Fine Particulate Matter in Harris County

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Unpaved roads can create high levels of particulate matter

FINAL REPORT

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I. Executive Summary



Picture taken from the Harris County Flood Control District's publication, "The Bayou Beat," Willow Waterhole Stormwater Detention Basin in 2006. Used with permission.

Harris County is one of the largest U.S. counties by population and area. It hosts one of the world's largest concentrations of petrochemical facilities and has a vast network of interstate highways and roads. Construction steadily moves rapidly forward, even during recessions when compared with the progress of other cities, yet the air quality is arguably significantly better than many other populated areas in the United States.

However, some issues still remain. Harris County is not in compliance with the current 75 ppb U.S. ozone standard and significant work remains to achieve that standard and the EPA has proposed new (lower) standards. The only other national ambient air quality standard (NAAQS) that has ever been in question is fine particulate matter (PM) or $PM_{2.5}$. In 2005 the $PM_{2.5}$ value exceeded the national standard of 15 $\mu g/m^3$. Over the next several years, with government, industry and non-governmental organizations (ngos) voluntarily working on a variety of projects together the measured concentration of fine particulate matter dropped dramatically. By December 2012, when the EPA lowered the standard to 12.0 $\mu g/m^3$, the $PM_{2.5}$ in Harris County was down to 12.1 $\mu g/m^3$. By 2013 the levels were below 12 and in January 2015 in their final designations the EPA has declared all of Texas, including Harris County, as "unclassifiable/attainment". This project has proceeded recognizing that even if Harris County is compliant with the standard there still may be work required to stay in compliance as the population and economy continues to grow.

There are two main approaches to reducing PM. One approach is to review the results of PM monitoring stations, analyzing the composition of the PM filters and perform studies to attempt to identify the original sources. Once the sources have been identified specific measures can be set in place. This is the practice that has been successfully implemented in Harris County, based on extensive sampling at the Clinton Drive monitor. A summary of the activities is provided later in this document and extensive details were assembled in 2014 by the Regional Air Quality Planning Advisory Committee (RAQPAC) are provided in Appendix A.

The second approach, used by the Houston Advanced Research Center (HARC) in this project, is to develop a detailed inventory of all significant sources of primary $PM_{2.5}$. Each state is required to provide to EPA every 3 years an inventory of all criteria pollutants for each county. At the time this project was initiated the last complete inventory for Harris County that the Texas Commission on Environmental Quality (TCEQ) provided to Harris County was for the year 2011. HARC employed SC&A, Inc. (a contractor with 30 years of experience in working on inventories), to assist in a detailed review and perform quality control and analysis of the most recent TCEQ inventory, as well as develop projections for the future. HARC has provided assistance in obtaining data and identify people and data sources for SC&A. Once the gaps in the inventory were identified HARC developed a detailed list of the $PM_{2.5}$ control methods used in the U.S. and elsewhere. Whenever possible this list included the efficiency of the control in reducing $PM_{2.5}$ and the cost effectiveness of the control expressed in dollars per ton of $PM_{2.5}$ reduced.

The ultimate goal of this project has been to provide Harris County with a list of options that could be taken to reduce the $PM_{2.5}$ inventory (regardless of what that amount is) by 10% and 25%, including the expected costs. Throughout the course of this project the revised inventory found that there were 20,469 tons/year of primary $PM_{2.5}$ identified in Harris County. Details of the revised inventory are provided in the SC&A report found in Appendix B.

If the expectation were that in each sector (unpaved roads, commercial cooking, cooling water towers, boilers, on-road, locomotives, etc.) had to reduce emissions by 10% and 25% we estimate that the costs would be close to $500 and $1500 million dollars respectively. However, by selecting specific sectors including commercial cooking, residential wood combustion and unpaved roads the costs of reducing $PM_{2.5}$ emissions by 10% and 25% is projected to be closer to $25 and $100 million respectively.

II. Introduction

Before PM was defined as a pollutant the original regulations in the U.S. were focused on total suspended solids (TSP) in the 1970's. TSP is defined as any solid or liquid besides ice or water that floats in the air. However, as time went on additional research demonstrated that the portion that was of greatest concern were those particles which are "breathable", that is they can enter the lungs through the mouth and lungs. The breathable portion of TSP includes those particles that are 10 microns or less in diameter, referred to as PM_{10}. The U.S. EPA implemented regulations for PM_{10} in the 1980's, but by the 1990's another distinction was made for even smaller particles. Some particles were found to be so small that they could enter the bloodstream after having been inhaled to the lungs. Those particles have been called $PM_{2.5}$ or "PM fine" – referring to particles in the air that have a diameter of less than 2.5 microns in diameter.

