and Jelen 1997). Despite these discrepancies, this book chapter is cited by many to show that modern sweeper technology is more effective than sweeper technology of the NURP era (Abdel-Wahab et al. 2011; Amato et al. 2010; Breault et al. 2005; Rochfort et al. 2007; Schilling 2005a; Selbig and Bannerman 2007).

A study for Florida Department of Transportation tested a mechanical sweeper and a regenerative air sweeper disclosed that the mechanical sweeper was better at picking up sediment, especially course sediment, than was the regenerative air sweeper. The regenerative air sweeper, however was better at picking up very fine sediment (Brinkmann et al. 1999). Sweeper efficiency was determined by measuring material left on the street after the sweeper had passed. Course material was defined as material collected after the sweeper had passed collected by a whisk-broom and dust pan. Fine material was defined as material collected by a shop-vacuum after the course material was collected. Very fine material was defined to be material collected from a sandbag dammed area after flushing. Two water samples were also collected from the curbside reservoir and one from the water delivery system to serve as a background control (Brinkmann et al. 1999). The test material applied was previously collected street sweepings representative to the area. Each sweeper was evaluated on three test strips on a closed street on a dry, calm day. Each test strip was 1.5 meters from the curb, was 10 meters long, and had 25 kg of material spread evenly to a depth of 0.5 ±0.2 cm, and had a minimum width of 1.25 meters (Brinkmann et al. 1999). The results of this study were summarized by Tobin and Brinkman (2002).

In another simulated study, U.S. Geological Survey tested for expected efficiencies of a mechanical sweeper, wet vacuum and regenerative air, a dry vacuum, and a "best available technology" sweeper. The "best available technology" sweeper was described as having produced the highest efficiencies found in the literature (Zarriello et al. 2002). When averaging the expected efficiencies for each sweeper for suspended solids, fecal coliform bacteria, total phosphorus, and total lead, the best available technology was expected to achieve an efficiency of 93%, followed by 63% for the dry vacuum 29% for the wet vacuum and regenerative air method, and 11% for the mechanical sweeper (Zarriello et al. 2002).

Among comparative studies in the grey literature, perhaps the most robust was performed by the City of Toronto and subsequently repeated by Prairie Agricultural Machinery Institute (PAMI) using Environmental Technology Verification (ETV)

Canada General Verification Protocol (ETV 2012a). This test protocol evaluated the sweepers pick-up efficiencies and the sweepers' ability to minimize PM_{10} and $PM_{2.5}$ emissions while sweeping (Toronto 2008) ETV has now verified four high-efficiency sweepers under the City of Toronto's PM_{10} and $PM_{2.5}$ Street Sweeper Efficiency Test Protocol (ETV 2011; ETV 2012a, b, c; Toronto 2008). These studies were conducted in an 80 x 11 m enclosed tent, in which two 2.75 x 30 m strips of calcium carbonate powder were distributed onto aged pavement with cracks and potholes. The powder particles had a mean diameter of 3 µm and total weight of about 270 kg. Water was not used for dust suppression by any of the sweepers tested (Toronto 2008).

The first sweeper, certified in 2005, a TYMCO Model DST-6 (regenerative air) removed >90% of the test material from the surface. PM_{10} and $PM_{2.5}$ air contamination concentrations were measured as being below the limit of detection (ETV 2012a). Other sweepers were tested in 2005, however results were not published. As a result of its 2005 performance levels, the DST-6 was used as the unofficial benchmark for subsequent tests performed in 2008 (TYMCO Inc. 2011, personal communication). Later tests performed in 2008 for the other sweeper models showed PM concentration results that were less than the limit of detection (i.e., for the test performed in 2005); therefore, below I will only compare the remaining three sweepers tested (ETV 2011; ETV 2012a, b, c).

Of the tests performed in 2008, the TYMCO Model DST-4 and Elgin Waterless Eagle showed similar pick-up efficiencies of 89% and 88% respectively, and the Elgin Crosswind NX efficiency at 82% pick-up efficiency followed. Total PM_{10} air contamination concentrations were 11, 2.63, and 6.12 mg/m^3-kg for the DST-4, Waterless Eagle, and Crosswind NX, respectively. Total $PM_{2.5}$ air contamination concentrations were 7.5, 1.44, and 4.71 mg/m^3-kg for the DST-4, Waterless Eagle, and Crosswind NX respectively (ETV 2011; ETV 2012b, c).

The only mechanical sweeper (viz., the Waterless Eagle) controlled ambient PM better than the Crosswind NX, followed by the DST-4 (ETV 2011; ETV 2012b, c). Such ambient PM control performance by the Waterless Eagle may be attributed to its use of shrouded gutter brooms that enhanced vacuum suction, a feature not present on the other sweeper models tested. Although shrouded gutter brooms with vacuum suction may be efficient in controlling ambient PM, they may push larger debris such as leaves to create a bulldozing effect that prevents them from being swept. It should be noted that the gutter broom shrouds were fastened in an elevated position that allowed the gutter brooms to make full contact with the curb during the test (ETV 2012c).

The U.S. Geological Survey (USGS) tested an Elgin Pelican Series P (mechanical sweeper) against a Johnston 605 (vacuum sweeper) (Breault et al. 2005). Street-sweeper efficiencies ranged from about 20-31% for the mechanical sweeper and from about 60-92% for the vacuum sweeper for the particle-size range tested. Efficiencies for particle sizes 2mm-250µm were at least 1.5-5 times greater for the vacuum sweeper than for the mechanical sweeper. The vacuum sweeper was at least 1.6-10 times more efficient than the mechanical one for all particle-size ranges examined (Breault et al. 2005).

The USGS performed another study, in which they compared an Elgin Pelican (mechanical sweeper), an Elgin Crosswind (regenerative air sweeper) and an Elgin Whirlwind (vacuum sweeper) (Selbig and Bannerman 2007). The regenerative air sweeper was replaced by the vacuum sweeper during the study, because industry executives considered it to be more effective. The regenerative air and vacuum sweepers had similar mean pickup efficiencies (i.e., 25 and 30%) compared to a mean of 5% of street-dirt yield for the mechanical sweeper. When comparing reductions in average basin street-dirt yield by analysis of covariance, the regenerative air sweeper provided the most reduction (76%), followed by 63% and 20% for the vacuum and mechanical sweepers respectively. The discrepancy between street-dirt yield reductions and pick-up efficiencies may be attributed to the abrasive nature of the gutter and rotary brooms that generate smaller particle-size loads. This added load from the brooms may also negate the stormwater quality benefits of street sweeping (Selbig and Bannerman 2007).

The National Water Research Institute (NWRI) in Canada compared a regenerative air sweeper, a mechanical sweeper and a high efficiency regenerative air sweeper (Rochfort et al. 2007). The study was conducted on a six-lane industrial/commercial arterial roadway in the outside lanes with dry samples taken from swept and unwept test strips on the street with an industrial vacuum. Although the study authors do not name brands or models of sweepers, the sweepers pictured appear to be a single engine Elgin Air Bear, which is referred to as “old-technology regenerative air” (ORA), an Allianz 4000, which is referred to as “conventional mechanical” (CM), and a TYMCO Model DST-6, which is referred to as “new-technology regenerative air” (NRA). The ORA and CM sweepers were examined at 8-15 km/h in 2004, while NRA sweeper was tested at 5-8 km/h in 2005. The ORA sweeper was tested in the northbound side of the roadway, the CM sweeper was tested in the southbound, and the NRA sweeper was tested in both (Rochfort et al. 2007).

The NRA sweeper was the only sweeper that effectively removed a statistically significant mass of solids from the road surface (48 kg/curb km), and appeared to remove solids to a “background (residual) level” (approximately 40-60 kg/curb km), beyond which further removal appeared unlikely. The CM exhibited similar effectiveness (40 kg/curb km). The ORA sweeper showed no improvement. Both CM and NRA sweepers provided consistent reductions in the largest size range >2,000 µm in the northbound side of the roadway (58% and 88% respectively). The NRA removed 73% of the total mass of particles that were >2,000 µm in the southbound side of the roadway, and the ORA was unable to pick up particles sized >2,000 µm. The performance difference of the NRA sweeper in the northbound side compared to the southbound side may be attributed to a difference in street dirt accumulation on the surface. Only the NRA was able to significantly pick up particles in the 64-2000 and <64 µm size ranges (62% and 35% removal efficiencies, respectively) (Rochfort et al. 2007).