Because the fine particulates can be absorbed by the bloodstream they can potentially have the greatest impact to health. Numerous scientific studies have linked $PM_{2.5}$ to health problems including:

- Premature death in people with heart or lung disease,
- Nonfatal heart attacks,
- Irregular heartbeat,
- Aggravated asthma,
- Decreased lung function, and
- Increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing.

People with heart or lung diseases, children and older adults are the most likely to be affected by particle pollution exposure.

Fine particulate matter can be categorized as primary or secondary. Primary is also known as direct $PM_{2.5}$. Primary $PM_{2.5}$ is identified in different ways. They can be "filterable" or "condensable". Filterable $PM_{2.5}$ is solid or liquid at stack temperatures, stable in the atmosphere and can be collected on a filter in an ambient sampler. Condensable $PM_{2.5}$ is a gas at stack temperature, condenses to liquid or solid at the gas exit, and is also stable in the atmosphere and can be collected on a filter in an ambient sampler.

Secondary $PM_{2.5}$ is formed in the atmosphere through a series of chemical reactions. These particulates are also collected on filters with ambient samplers.

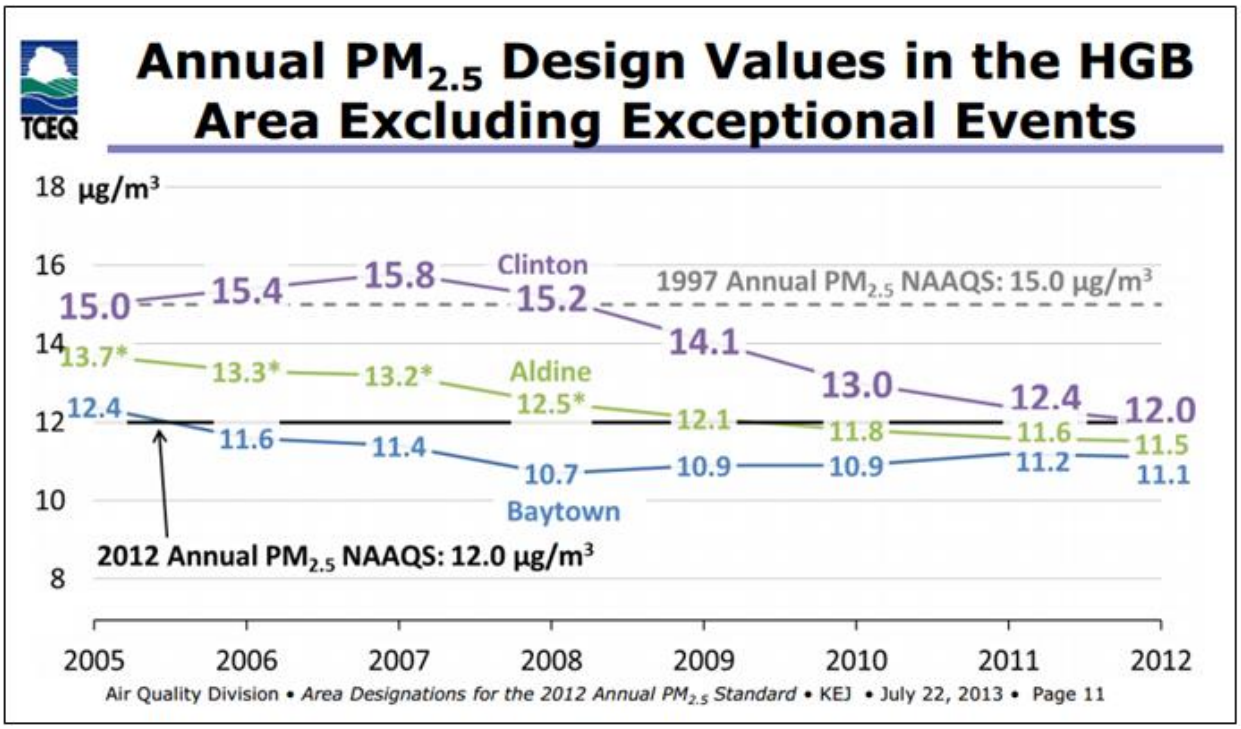
This study is focused on the emission inventory of primary $PM_{2.5}$. Secondary $PM_{2.5}$ is not included in fine particulate inventories because the chemical formations are very complex and the reaction times often occur over several hours or longer over many miles so identification of specific sources of secondary $PM_{2.5}$ for the inventory is not practical.

III. Particulate Matter in Harris County

Harris County has never been out of compliance with PM regulations. According to EPA documents[1], EPA began regulating TSP in 1971. The focused changed from TSP to regulation of PM_{10} beginning in 1987. Ten years later a regulation and national ambient air standard was added for $PM_{2.5}$. In 2006 the regulation for the 24 hour $PM_{2.5}$ standard was reduced from 65 $\mu g/m^3$ to 35 $\mu g/m^3$ and most recently in December of 2012 the $PM_{2.5}$ annual standard was reduced from 15 $\mu g/m^3$ to 12 $\mu g/m^3$. EPA has never identified any county in Texas as out of compliance with these standards. However, from 2005 to 2008 and again from 2012 to 2014 Harris County was close to being designated as non-attainment for both the 15 $\mu g/m^3$ and the 12 $\mu g/m^3$ standards respectively.

The plot below taken from a TCEQ presentation[2] shows the historical design values of $PM_{2.5}$ in Harris County from 2005 to 2012.

Figure 1.



Although the annual $PM_{2.5}$ values exceeded the standard in 2006-2008, TCEQ was able to demonstrate that sufficient progress was being made on bringing the values into compliance.

On October 8, 2009 the EPA sent a letter[3] to the Texas Governor indicating that all counties in Texas were in attainment for $PM_{2.5}$, but recent readings in Harris County showed indications of a new violation that needed to be addressed. The Governor and TCEQ responded with

information confirming that all Texas' Counties, including Harris County, were still in compliance. EPA reviewed the information and on April 28, 2010 sent a second letter[4] confirming the "unclassified/attainment" designation.

The downward trend observed between 2005 and 2012 at the Clinton site has been attributed to a number of cooperative voluntary actions taken by Harris County, the City of Houston, TCEQ and local industry. Some of these activities included repaving roadways and parking lots, installing traffic lights and guardrails to reduce dust from traffic in the area, upgrading diesel engines and other activities to reduce diesel emissions. Other actions that stopped steel loading activities on dirt surfaces, enhancing local requirements for dust reduction activities, and federal and international agreements related to reducing marine vessel emissions also played a role. A detailed summary of the $PM_{2.5}$ reduction activities that have been implemented or are currently underway in Harris County were assembled in a document[5] by RAQPAC in 2013. This document was prepared for the development of PM Advance, a voluntary program sponsored by EPA with the intent to encourage areas that may become subject to regulatory action to take preventive actions. A copy of the RAQPAC document is provided in Appendix A.

In August 2014 EPA notified Texas Governor Rick Perry of EPA's intention to give all of Texas a designation of "unclassified/attainment"[6]. TCEQ responded in September of 2014 recommending that 11 counties in Texas which had monitors should be designated as "attainment" only and not "unclassified/attainment"[7]. Harris County was one of those 11 counties.