Runoff studies were also conducted with samples taken from catch basins adjacent to the swept and unswept test strips. The initial study in 2004 used a sealed 50 L catch basin insert and dechlorinated tap water from a garden hose equipped with a gentle rain-like spray head delivering 110 L for 16 minutes with an intensity of 5.16 mm/h. Since runoff samples were typically 70 L, the excess runoff was pumped into sample containers before completion of the washdown. Several changes were implemented in the 2005 test, including a larger 100 L catch basin insert, a low-pressure water broom powered by a more powerful water pump delivering 110 L for 6.5 minutes with an intensity of 12.7 mm/h, and the water was acidified to reduce the pH to 6.0. However, pH was often measured >7.0 following day of testing (Rochfort et al. 2007).

Both the ORA and CM sweepers showed slight reductions of solids. The NRA sweeper showed an increase of solids in the northbound side, and only minor reductions in the southbound side. The difference in these results between the 2004 and 2005 tests may be attributed to changes in the test procedure mentioned above, with the higher pressure and acidity dislodging more solids. None of the sweepers showed significant reduction in total metals. Whereas total zinc showed no change, dissolved zinc showed reductions or 46% for the ORA sweeper and 56% for the NRA sweeper. There were no significant changes for polycyclic aromatic hydrocarbons (PAHs) for any of the sweepers (Rochfort et al. 2007).

Weston Solutions, Inc. (2010) measured pounds of material swept per curb mile for three street sweepers by weighing street dirt material in dump bins from sweeping routes for a Johnston 4000 (mechanical), an Elgin Whirlwind (vacuum), and a Schwarze A7000 (regenerative air) and found a high degree of variability from week to week, and by sweeping routes. In general, the vacuum sweeper picked up the most material per curb mile, followed by the regenerative air and the mechanical sweepers. At route 3J, average pounds collected per curb mile were 82.1, 54.0, and 37.1 for the vacuum, regenerative air, and mechanical sweeper respectively. At route 1C, average pounds collected per curb mile were 68.6 for the vacuum sweeper, and 57.3 for the mechanical sweeper. The regenerative air sweeper was not evaluated at this site. At route 103, average pounds collected per curb mile were 157.4, 135.2, and 133.4 for the vacuum, regenerative air, and mechanical sweeper respectively. Combined average pounds collected per curb mile for routes 617 and 618 were 110.4 for the regenerative air sweeper and 95.9 for the mechanical sweeper. The vacuum sweeper was not evaluated at routes 617 and 618. Pick-up efficiency could not be calculated as the amount of material on the street was not measured before and after the sweeper pass.

Most recently the USGS tested a TYMCO Model DST-6 (high efficiency regenerative air sweeper) on multi family residential and commercial land use streets in Cambridge, MA (Sorenson 2013). Between May and December 2011, average street dirt accumulation was determined to be 740 pounds per curb mile on multifamily residential streets, and 522 pounds per curb mile on commercial streets. After the winter in March 2011, accumulations were much higher, with an average of 2,609 pounds per curb mile on multifamily residential land use streets and 4,788 pounds per curb mile on commercial streets. Between May and December 2011, the Model DST-6 was able to pick up 82% of material on multifamily land use streets, and 78% of material on commercial land use streets (Sorenson 2013)

A computer model was used to determine estimated percent reduction of solids contributing to stormwater with a single pass of the Model DST-6 vs. a mechanical and a vacuum sweeper with previously collected data from another study at various sweeping frequencies. The model showed reductions of 2.7, 5.2, and 16% for the mechanical, vacuum and regenerative air sweepers respectively with monthly sweeping. Bimonthy sweeping showed reductions of 3.3, 7.0, and 18% for the mechanical, vacuum and regenerative air sweepers respectively. Weekly sweeping showed reductions of 4.2%, 9.6%, and 18% for the mechanical, vacuum and regenerative air sweepers respectively. Sweeping three times per week showed reductions of 6.0, 14, 19% for the mechanical, vacuum and regenerative air sweepers respectively. Although there was little improvement with increased sweeping frequency for the Model DST-6, sweeping monthly with it was still more effective than sweeping three times a week with mechanical or vacuum technologies (Sorenson 2013).

There are insufficient studies that compare sweeper technologies, differences amongst manufacturers, and study parameters to draw solid conclusions from the literature about what technique or equipment type works best. Nevertheless here I have attempted to combine efficacy data from various studies to gain a better understanding of technology efficacy differences (Table 2).

Because simulated computer models were used to determine expected efficiencies, or compare technologies Sutherland and Jelen (1997), Sorenson (2012), and Zarriello et al. (2002) were not included. Brinkmann et al. (1999) was not also included in our analysis here, because only material left behind was considered, which excludes material that may have been displaced outside of the sweeper and street, and particle size is not quantifiably defined. As expected efficiencies were much higher for high efficiency sweepers, with pick-up efficiencies of the 3 μm mean diameter test material of 82% for the Elgin Crosswind NX (regenerative air), 88% for the Elgin Waterless Eagle (mechanical), 89% for the TYMCO Model DST-4 (regenerative air), and 90% for the TYMCO Model DST-6 (regenerative air) (ETV 2011, 2012a, b, c).

Table 2 shows a high degree of variability amongst sweeper experiments performed to date, even when the same sweeper model is tested. For example, the TYMCO Model DST-6 was 90% efficient in the ETV study, but only up to 35% efficient in the test done by NWRI in the smallest particle size range (ETV 2012a; Rochfort et al. 2007). This discrepancy is likely due to several notable differences between these two studies; most notably that the ETV test used a test material with an average diameter of 3μm in a controlled environment, while NWRI was a "real world" study, which picked up material of variable diameter from a non-controlled environment (Rochfort et al. 2007; ETV 2012a). Similarly, the Elgin Pelican was up to 55% efficient in the largest

Table 2. Variations in testing of efficacy of street sweeper technologies.

Technology	% Efficiency	Sweeper Model	Particle Size	Reference
Mechanical				
	13	Elgin Pelican Series P	<63 µm	Breault et al. 2005
	9-40	Elgin Pelican Series P	63-2000 µm	Breault et al. 2005
	20-31	Elgin Pelican Series P	Overall	Breault et al. 2005
	No significant change	Allianz 4000*	<64 µm	Rochfort et al. 2007
	No significant change	Allianz 4000*	64-2000 µm	Rochfort et al. 2007
	55	Allianz 4000*	>2000 µm	Rochfort et al. 2007
	-41-46	Elgin Pelican	Overall	Selbig and Bannerman 2007
Vacuum				
	39-81	Johnston 605 Series	<63 µm	Breault et al. 2005
	31-93	Johnston 605 Series	63-2000 µm	Breault et al. 2005
	60-92	Johnston 605 Series	Overall	Breault et al. 2005
	-2-52	Elgin Whirlwind	Overall	Selbig and Bannerman 2007
Regenerative Air				
	No significant change	Elgin Air Bear*	Overall	Rochfort et al. 2007
	-3-51	Elgin Crosswind	Overall	Selbig and Bannerman 2007
High Efficiency Mechanical				
	88.1	Elgin Waterless Eagle	3 µm mean	ETV 2012c
High Efficiency Regenerative Air				
	No significant change-35	TYMCO Model DST-6*	<64 µm	Rochfort et al. 2007
	No significant change-62	TYMCO Model DST-6*	64-2000 µm	Rochfort et al. 2007
	73-88	TYMCO Model DST-6*	>2000 µm	Rochfort et al. 2007
	90	TYMCO Model DST-6	3 µm mean	ETV 2012a
	89	TYMCO Model DST-4	3 µm mean	ETV 2011
	81.8	Elgin Crosswind NX	3 µm mean	ETV 2012b

*Indicates the sweeper manufacturers and models were not named in the literature; however I have attempted to identify them by their respecitve photos.

particle size range (>2,000 µm) of the NWRI test, while in the USGS test efficiencies ranged widely with the Pelican actually adding to street dirt yield by up to 41% and reducing the street dirt yield by up to 46% (Rochfort 2007; Selbig and Bannerman 2007; Table 2). Surprisingly, the vacuum sweeper performed better than the regenerative air sweeper when considering results from the various studies within the technology categories, but once again there was a high degree of variability with overall efficiencies as high as 92% and as low as -2% in two separate USGS studies with different vacuum sweeper models evaluated (Breault et al. 2005; Rochfort et al. 2007; Selbig and Bannerman 2007;Table 2). As expected the high-efficiency models of each type generally performed better than the standard models, with efficiencies as high as 81-90% in the ETV tests (ETV 2011; ETV 2012a, b, c).