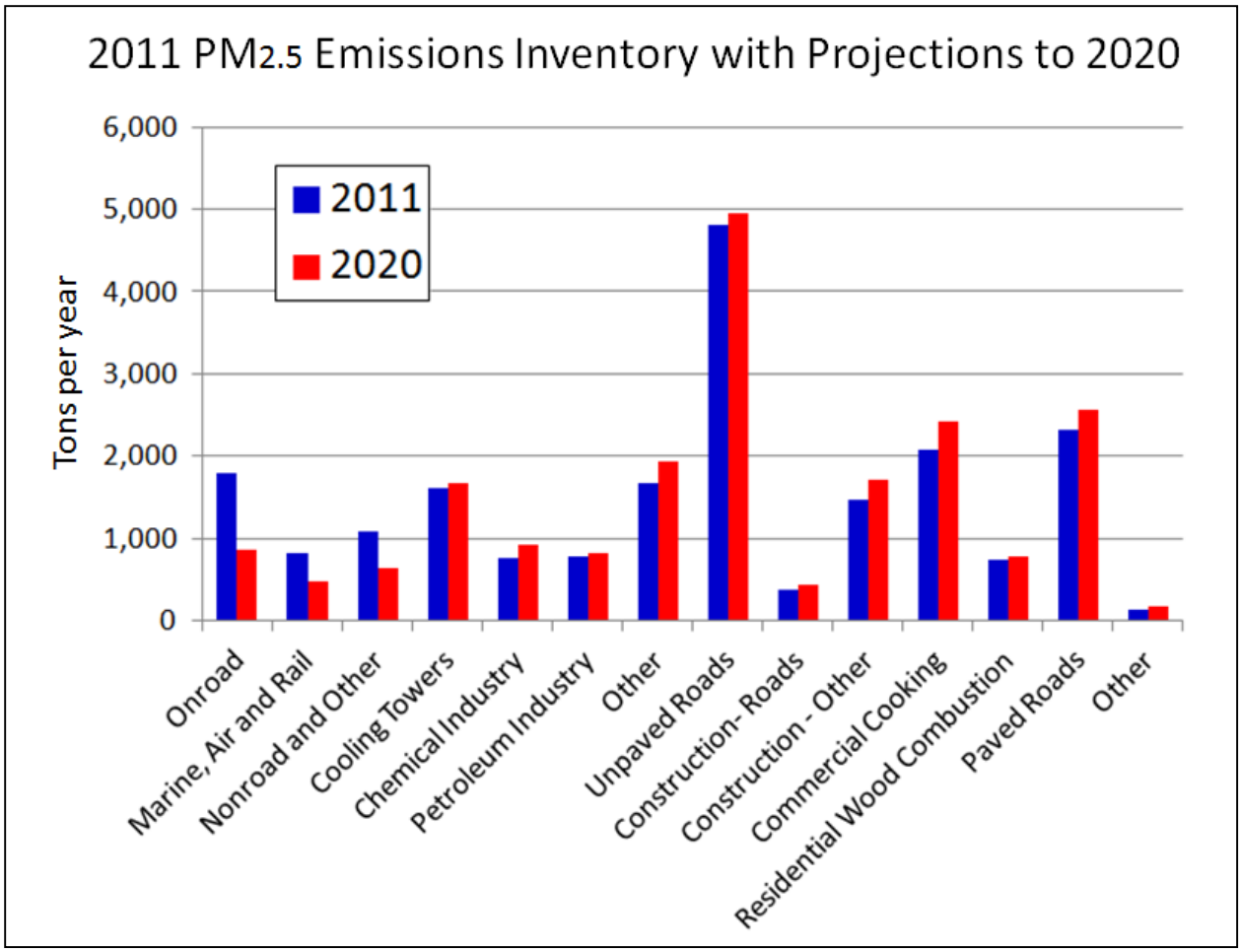
EPA's final ruling came out on January 15, 2015. In EPA's final ruling all Texas counties, including Harris County, have been designated as "unclassifiable/attainment"[8].

IV. The Inventory

Every 3 years the states are required to submit an emissions inventory for all criteria pollutants (particulate matter, volatile organic compounds, nitrogen oxides, sulfur dioxide, carbon monoxide and mercury) for each county. The last county-level inventory that TCEQ provided to EPA when this project began was in 2011. TCEQ provided their 2011 emissions inventory to HARC and their subcontractor, SC&A. A detailed quality assurance/quality control review was made of the $PM_{2.5}$ inventory for Harris County and was updated as part of this project. A copy of the final report by SC&A is provided in Appendix B.

A summary of the updated 2011 emissions inventory with projected emission to 2020 is shown in Figure 2. Overall the total 20,469 tons per year of $PM_{2.5}$ emissions identified in 2011 are anticipated to drop by 0.5% in 2020 to 20,377 tons per year. The increases in certain areas are largely due to expected increases in population. Most of the decreases are associated with the new rules implemented by EPA for reducing $PM_{2.5}$ in diesels engines.