Environmental Regulation in the US

The first major law to address water pollution was the Federal Water Pollution Control Act of 1948 (FWPCA). The FWPCA was amended to address public concerns associated with water pollution, establishing the Clean Water Act (CWA) in 1972 (USEPA 2013a). CWA outlined a basic regulation structure for pollutant discharges in US waters, set standards for industry discharges, and for surface water quality, required a permit for point source discharges, established grants for municipal sewage treatment, and established a planning need for the problems associated with nonpoint source pollution, including that from street surface runoff (USEPA 2013a). Of particular relevance to street cleaning, point source and nonpoint source stormwater pollution are regulated by the National Pollutant Discharge Elimination System (NPDES), for municipal separate storm sewer systems (MS4s), construction activities, and industrial activities by permit (USEPA 2013b).

NPDES permits for MS4s fall under two categories: Phase I and Phase II. Phase I, issued in 1990 requires stormwater discharge permits for medium and large cities, and some counties with populations of 100,000 or greater. Phase II, issued in 1999 requires stormwater discharge permits for small MS4s in and around urbanized areas (USEPA 2013c). NPDES requires six MS4 program elements called “minimum control measures,” including: public education and outreach such as distribution of educational materials about the impacts of stormwater discharge on water quality; public participation and involvement such as public hearings on stormwater regulations; illicit discharge detection and elimination such as developing a plan to track and enforce illegal dumping; construction site runoff control such as silt fences for erosion control, post-construction runoff control such as ponds, wetlands, and porous pavement; and pollution prevention/good housekeeping with control measures such as regular street sweeping, catch-basin cleaning, and reduction of pesticides and salts (USEPA 2005a). To obtain a permit, MS4s operators must submit a Notice of Intent (NOI) including its chosen Best Management Practices (BMPs) and measureable goals for each minimum control measure (USEPA 2005a). BMPs include municipal landscaping, parking lot and street cleaning, storm drain system cleaning, and others (USEPA 2005b).

Another regulation in the US of relevance to street cleaning was the Clean Air Act (CAA) of 1970 (USEPA 2013d). The CAA regulates emissions from stationary sources, such as coal fired power plants, and mobile sources, such as vehicles. Under the CAA, EPA sets National Ambient Air Quality Standards (NAAQS) to regulate hazardous emissions for the sake of public health and welfare. The CAA was amended in 1977 and 1990 to set new goals for NAAQS standards that were not met (USEPA 2013d).

Arguably the NAAQS region most impacted by poor air quality is the South Coast Air Quality Management District (AQMD) covering all of Orange County and the urban portions of Los Angeles, Riverside, and San Bernardino counties in Southern California (AWMD 2012). In order to reduce ambient PM from paved and unpaved roads and livestock operations, AQMD adopted Rule 1186 in 1997 (AQMD 2008). Regarding street sweepers, Rule 1186 requires municipal use street sweepers to be certified by AQMD to be Rule 1186 compliant. In order to be certified sweeper manufacturers must submit a certification request to the AQMD executive officer accurately describing the sweeper's dust collection and suppression system. Sweepers are then tested under the district's test protocol developed in 1999, requiring that the sweeper have a pick-up efficiency of 80% or better of test material consisting of 90% Department of Transportation washed sand and 10% #10 Georgia Paint Pigment (calcium carbonate). One thousand pounds per curb mile is placed on the track with half of the material within the first six inches and the other half of the material placed in the adjacent 18 inches. Testing is done in a tunnel with at least 1 PM_{10} monitor upwind and downwind from the tunnel (AQMD 1999).

Though the original intent of the Rule 1186 sweeper test was to determine which sweepers were efficient at picking up PM_{10}, it has been criticized because the testing procedure never actually measures particle size of the material removed (Sutherland 2011). In addition, only about 3% of the test material was 10 µm or less, so with a minimum pick-up efficiency of 80% a sweeper could easily be certified without picking up any PM_{10} material (Sutherland 2011). AQMD Rule 1186.1, adopted in 2000, requires sweepers within the district owned or leased by any federal state, county, city or governmental department or agency, special district, or private firm who own or leases 15 or more vehicles to be run on alternative fuel or otherwise less polluting sweepers to reduce toxic and criteria pollutant emissions (AQMD 2009).

Characteristics of Street Dust

Typical street sweepings consist of soil, sediment, small pieces of pavement, leaves and litter. Several factors may affect variability in the composition of street sweepings including: sweeping method and technology, street surface type, traffic load, geographic area, and weather (Jang et al. 2009). Sediments found in street sweepings typically consist of local crustal material such as eroded rock and soil and anthropogenic materials such as eroded material from bricks, concrete, other building materials, and roadway debris (Brinkmann and Tobin 2001). Crustal material grain size naturally varies by location. For example, soil in Milwaukee, Wisconsin tends to contain more clay from glacial tills, whereas crustal material in Sarasota, Florida contains more sand (Brinkmann and Tobin 2001). Anthropogenic sediment sources are not as prevalent as natural sources and tend to be coarser in nature (Brinkmann and Tobin 2001).

Herngren et al. (2006) analyzed road-deposited sediments for three different land uses (residential, industrial, commercial) in Queensland, Australia and found a clear pattern in particle size distribution was apparent at all sites. The highest percentage of total mass collected was consistently in the 0.45–75 μm size range followed by the 76–150 μm size range. It was found that over 90% of the particles at each site were below 150μm.

In Santa Monica, CA, Lau and Stenstrom (2005) collected street dust samples from 18 locations spanning five different land uses including industrial, streets, multi-family residential, single family residential, and commercial areas. For combined land uses, 47.7% of the total mass of street dust collected was in the 100-250 µm size range. In all of the land use areas, the 100-250 µm was considered to be the most important, with the exception of the single family residential areas, which showed a larger proportion of mass within the <43 µm size range.

Particle size is particularly important, because pollutants tend to bond with smaller size particles more than larger size particles, due to the negative electrical charge of smaller particles and the positive electrical charge of pollutants and because smaller particles have more surface area than larger particles (Brinkmann and Tobin 2001; Lau and Stenstrom 2005; Liebens 2001). Smaller size particles also have a low density, allowing them to be easily carried by surface runoff (Zhao et al. 2009).

Contaminants in Street Sweepings

Sources of contaminants in street sweepings and roadside sediment include: emissions from vehicles, tire wear, road wear, control additives in tires, pesticides, fertilizers, and industrial emissions (Jang et al. 2009). From these sources, a number of chemical contaminants arise, including many heavy metals and organic compounds. For instance, manganese and chromium are associated predominantly with brake dust (Tandon et al. 2008), while sources of zinc include: exhaust emissions, tire and body wear of vehicles, fluid leakage from vehicles, galvanized steels in road structures, and the weathering of asphalt and concrete (Jang et al. 2009; Lindgren 1996). Sources of nickel include gasoline, oil, asphalt vehicle exhaust, and the weathering of asphalt and concrete

(Lindgren 1996; Muschack 1990). Sources of copper include brake linings, tires, alloys in motor vehicles, and the weathering of asphalt and concrete (Jang et al. 2009; Sadiq et al. 1989). Aluminum, potassium, silica, calcium, titanium, and strontium are thought to arise in street dust from local crustal materials (i.e., soil, sand, etc.) (Abu-Allaban et al. 2003; Amato et al. 2010a, b). Organic contaminants, such as PAHs, phthalates, dioxins, furans, and pesticides, are frequently found in street dust. Sources of organics in street dust are obviously numerous, but routinely are derived from asphalt, motor oil, gasoline, tire particles, wood soot, and vegetation (Breault et al. 2005). Nutrients are another contaminant of potential concern in street dust. Nutrients in street dust originate from lawns, pet wastes, failing septic systems, and atmospheric deposition from industry and automobile emissions (USEPA 2005c).

Below I more closely examine available information for these various contaminants in street dust. For example, the USGS, in cooperation with the EPA, Massachusetts Department of Environmental Protection, and the city of New Bedford Department of Public Works, examined accumulation rates and chemical composition of street dirt in residential areas (Breault et al. 2005). Substantial concentrations of trace metals and PAHs were found in residential areas, with several metals exceeding probable effects concentrations (PEC) for adverse biological effects to occur within several particle size ranges and two PAHs exceeding their exposure based guidelines. The largest mass of trace metals, including cadmium, chromium, copper, lead, nickel, and zinc made up about 30% in the 250-2,000 μm size range, while the sum of parent PAHs made up about 27%, however the largest concentrations of trace metals and PAHs were found in the smaller particle size range (<63 μm). PAH levels were similar to those measured in asphalt and used motor oil in a previous unpublished study by the USGS (Breault et al. 2005).

Metals. A number of metals that are of importance to street dust including antimony, arsenic, beryllium, bismuth, cadmium, cobalt, copper, gold, lead, mercury, nickel, palladium, selenium, silver, tellurium, thallium, tin, and zinc (Brinkmann and Tobin 2001; Table 3). In the analyzed studies, aluminum, cadmium, chromium, copper, lead, nickel, and zinc were quantified most frequently. Geographic locations of these studies ranged from, Massachusetts and Florida, USA; Xincheng, China; Brisbane, Australia; and Jonkoping and Lulea, Sweden. Few trends can be established based on geography, because the available data is not extensive enough to allow for a systematic evaluation. A few studies have compared concentrations of pollutants found in street dust to background levels, soil cleanup target levels, probable effect concentrations or other benchmarks. In Florida, zinc and copper concentrations in street dust were found to be statistically greater ($p< 0.05$) than those found in Florida soils (10.7 mg/kg for copper and 46.7 mg/kg for zinc compared to 3.7 mg/kg for copper and 12.0 mg/kg for zinc) (Jang et al. 2009). Breault et al. (2005) tested street dust for metals and found that beryllium and lead concentrations exceeded Massachusetts Department of Environmental Protection exposure-based soil standards of 0.7 mg/kg and 300 mg/kg by 1.3 and 4.1 times respectively in the smallest particle size range (<63 μm). Lead also exceeded exposure-based guidelines for all particle size ranges <250 μm and was its whole sample concentration 1.1 times greater than its exposure based guideline.

Breault et al. (2005) also compared metal concentrations to probable effects concentrations (PEC) for adverse biological effects to occur in aquatic sediments.

Table 3. A summary of concentrations of metals detected in samples of street dust.

Metal	Concentration (ppm)	Particle Fraction	Geographic Location	Sample	Citation
Aluminum					
	7600	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	9800	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	18000	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	0.01	<0.45 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.01	<0.45 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.07	<0.45 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	8.80	.45-75 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	13.59	.45-75 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	5.51	.45-75 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	8.80	75-150 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.63	75-150 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	3.52	75-150 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
Antimony					
	6	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	6	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Arsenic					
	6	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	5	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	9	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Barium					
	98	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	110	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	210	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Beryllium					
	0.5	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	0.6	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	0.9	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Cadmium					
	1	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	2	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	3	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	0.003	<0.45 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.002	.45-75 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.002	.45-75 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.002	75-150 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.01	75-150 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
Chromium					
	350	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	300	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	200	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005

Table 3. A summary of concentrations of metals detected in samples of street dust. (continued)

	193	<63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	168	125-63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	133	250-125 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	0.02	.45-75 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.06	.45-75 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.03	.45-75 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.01	75-150 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.003	75-150 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.02	75-150 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.01	151-300 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.002	151-300 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.01	151-300 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
Cobalt					
	6	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	9	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	11	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Copper					
	91	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	140	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	250	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	285	<63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	258	125-63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	182	250-125 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	0.08	<0.45 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.01	<0.45 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.12	<0.45 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.56	.45-75 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.96	.45-75 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.26	.45-75 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.48	75-150 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.04	75-150 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.24	75-150 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
Iron					
	33000	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	34000	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	33000	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	0.01	<0.45 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.96	<0.45 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	14.00	.45-75 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	43.96	.45-75 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	16.78	.45-75 µm	Brisbane, Australia	Commercial	Herngren et al. 2006

Table 3. A summary of concentrations of metals detected in samples of street dust. (continued)

	12.80	75-150 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	2.16	75-150 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	9.59	75-150 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
Lanthanum					
	12	125-250 µm	New Bedford, MA, USA	Residential	Breault et al., 2005
	18	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	24	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Lead					
	420	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	490	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	1240	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	311	<63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	333	125-63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	203	250-125 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	0.01	<0.45 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.04	.45-75 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.96	.45-75 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.34	.45-75 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.03	75-150 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.04	75-150 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.19	75-150 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
Lithium					
	9	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	12	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	22	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Manganese					
	350	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	400	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	440	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	0.01	<0.45 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.02	<0.45 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.27	<0.45 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.23	.45-75 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.51	.45-75 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.22	.45-75 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.20	75-150 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.02	75-150 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.16	75-150 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
Molybdenum					
	4	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	4	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	5	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005

Table 3. A summary of concentrations of metals detected in samples of street dust. (continued)

Nickel					
	35	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	44	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	55	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	165	<63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	135	125-63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	96	250-125 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
Scandium					
	2.7	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	3.8	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	3.9	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Silver					
	0.4	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	1.0	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	1.2	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Strontium					
	30	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	36	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	46	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Tin					
	12	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	19	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Titanium					
	800	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	100	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	1300	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Vanadium					
	36	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	49	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	75	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Yttrium					
	11	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	13	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	15	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
Zinc					
	270	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	320	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	810	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	529	<63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	438	125-63 µm	Xincheng, China	Street Dust	Zaho et al. 2009a
	384	250-125 µm	Xincheng, China	Street Dust	Zaho et al. 2009a

Table 3. A summary of concentrations of metals detected in samples of street dust. (continued)

	0.39	<0.45 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.18	<0.45 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.83	<0.45 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	1.80	.45-75 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	2.32	.45-75 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.42	.45-75 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
	0.72	75-150 µm	Brisbane, Australia	Residential	Herngren et al. 2006
	0.11	75-150 µm	Brisbane, Australia	Industrial	Herngren et al. 2006
	0.30	75-150 µm	Brisbane, Australia	Commercial	Herngren et al. 2006
Zirconium					
	13	125-250 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	10	63-125 µm	New Bedford, MA, USA	Residential	Breault et al. 2005
	7.1	<63 µm	New Bedford, MA, USA	Residential	Breault et al. 2005

Chromium and nickel were higher than their respective PECs of 111 and 22 mg/kg in all of the particle size ranges with the exception of those >2,000 µm. Cadmium and zinc were higher than their PECs of 4.98 and 459 mg/kg respectively only the smallest particle-size range (<63 µm), while copper was found to be greater than its PEC of 149 mg/kg in the smallest and largest particle size ranges of <63 µm and >2,000 µm respectively.

Zhao et al. (2009a) tested for heavy metals including chromium, copper, nickel, lead, and zinc in street dust particles in a small town near the Yangtze River delta in China and found that about 63-71% of heavy metals were found in the <250 µm particle size range, which accounted for 40% of the total mass of material collected from the street. When looking at land use, industrial areas had the highest concentration of metals, followed by main traffic roads, old residential, commercial, and new residential roads respectively.

In Queensland, Australia, Herngren et al. (2006) analyzed road deposited sediment from residential, industrial, and commercial areas for eight heavy metals, and found that the highest concentrations were consistently found in the 0.45-75 μm size range overall. Over 90% of the total mass of road deposited sediment collected was <150 μm. More than half of the total heavy metal concentrations were found in the <75 μm range. For all of the metals tested, the highest concentrations were found at the industrial site, with the possible exception of cadmium, which was usually below the detection limit. Metals with the highest concentration were usually iron and aluminum.

In each of the studies examined above, concentrations generally increased with decreasing particle size.