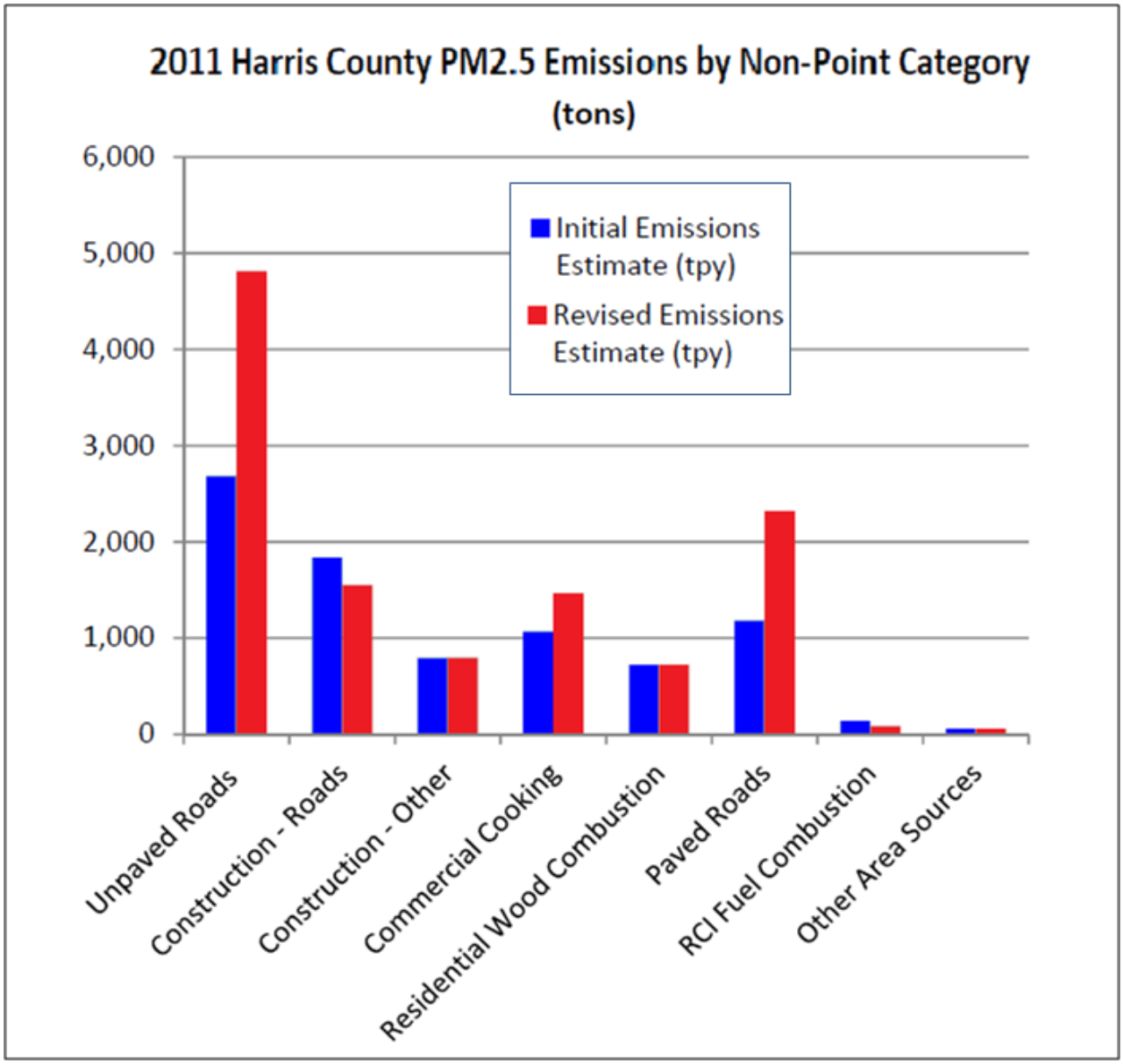
Figure 2.



Revisions to Area or Non-Point $PM_{2.5}$ Sources

Area or Non-Point sources make up 58.3% of the inventory. The most significant revisions made to the entire TCEQ inventory occurred in the area source category in unpaved and paved roads. The TCEQ receives an estimate of emissions from each county for these categories from EPA's National Emissions Inventory (NEI). The changes made below are largely due to data gathered from the Texas Department of Transportation and other updated reports that have been filed since the original estimates were made. More details are provided in the SC&A emissions inventory report in Appendix B.

Figure 3.



The NEI estimates developed by EPA are based on surrogate information such as population and population density as well as some local information that is provided by either national or local agencies such as the U.S. Department of Transportation or the Texas Department of Transportation. All states have the option of revising the inventory provided by EPA with more detailed local information that may include more recent than the data sources that EPA uses. Also, EPA does not provide inventory estimates for all sources. Often states opt to simply use the inventory that EPA provides as part of the NEI and then complete the remaining inventory estimates themselves. Texas, for example, has 254 counties and limited resources on the TCEQ staff to re-estimate the entries provided by EPA in the NEI. In the case of the 2011 inventory, the $PM_{2.5}$ emission values that EPA developed for the NEI for unpaved roads, paved roads, road construction and construction – other were not altered by TCEQ when submitting the 2011 inventory.

Commercial cooking was also found to be higher than the original estimates, largely due to selecting an estimation method that is based on the number and type of restaurants in the Harris County, rather than what has been done in the past, which has been to base the estimates on population. This approach is expected to provide a more accurate emissions estimate for this category.