Aluminum in street dust primary arises from local soils (Amato et al. 2010b). The highest concentrations were recorded in New Bedford, Massachusetts where total aluminum concentrations ranged from 6,700-18,000 mg/kg, followed by Pensacola and Escambia County, Florida, where concentrations ranged from 1,278-17,312 mg/kg (Breault et al. 2005; Liebens 2001). Concentrations in Brisbane, Australia were comparatively much lower, ranging from 0.01-13.59 mg/kg (Herngren et al. 2006). Here again, aluminum in street dust will be site-specific.

Cadmium in street dust is thought to arise from vehicle exhaust, tire wear, and industrial emissions (Hood 2006; Legret and Pagotto 1999). Concentrations were the highest (3 mg/kg) in the lowest particle size range (<63 μm) in Massachusetts (Breault et al. 2005). Concentrations in other studies were comparatively lower, ranging from below the limit of detection to 1.37 mg/kg in Florida, below the detection limit to 0.01

mg/kg in Australia, and 0.049-0.23 mg/kg in Sweden (Herngren et al. 2006; Liebens 2001; Viklander 1998).

Chromium is mainly associated with brake dust (Tandon et al. 2008). There is a high degree of variability within chromium. For example, maximum concentrations were measured as high as 193 mg/kg (Xincheng, China) and 200 mg/kg (New Bedford, Massachusetts) in particles <63 μm, but were also observed at levels as low as 0.02-0.06 mg/kg (Brisbane, Austrialia) in comparable size ranges (Breault et al. 2005; Herngren et al. 2006; Zhao et al. 2009a). Concentrations tended to increase with smaller particle size ranges. Concentrations in China were much higher when compared to other countries, with concentrations ranging from 87 mg/kg in the largest particle size range (250-900 μm) to 193 mg/kg in the smallest particle size range (<63 μm) (Zhao et al. 2009a). Concentrations were the lowest in Australia (<1 in all ranges) (Herngren et al. 2006). In the United States, residential concentrations were lower in Florida (9.57 mg/kg) when compared to Massachusetts (200-350 mg/kg) (Breault et al. 2005; Liebens 2001).

Sources of copper include brake linings, tires, motor vehicle alloys, and weathered pavement (Jang et al. 2009; Sadiq et al. 1989). Copper also had a high degree of variability. Concentrations were highest in China (285 mg/kg) and Massachusetts (250 mg/kg) in the lowest particle size range (<63 μm) and in Sweden (282±63 mg/kg in the <.25 mm size range) (Breault et al. 2005; German and Svensson 2002; Zhao et al. 2009a). Concentrations were much lower in Brisbane (<1 μm) in all particle size ranges (Herngren et al. 2006).

Traditional sources of lead are leaded paint and gasoline (Gulson et al. 1995). Although lead has been banned from paint and gasoline and paint for some time in the

United States, lead may still come from washoff of lead paint from older buildings and structures (Davis et al. 2001). Maximum concentrations in lead were measured as high as 1,240 mg/kg in Massachusetts, with its whole sample concentration slightly exceeding its exposure based guideline (Breault et al. 2005). The second highest concentration of lead was recorded in China at 311 mg/kg (Zhao et al. 2009a). Concentrations of lead were measured between 0.01 and 0.96 mg/kg (multiple particle size fractions) in Australia, and orders of magnitude higher in the United States, ranging from 82-1240 mg/kg in Massachusetts, and up to <LOD-94 mg/kg in Florida (Breault et al. 2005; Herngren et al. 2006; Jang et al. 2009; Liebens 2001). Lead concentrations were found to be comparable in two separate studies in Florida (18.3 mg/kg and 19.98 mg/kg) (Jang et al. 2009; Liebens 2001). Concentrations in Sweden were found to be 45±8 mg/kg at <0.25 mm (German and Svensson 2002).

Nickel is associated with gasoline, oil, asphalt vehicle exhaust, and the weathering of asphalt and concrete (Lindgren 1996; Muschack 1990). Nickel concentrations were found be greatest in China (165 mg/kg), followed by Massachusetts (55 mg/kg) in the lowest particle size range (<63 μm) (Breault et al. 2005; Zhao et al. 2009). Florida concentrations were in the lowest concentrations (~6-9 mg/kg) in two separate studies (Jang et al. 2009; Liebens 2001). Sweden concentrations were in the middle range (~25 mg/kg in the <0.25 mm range) (German and Svensson 2002).

Zinc is associated with exhaust, tires, body wear, and fluid leakage from vehicles, weathered steel structures, and weathering of pavement (Jang et al. 2009; Lindgren 1996). Zinc concentrations were highest (810 mg/kg) in Massachusetts in the lowest particle size range (<63 μm) (Breault et al. 2005). In China concentrations were comparatively lower (529 mg/kg) in the <63 μm range (Zhao et al. 2009). The lowest concentrations were found in Brisbane ranging from 0.04-2.32 in all particle size ranges (Herngren et al. 2006). Two separate studies in Florida found concentrations in the middle range at 65.1 mg/kg and 38.48 mg/kg without particle size being taken into account (Jang et al. 2009; Liebens 2001). Concentrations in Sweden were relatively higher at 257±40 in the <0.25 mm range (German and Svensson 2002).

Organic contaminants. Though metals are the most frequently studied contaminants in street dust, a number of studies have characterized levels of PAHs in this medium and also in stormwater runoff (Breault et al. 2005; Jang et al. 2009; Rochfort et al. 2007; Zhao et al. 2008; Zhao et al. 2009a; Table 4). PAHs in street dust originate from several sources including vehicle exhaust, motor and waste oil, greases, gasoline, tire and asphalt particles, and wood soot (Breault et al. 2005; Jang et al. 2009; Takada et al. 1990). A forensic study in urban Beijing, China found that vehicle emissions contributed to 57% of PAHs in road dust, followed by 42% contribution from coal/oil combustion (Zhang et al. 2008). In the United States and other Western countries, where coal is not used for residential heating, the profile of PAH sources would clearly be expected to differ. For example, a study conducted in Paris indicated that traffic was the primary contributor to PAHs there (Gasperi et al. 2005). Tire and brake lining particles contain noteworthy concentrations of a number of PAHs (Rogge et al. 1993). It has also been noted that vehicular PAHs may adsorb to road salt particles, which would suggest that colder weather environments might be expected to have higher concentrations of PAHs in spring runoff (Harrison et al. 1996). Furthermore, though traffic is a predominant source, industrial activities are another important contributor

Table 4. A summary of concentrations of organic contaminants detected in samples of street dust.

Analyte	Concentration (ppm)	Particle Fraction	Geographic Location	Street Type	Citation
acenaphthene					
	0.033	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.033	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.03	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.029	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.017	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.033	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.052	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.031	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.025	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
acenaphthylene					
	0.086	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.086	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.083	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.072	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.043	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.19	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.076	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.045	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.037	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
anthracene					
	0.168	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.168	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.172	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.161	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.113	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.31	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.2	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.12	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.084	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
benzo(a)anthracene					
	0.015	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
	0.364	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.364	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.283	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.218	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.167	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	1.02	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.69	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.45	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.22	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
benzo(a)pyrene					
	0.009	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
	0.537	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.537	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.37	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.246	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.157	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	1.4	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.96	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.58	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.25	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005

Table 4. A summary of concentrations of organic contaminants detected in samples of street dust. (continued)

benzo(e)pyrene					
	1.4	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.76	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.49	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.22	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
benzo(b)fluoranthene					
	0.0132	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
	0.917	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.917	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.736	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.531	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.224	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	1.87	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.25	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.84	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.33	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
benzo(g,h,i)perylene					
	0.0076	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
	0.491	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.491	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.377	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.288	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.164	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	1.23	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.716	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.39	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.13	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
benzo(k)fluoranthene					
	0.315	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.315	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.227	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.124	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.076	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	1.7	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	1.08	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.72	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.26	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
chrysene					
	0.613	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.613	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.467	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.366	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.195	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	1.91	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	1.25	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.77	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.36	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
dibenzo(a,h)anthracene					
	0.436	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.436	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.208	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.176	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.18	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008

Table 4. A summary of concentrations of organic contaminants detected in samples of street dust. (continued)

	0.33	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.13	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.12	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.054	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
fluoranthene					
	2.3	<64 µm	Toronto, Ontario, Canada	Industrial	Rochfort et al. 2007
	0.8	64-2000 µm	Toronto, Ontario, Canada	Industrial	Rochfort et al. 2007
	0.0054-0.0334	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
	0.925	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.925	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.698	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.54	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.353	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	2.96	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	2.55	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	1.75	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.71	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
fluorene					
	0.158	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.158	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.139	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.123	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.073	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
indeno(1,2,3-cd)pyrene					
	0.229	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.229	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.16	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.142	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.065	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	1.33	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.44	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.48	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.18	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
naphthalene					
	0.322	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2009b
	0.322	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.365	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.389	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.223	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
		<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.03	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.015	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	0.013	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
phenanthrene					
	1	<64 µm	Toronto, Ontario, Canada	Industrial	Rochfort et al. 2007
	0.5	64-2000 µm	Toronto, Ontario, Canada	Industrial	Rochfort et al. 2007
	1.022	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	1.022	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	1.035	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.858	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.587	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	1200	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	785	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	412	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	267	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005

Table 4. A summary of concentrations of organic contaminants detected in samples of street dust. (continued)

pyrene					
	1.9	<64 µm	Toronto, Ontario, Canada	Industrial	Rochfort et al. 2007
	0.7	64-2000 µm	Toronto, Ontario, Canada	Industrial	Rochfort et al. 2007
	0.645	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.645	<63 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.483	63-125 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.395	125-250 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	0.271	250-900 µm	Xincheng, Zhejiang, China	Various	Zhao et al. 2008
	2300	<63 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	1950	63-125 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	1150	125-250 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
	550	250-2000 µm	New Bedford, MA, USA	Residential	Brealt et al. 2005
bis(2-ethylhexyl)phthalate					
	0.0054-0.0149	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
di-n-butyl phthalate					
	0.0055-0.0157	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
di-n-octyl phthalate					
	0.0054-0.0149	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
DDD					
	0.0287-0.111	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
DDE					
	0.0289-0.0494	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
DDT					
	0.0251-0.461	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
alpha-BHC					
	0.05	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
beta-BHC					
	0.0281-0.0326	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
alpha-chlordane					
	0.0426-0.127	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
gamma-chlordane					
	0.0264-0.0489	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
dieldrin					
	0.0338-0.235	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
endosulfan II					
	0.039-2.410	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009
endrin					
	0.0732-0.0787	raw sweepings (<4.75mm)	Florida, United States	Various municipal	Jang et al. 2009

(Hoffman et al. 1984). Numerous studies conducted by USGS have documented increasing environmental concentrations of PAHs attributable to the use of coal-tar based pavement sealants, though this has not been directly assessed in street dust to date (Van Metre et al. 2009; Mahler et al. 2010).

Lau and Stenstrom (2005) found that heavier molecular weight PAHs such as chrysene and benz[a]anthracene increased as particle size decreased, with concentrations as much as 10 times more in the <43 μm range than the 250-841 μm range in commercial and residential areas. This is consistent with findings reported elsewhere (Krein and Schorer 2000; Yang et al. 1997; Zhao et al. 2009b). However, no such trend was found in lower molecular weight PAHs such as biphenyl and acenaphthene (Krein and Schorer 2000; Lau and Stenstrom 2005).

In a study on characterization of pollutants in Florida street sweepings for management and reuse, Jang et al. (2009) tested for 74 volatile organic compounds (VOCs) and 116 semi-volatile organic compounds (SVOCs). Five VOCs were detected including: n-butyl benzene, isopropyl benzene, isopropyl toluene, 1,3,5-trimethylbenzene, and o-xylene were detected in some samples. PAHs were also detected in a small number of the 169 samples analyzed (Jang et al. 2009). Some of the total samples contained two base–neutral phthalate compounds, bis(2-ethylhexyl)phthalate and di-n-butyl phthalate, which are phthalic acid esters (PAE). The source of phthalates in street dust is likely discarded plastic materials (Jang et al. 2009).

Breault et al. (2005) detected 27 out of 30 PAH analytes in street dust, with concentrations increasing with decreasing particle size. Four PAH concentrations were measured above their exposure based guidelines of 0.7 mg/kg (MDEP, 1996; method 2, soil category S-1), including benzo[*a*]anthracene and indeno[1,2,3-*cd*]pyrene concentrations (<63 μm). Benzo[*a*]pyrene concentrations also exceeded these guidelines in the 63-125 μm size range. Benzo[*b*]fluoranthene concentrations exceeded exposure-based guidelines by 1.2, 1.8, and 2.7 times, in the <63 μm, 63-125 μm, and 125-250 μm particle size ranges respectively.

Pesticides have also been detected in street dust. Low concentrations of DDT (25.1-461 mg/kg) were detected in 34/193 street sweeping samples in Florida, though it hasn't been in use for almost 40 years. Endosulfan II was also detected in 35/193 samples with concentrations ranging from 39-2410 mg/kg in the same study (Jang et al. 2009).

Nutrients. Another group of pollutants of concern in urban dust is nutrients, namely nitrogen and phosphorus (Table 5). Urban nonpoint sources of nutrients include fertilizers in runoff from lawns, pet wastes, failing septic systems, and atmospheric deposition from industry and automobile emissions (USEPA 2005c). Fertilizers may be slow release or rapid release. Rapid release fertilizers are of greater concern, because they are readily soluble and are easily transported into storm sewers (Brinkmann and Tobin 2001).

During a rainfall event, nutrients from these sources can make their way to streets in surface runoff, which in turn flows to storm sewers, and then enters aquatic receiving system where it can impair surface water quality (USEPA 2005c). Moderately high concentrations of nutrients, for example, can lead to eutrophication of sensitive receiving waters, which include oligotrophic or mesotrophic lakes where phosphorus is a limiting nutrient, or coastal or estuarine areas where nitrogen is limiting. Fish kills can also result from hypoxia and anoxia due to extreme eutrophication (USEPA 2005c). In the Gulf of Mexico areas of chronic hypoxia are coincident with increasing nitrogen loads from the

Mississippi River system beginning in the 1950s (Rabalais et al. 2007). Monitoring data suggest that urban sources of nitrate are not high enough to pose a direct risk to humans, but excessive nutrient levels in receiving waters can lead to exceedances of drinking water criteria (10 mg/L for nitrate-nitrogen) (USEPA 2005c).

Table 5. A summary of concentrations of nutrients detected in samples of street dust.

Nutrients	Concentration (ppm)	Geographic Location	Sample	Citation
Total Kjeldahl Nitrogen				
	2400	Toronto, ON, Canada	North Bound Unswept Street 2004	Rochfort et al. 2007
	1055	Toronto, ON, Canada	South Bound Unswept Street 2004	Rochfort et al. 2007
	1133	Toronto, ON, Canada	North Bound Unswept Street 2005	Rochfort et al. 2007
	937	Toronto, ON, Canada	South Bound Unswept Street 2005	Rochfort et al. 2007
Total Nitrogen				
	1999	Florida, USA	Highway - Commercial	Berretta et al. 2011
	3587.7	Florida, USA	Highway - Residential	Berretta et al. 2011
	2342.4	Florida, USA	Highway - Highway	Berretta et al. 2011
Total Phosphorus				
	1333	Toronto, ON, Canada	North Bound Unswept Street 2004	Rochfort et al. 2007
	1185	Toronto, ON, Canada	South Bound Unswept Street 2004	Rochfort et al. 2007
	1313	Toronto, ON, Canada	North Bound Unswept Street 2005	Rochfort et al. 2007
	1335	Toronto, ON, Canada	South Bound Unswept Street 2005	Rochfort et al. 2007
	474.6	Florida, USA	Highway - Commercial	Berretta et al. 2011
	702.8	Florida, USA	Highway - Residential	Berretta et al. 2011
	759.4	Florida, USA	Highway - Highway	Berretta et al. 2011

Total Kjeldahl Nitrogen is the sum of organic nitrogen, ammoia (NH_3, and ammonium (NH_4^+)
Total Nitrogen is the sum of nitrate-N and nitrite-N and TKN

The National Research Institute in Canada conducted a street cleaning study and found that nutrients were preferentially associated with finer street particles by nearly 2 fold on average; this observation would mean they would be much more likely to be transported by even small amounts of stormwater runoff (Rochfort et al. 2007).