Point $PM_{2.5}$ Sources

Point sources make up 23.6% of the total $PM_{2.5}$ emissions in the revised 2011 inventory. These emissions are reported to TCEQ by the various point sources. The general categories included cooling water towers, internal combustion engines, gas fired heaters, boilers, fuel fired equipment, plastics production, glass manufacturer, metal abrasive blasting and "other point sources" which includes 25 subcategories shown in Table 21 later in this document.

In reviewing these reported emissions most categories did not demonstrate any significant level of concern for being outside of expected emissions. Some questions were raised about flares and the potential for $PM_{2.5}$ being much higher than reported, however to date there has not been sufficient research performed that could provide more accurate estimates of the $PM_{2.5}$ from flare emissions.

A lot of discussion was generated among various stakeholders and regulators about $PM_{2.5}$ emissions from forced draft cooling water towers. In most cases those reporting cooling water $PM_{2.5}$ emissions to TCEQ have simply entered their total PM_{10} values, some have entered a value of zero, and a few of the submitters have provided $PM_{2.5}$ values that are a very small fraction of the total PM_{10} value. By reporting all $PM_{2.5}$ emissions as PM_{10} the submitters can substantially reduce time in the emissions reporting process. In many cases due to concerns regarding permitting, selecting $PM_{2.5}$ equal to PM_{10} is the best option. Some industry based research suggests that $PM_{2.5}$ emissions should be close to zero, however EPA disagrees with this assessment and thinks the $PM_{2.5}$ emissions should be much higher. In order to adjust for this issue, after discussions with industry and other stakeholders as well as regulatory personnel, for the purposes of this report it has been assumed that cooling water $PM_{2.5}$ emissions are equal to

60% of the reported PM_{10} values. This revision created a slight drop in the $PM_{2.5}$ emissions from the original TCEQ 2011 inventory.

Other potential point sources were identified that may be under-reporting $PM_{2.5}$ emissions in the inventory based on complaints that were made to Harris County Health Officials include: rock crushing, metal recycling and sandblasting at pipe yards. Emissions may be underreported at rock crushing facilities, however there are very few facilities in Harris County, and more detailed information about the activities must be identified before any changes in the inventory would be recommended. There are several metal recyclers in Harris County, however most are below the threshold in size to be considered a point source and therefore do not report their $PM_{2.5}$ emissions. PM emissions from these sources come from equipment such as torch cutters and shredders, as well as from normal loading and unloading. A review of the sandblasting and other abrasive blasting facilities found that the reported numbers had a substantially higher $PM_{10}/PM_{2.5}$ ratio than what has been determined by EPA (10:1), so these numbers have been modified downwards.

Mobile $PM_{2.5}$ Sources

For mobile emissions there were no substantial issues identified in the calculations for most sectors including on-road vehicles and off-road equipment. One area that was adjusted significantly, from 280 tons per year of $PM_{2.5}$ emissions to 661 tons per year of $PM_{2.5}$ emissions was done for commercial marine vessels (CMV). SC&A identified three different emissions inventory reports performed for the Port of Houston in recent years. In a careful review of the emissions factors and the activity levels they determined that a value of 661 tons per year was more appropriate for the CMV inventory. Details are described in the SC&A emissions inventory report found in Appendix B.

Projections to 2020

As was shown in Figure 2 the $PM_{2.5}$ emissions inventory for $PM_{2.5}$ is expected to change less than 1% between 2011 and 2020. The reason is that the overall increases associated with population increases are off-set by decreases expected in fleet turn-over with newer, cleaner running diesel engines. Since EPA in their final rule in 2015 declared all of Texas, including Harris County, as “non-classifiable/attainment”, Harris County may be safe from regulations. However the emissions from the EPA Federal Reference Method monitors are not far from the regulatory threshold of 12 $\mu g/m^3$, so these values must continue to be monitored, and some consideration should be given to bringing the emissions down further to provide a cushion in the future.

V. Emission Sources and Controls

When developing emissions inventories emissions sources are divided into three categories: area, point and mobile. Area sources (also called "non-point") emissions typically occur over a wide area, as the name implies. In contrast, point sources occur at a specific location such as a manufacturing plant. In many cases the distinction between area and point source emissions is purely a matter of size. A source may be declared a point source if it emits more than some specified amount of pollutants per year; otherwise it is deemed to be an area source. The third category of mobile sources is typically further divided into on-road and off-road sources. Cars and trucks and everything else that commonly travels on the road fall into the "on-road" grouping. Off-road emitters include construction equipment, locomotives, marine vessels and aircraft. The classification of emission sources is not always obvious. For example, particulate matter or dust generated by on-road vehicles or off-road construction equipment is considered an area source; however the emissions are emitted through the gasoline or diesel exhausts of the same vehicles and equipment are considered part of mobile emissions.