In a study to determine the magnitude of nutrient runoff from near shore residential lawns surrounding Lauderdale Lakes in Wisconsin, fertilizer use did not affect nitrogen concentrations in runoff (USGS 2002). However, total phosphorus concentrations in lawn runoff was directly related to phosphorus concentration of lawn soils, and test sites that used regular fertilizer had dissolved phosphorus concentrations that were twice than that from test sites that used non-phosphorus fertilizer or that did not use fertilizer (USGS 2002).

A study in Melbourne, Australia showed that as much as 50% of the surface pollutants are associated with street dust particles smaller than 300 µm, suggesting that treatment facilities, e.g. ponds, wetlands, and sediment basins are able to remove the finer particles (down to 50 µm for TP and down to 10 µm for TN), and not just the total sediment or suspended solid load (Vaze and Chiew 2002)..

Relevance of Street Cleaning Technologies and Environmental Risk and Human Health

Ecological Risk

Despite over 150 years of technological development of street cleaning as a BMP for improving environmental quality, limited quantitative studies exist for comparative risk for human health and ecological risk. Several information gaps were previously identified in a review of 44 reports on biological effects of highway runoff on local ecosystems, citing a lack of consistency of methods and sufficient documentation (Buckler and Granato 1999). Studies that modeled contaminant concentrations in highway runoff predicted low acute toxicity. However, other investigations have indicated that highway runoff can impart contaminant loads to soils and sediments that can affect ecosystems near discharge points. Analysis of aquatic biota revealed bioaccumulation of metals from highway runoff reviewed by Buckler and Granato (1999). One study examined whether artificially generated runoff (simulated rain on a street) resulted in differential aquatic toxicity to rainbow trout and *Daphnia magna* during a comparison of a regenerative air sweeper, a mechanical sweeper and a high efficiency regenerative air sweeper. After exposure to simulated runoff, *D. magna* did not experience 50% mortality (i.e. LC50). The high efficiency regenerative air sweeper showed a reduction of toxicity in these studies, though similar reductions were not observed by the mechanical and older regenerative air sweepers (Rochfort et al. 2007).

Zhao et al. (2008, 2009b) conducted a risk assessment of PAHs in street dust contributing to water quality degradation in China through surface runoff and found several measurements above effects range low (ERL) and effects range median (ERM) values, which may respectively moderately and severely impact biota health, with total PAHs concentrations increasing 43-62% during rainfall events (Long et al. 1995; Zhao et al. 2008, 2009b)

In a study of stormwater runoff from a parking lot that received coal tar sealant nine months earlier, total PAH concentrations >90 mg/kg in sediment near the stormwater outfall exceeded a NOAA effects range median (ERM) of 44.7 mg/kg, compared to <5 mg/kg near non-sealed surfaces. Concentrations remained elevated three years after the initial application. Dust samples on coal tar sealed surfaces were as high as 1,192 mg/kg compared to <2 mg/kg on non sealed surfaces (Watts et al. 2010a, b).

A risk assessment of runoff related input of 5 heavy metals in a several tributaries of the Yangtze River delta was also conducted with results published in a separate paper (Zhao et al. 2009a). Each of the metals (chromium, copper, nickel, lead, zinc) examined were observed above “severe effect screening levels” (SEL) within the <63 µm, 63-125 µm, and 125-250 µm size ranges, with the exception of nickel in the 125-250 µm size range in street dust and suspended solids during two rain events (NYSDEC 1999; Zhao et al. 2009a). Lead exceeded a SEL in the 250-900 μm size range. Copper and lead were also greater than SEL values in stream sediments (Zhao et al. 2009a).

In a study observing the effects of road surface runoff on freshwater ecosystems in Great Britain, elevated concentrations of total hydrocarbons, aromatic hydrocarbons and heavy metals were found in water and sediment downstream from runoff discharge points (Maltby et al. 1995a). Changes in the diversity and composition of macroinvertebrate populations were also observed downstream versus upstream from discharge points in four out of seven streams. This was likely due to reduction of the decomposition of leaves and a change from a population based on coarse particulate matter to a population based on fine organic matter and benthic algae. No changes were observed in epilithic algae populations. In the most heavily polluted site, a smaller diversity of aquatic hyphomycetes were observed (Maltby et al. 1995a).

Subsequently, toxicity tests were done using the benthic amphipod *Gammarus pulex*. While exposure to contaminated streamwater showed no toxicity, exposure to sediment did show a decline in survival for *G. pulex* from 96% upstream to 90% downstream (Maltby 1995b). Further testing showed that three PAHs: pyrene, fluoranthene, and phenanthrene, account for 30.8-120% of extracted sediment's toxicity. Individual toxicity was 44.9%, 16%, and 3.5% for pyrene, fluoranthene, and phenanthrene respectively (Boxall and Maltby 1997).

Human Health Risk

Re-entrainment of street dust is a major source of urban $PM_{2.5}$ and PM_{10}, which have significant impacts on human health. An association between ambient levels of PM and mortality has been observed in numerous studies (Brunekreef and Forsberg 2005;

Ruckerl et al. 2011). Recently, street sweeping has been explored as a potential method for reducing ambient PM levels, with studies reporting mixed evidence on effectiveness (Amato et al. 2010b; Gertler et al. 2006; Keukenn et al. 2010). A study conducted in Nevada showed an increase in re-entrainment of street dust when "brush and water wash street sweepers" were used (Gertler et al. 2006). Another study conducted in the Netherlands using similar technology indicated that sweeping did not reduce non-exhaust PM emissions (Keuken et al. 2010). However, a trial conducted using a vacuum-assisted mechanical sweeper did show a small but significant reduction in ambient PM (Amato et al. 2010b). The use of water for PM suppression in each of these trials may suggest the trading of reduction in one risk (human health) for a potential increase in another (environmental). The comprehensive comparison of the available technologies on reduction of PM was conducted under the City of Toronto's Clean Roads to Clean Air initiative. These studies concluded that regenerative air sweepers were the most effective at reducing re-entrainment of PM (Morgan and Stevanovic-Briatico 2007).

Beyond the potential impacts posed by PM, street dust presents hazards to human health through other avenues. For example, in East China, PAHs from stormwater runoff have contaminated a potential drinking water supply (Chen et al. 2007). One hazard analysis indicated that ingestion of more than 100 mg/day of street dust could pose an unacceptable risk to human health, though ingestion of this material at this quantity seems unlikely in the long term (Lorenzi et al. 2011).

Research Needs and Conclusions

A primary objective of this paper was to provide a critical review of the efficacy of various street cleaning technologies and practices for managing environmental risks associated with stormwater and air quality. Forty-nine articles regarding street cleaning have been examined (Table 1), while only nine studies have compared the various street cleaning technologies.

Several variables make it difficult to develop a firm conclusion on comparative street cleaning technologies including:

1. A lack of studies and data on the subject: Several authors have commented on the lack of available comparative data on the effectiveness of street cleaning (Amato et al. 2010a; Breault et al. 2005; Kang et al. 2009; Selbig and Bannerman 2007; Sutherland 2011).
2. Regional climate and soil types: While pollutant concentrations are higher with smaller particles, regional soil types vary from location to location. Arid regions will likely have more ambient PM than regions with more rainfall.
3. Street cleaning frequency: Several authors have attempted to determine sweeper effectiveness by sweeping frequency (Brinkman and Tobin 2001; Sorenson 2013). However, optimum sweeping frequency depends on the effectiveness of individual sweeping technologies (Sorenson 2013). Computer modeling shows that sweeping once a month with a high efficiency regenerative air sweeper is more effective at reducing total solid contributions to stormwater than sweeping three times a week with a mechanical or vacuum sweeper (Sorenson 2013).
4. Road surface type and conditions: Sweeper technology descriptions have pointed out that mechanical sweepers have a tendency to fill cracks and

imperfections on street surfaces with dirt, while vacuum and regenerative air sweepers can emit fugitive dust on uneven pavement (Sutherland 2011; Schilling 2001a). Road surface types and conditions introduce variability in testing.

5. Variations in technology types amongst street sweeper manufacturers: While many studies do not name the sweeper model or brand tested, generically applying performance efficiencies across the board for technology types may not be accurate (Rochfort et al. 2007)
6. Variations in testing parameters: Real world and simulated studies yield different results for the same sweeper. The TYMCO Model DST-6 was rated 90% efficient by ETV (2012a), 51% efficient by Rochfort et al. (2007), and up to 82% efficient by Sorenson (2013).

The inherent problem with studies using a simulated test material in a controlled environment conducted thus far, is that these studies usually cannot account for real world conditions such as potholes and cracks in streets, wet vs. dry weather conditions, flat vs. crowned streets, and impervious vs. pervious pavement. Conversely, "real-world" studies have the problem of variability in data due to a variable amount of material available to pick up, wind, geographic location, weather, climate, and traffic. Operator error, testing different sweepers at different speeds, times of the year, or places may also affect street cleaning test results (Rochfort et al. 2007). Some studies have noted improvements in stormwater quality due to combination of changes in street sweeper technology and management practices, but did not evaluate changes in street sweeper technology and management practices separately (DeLuca et al. 2012; Talend 2012).

Other studies have attempted to combine results from other studies in an effort to compare technology efficacy, but the many variables listed above give ample opportunities for confounding results (Sutherland and Jelen 1997; Zarriello et al. 2002).

It is therefore recommended that a comparative study be conducted evaluating the performance of different sweeper technologies in various controlled environments and conditions using a tiered approach (Fig. 4).

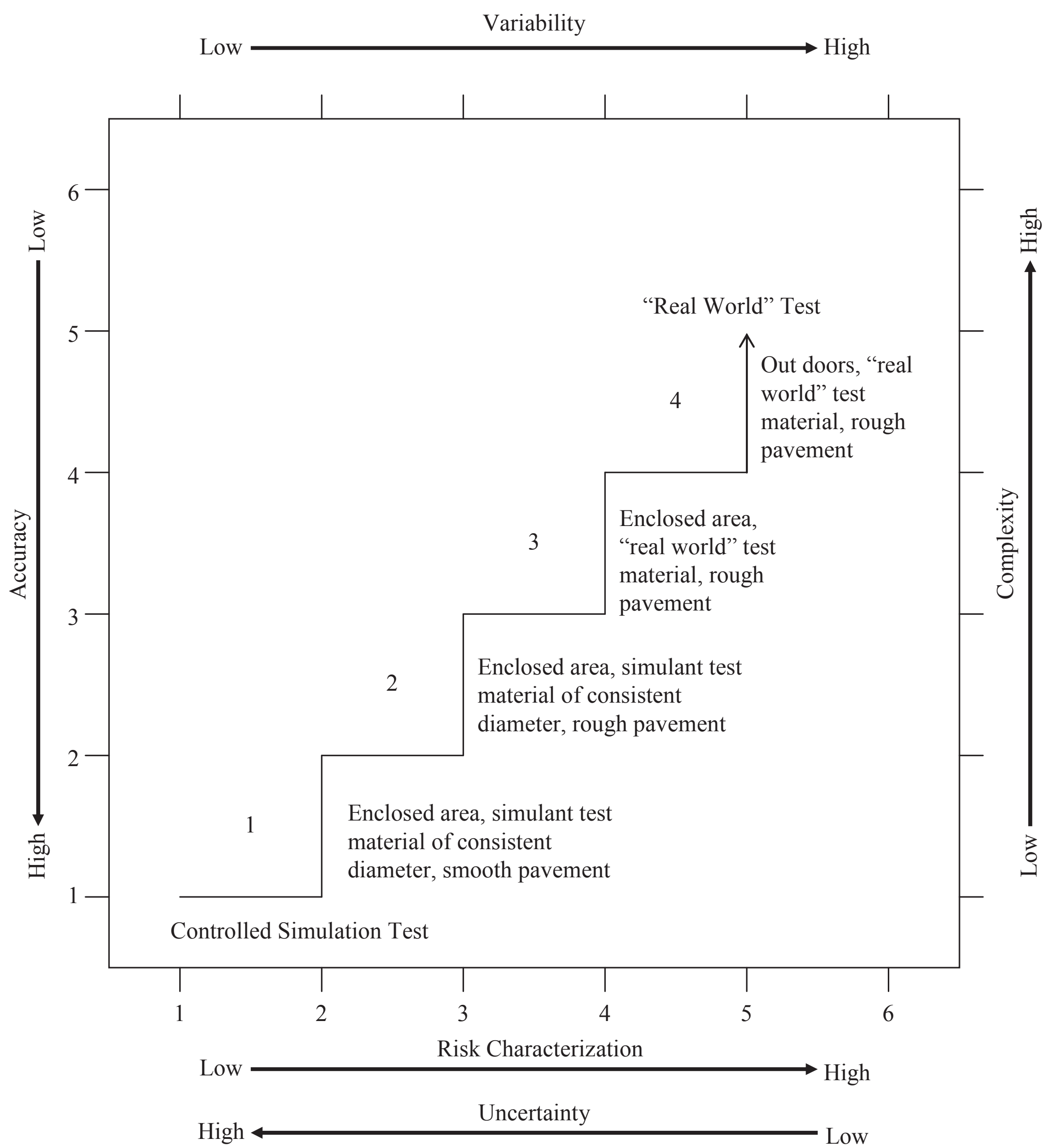


Figure 4. A tiered approach to evaluating street sweeper efficacy.

I recommend the following experimental parameters and goals for establishing a framework for street cleaning technology evaluation:

1. Ambient air quality in an enclosed area similar to the Canadian ETV study.
2. Different types of material at different particle size ranges and various accumulations and densities including:
    a. Simulant material such as that used in the ETV study.
    b. Pure sand, silt, clay, and gravel at various moisture levels.
    c. Actual collected street sweeping materials from various regions.
        i. Dirt, leaves, sticks, garbage, grass clippings, bulky material.
3. With and without water for dust control.
4. Measure water output.
5. Various street surface conditions.
    a. Smooth and rough pavement.
    b. Damaged and undamaged pavement.
    c. Curbed and non-curbed pavement
    d. Crowned and non-crowned surface.
    e. Porous and non-porous pavement.
6. Evaluate fuel usage per material removed.
7. Evaluate sweeper engine emissions per material removed.
8. Establish a standard test protocol for street cleaning technologies.
9. Evaluate each type of street cleaning technology.

10. Evaluate street cleaning technologies at various sweeping speeds.
11. Evaluate street cleaning technologies at various sweeping frequencies.
12. Evaluate street cleaning technologies at various weather conditions.
    a. Wet, dry, hot, and freezing.
13. Evaluate street cleaning technologies at various fan/broom RPMs.
14. Street cleaning manufacturers should voluntarily participate.
15. Develop achievable national standards for air and water quality through street cleaning mitigation.
16. Determine margins of safety for stormwater hazards and human health under multiple street cleaning strategies and technologies.

I also reviewed the literature to quantify various constituents on street surfaces including metals, organic contaminants, and nutrients. Few studies however, have evaluated street cleaning in relation to environmental and human health risks (Brunekreef and Forsberg 2005; Rochfort et al. 2007; Ruckerl et al. 2011; Zhao et al. 2008, 2009a, b). Furthermore, none of the studies characterized margins of safety and/or relative risk to human health and the environment between the available technologies and strategies for street cleaning.

In this study I examined the available literature comparing various street cleaning technologies and their efficacy. These technologies include standard and high-efficiency mechanical, vacuum, regenerative air sweepers. The available literature suggests that vacuum and regenerative air sweepers are more efficient at picking up smaller particles and may be better at controlling ambient PM than mechanical sweepers (Breault et al. 2007; Rochfort et al. 2007; Selbig and Bannerman 2007). The technology descriptions seem to point to regenerative air as superior technology vacuum sweepers; however, variability within tests and their results suggest that this initial assessment remains inconclusive (Sutherland 2011; TYMCO 2012b; Weston Solutions 2010).

The wide variation in experimental test protocols used to date made any rigorous assessment of comparative efficiency of the available street sweepers impossible. Thus, I recommend establishing a standard for assessing the comparative efficiency and efficacy of street cleaning technologies based on proven test protocols, establishing national standards for air and water quality through street cleaning mitigation, and establishing margins of safety for stormwater hazards and human health under multiple street cleaning strategies and technologies.

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