Inventories are used to help identify which source categories and individual sources are responsible for the emissions. These groupings help to prioritize which sources should be targeted for emission reductions. Emission inventories are developed because it is not economical or practical to use monitoring devices to identify the emissions. Also, monitors tend to measure concentrations at specific locations that are at some unknown distance from a variety of potential sources. This makes it extremely difficult to identify specific sources or to calculate an emission rate or pounds of pollutants released over time.

Emission controls vary widely depending on the type of pollutant and the source. Emission controls are typically chosen based on their cost, efficiency and effectiveness. For example it may be very expensive to pave a dirt road, but paving (and maintaining) a road is considered 99% or more efficient in removing particulates for 25 years or more. Another option is to add water to the road to keep the dust down, but that is considered only 18% efficient and lasts only a single day. These and other control options are evaluated based on the cost effectiveness measured in dollars per ton of pollutant which is reduced. Sometimes, as in the case of paving a road versus watering a road, the control with the lower cost effectiveness (paving a road) has a much higher upfront cost, and so a short term option, like watering a road every day, might be chosen even though in the long term it will cost more.

VI. Sources of Error

Emission inventories are prone to errors for the following reasons:

1. Incomplete or inaccurate counts of the total number of emission sources.
2. Errors associated with the emission factors that are used to estimate the total emissions based on the expected emission rate and number of the sources.
3. Errors associated with not knowing how many emission sources already have emission controls in place.

There are several types of error that occur in an emissions inventory. Typically they fall under two broad categories of getting an accurate count of the emission sources and properly estimating the emissions based on those counts.

As one example, consider the errors that may occur in determining the emissions from an unpaved road. There are several questions that must be answered. How many unpaved roads are there? How much traffic occurs on each road? How fast do the vehicles travel on the unpaved roads? What is the condition of the roads? How often does it rain? How common is it to implement particulate controls on these unpaved roads? How efficient are the control methods used? All of these variables can have a significant impact on the emissions estimate.

There are several different methods for calculating the number of sources. The simplest way is to estimate the number of sources based on some surrogate, for example population or population density. Another way is to gather data that is available from various sources such as the federal and state department of transportation, county and city records, etc. and with a combination of queries and models identify estimate the number of unpaved roads, the amount of traffic on those roads, typical speeds, etc. Finally, a survey can be performed where people actually go out and record the number of sources found.

There are several possibilities for error in each method. In the surrogate example, it is often difficult to know how well or how poorly a surrogate, such as population, relates to the number and size of sources in an area. Regional differences due to local industries, economics, urban vs. rural and many other factors can skew the results. Gathering data from a number of databases and performing analyses is often seen as reasonable approach towards developing an inventory, however it is not always easy to determine how complete the databases are. There are always some assumptions that have to be made. A physical survey can have the potential for capturing all the data points, but it is also very capital and labor intensive. Even so, there is still no guarantee that all of the sources have been located.

For particulate matter another source of error is distinguishing what fraction of PM_{10} is $PM_{2.5}$. For many years PM_{10} reporting has been a requirement, but $PM_{2.5}$ relatively new. In many instances there has not been sufficient review of the data to determine what fraction of PM_{10} is $PM_{2.5}$. Therefore there is questionable confidence in some estimates of how much PM_{10} is $PM_{2.5}$.

VII. Unpaved Roads



Photographed by Alex Cuclis

A. Source Definition

An unpaved road can be any dirt or gravel road. Different emissions are generated by unpaved roads depending on the amount of traffic flow, the weight of the vehicles and whether it is designed for urban or rural traffic. Urban roads (paved and unpaved) typically must comply with stricter standards to address concerns such as speed and safety. Urban roads generally have fewer emissions than rural roads.

B. Description of how the source emits $PM_{2.5}$

Emissions arise as vehicles travel down unpaved roads, pulverizing the ground and throwing off particles. Emissions are higher with heavier vehicles, vehicles traveling at faster speeds and with increasing traffic. Emissions will also be higher under dry conditions.

Most of the particulate matter associated with road dust is fairly large. Some estimates place the $PM_{2.5}$ portion of PM_{10} at 10%. Also, unlike particulate matter from other sources, most road dust does not travel more than 15 feet above ground level and some of it is trapped or adsorbed by vegetation and building structures. The EPA discount factors[9] that have been developed have been applied to the Harris County road dust emissions inventory to account for dust that will be trapped or adsorbed.

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

Typically estimates for unpaved roads are expressed in terms of vehicle miles traveled (VMT) rather than simply the number of miles of unpaved roads. This combines the miles of unpaved roads with the usage. Often inventories are developed based on statewide averages allocated to each county using surrogates based on population or other factors. According to the EPA, unpaved road conditions vary tremendously and can cause orders of magnitude errors in estimating road dust emissions. Getting accurate local information is critical.[10]

2. Capacity/Usage Rate/Duty Cycle

EPA's National Emissions Inventory or NEI, EPA's compilation of quantitative information concerning the mass of air pollutants emitted into the atmosphere through smokestacks, tailpipes, vents, etc., estimated 64 million VMT on unpaved roads for Harris County using top down estimates of unpaved road travel and associated emissions, however contractor SC&A reviewed data from the Texas Department of Transportation (TxDOT) and found the total to be 260 million VMT.[11]

3. Condition

The NEI has 6 different unpaved road types based on road size, traffic levels and location (urban or rural), each with a distinct emission factor. As part of this study contractor SC&A used data from TxDOT and assigned the 6 different emission factors as part of their analysis.

4. Fluctuations due to time of day, day of week and time of year

There are changes during the day, week, and season in uses of unpaved roads. Annual averages are estimated here. Activity and emissions are highest for unpaved roads during normal working hours.

5. How is the $PM_{2.5}$ emission factor determined?

The emission factor[12] for unpaved roads is based on an empirical formula that includes the number of miles of unpaved road, the mean vehicle weight, the surface material silt content, the surface material moisture content under normal conditions and the number of days per month the moisture is greater than 0.01 inches. Days with precipitation are estimated to have no road dust emissions.

There are three basic methods for determining emissions, [13] all of which look at the number of unpaved roads and the amount of traffic on those roads. These calculations are used to develop the number of VMT on the roads of interest. The three methods are:

1. Use statewide data and apply them to the county level.
2. Conduct a statistical analysis on local data using either county or statewide data, to generate the VMT.
3. Develop a detailed survey or inventory of local roads and traffic activity or make assumptions about average daily traffic

Method 1 is the simplest approach, but may not reflect differences between state and county, which can be substantial. Method 2 is still relatively simple, but requires work gathering data and it may be difficult to get statistically significant data that provides better results than Method 1. Method 3 provides information that is very specific to local conditions and activity, but requires a lot of work to perform the surveys and develop inventories, etc. Also, the information gathered may not reflect what is happening on the roads that did not make it into the surveys.

D. Control Methods, Efficiencies and Costs

Efficiencies and costs reported in the literature are generally reported in terms of PM_{10}. Many of these estimates were developed more than 10 years ago, and need to be updated. The numbers are provided below. In the cases below it has been assumed that the control effectiveness for PM_{10} is the same as that for $PM_{2.5}$. This is an approximation used through-out this document. When there is data that indicates that control efficiency is significantly different for PM_{10} versus $PM_{2.5}$, like street sweeping which is efficient at reducing PM_{10}, but not as efficient as removing $PM_{2.5}$, it will be noted. In the most recent inventory provided by SC&A, the Harris County the PM_{10} for unpaved roads was 48,354 tons per year and the $PM_{2.5}$ was 4,815 tons per year. On unpaved roads in Harris County the $PM_{2.5}$ is estimated at 10.0% of PM_{10}, and this fraction is used to generate $PM_{2.5}$ numbers. The data that was used to complete this section came from EPA's Menu of Control Options,[14] EPA's Control Measures Database for Stationary Sources,[15] an Economic Feasibility Analysis prepared by Sierra Research, Inc. for the San Joaquin Valley,[16] the San Joaquin Valley PM 2012 Plan,[17] Pima County's Dust Control Pamphlet,[18] a manual on Controlling Fine PM assembled by state and local regulators, [19] a

Fugitive Dust Handbook developed by Countess Environmental,[20] and Top Ten Dust Control Techniques developed by the State of Alaska.[21]

The options for controlling $PM_{2.5}$ from unpaved roads listed below. The items with an asterisk are regulated in San Joaquin Valley, California under Rules 8061 and 8071.

1. Apply Water to the Unpaved Road

This is the simplest and cheapest way to address dust from unpaved roads; however, it is also the least effective. Water causes particles in the soil to stick together, but it also evaporates quickly. As a result most of the effectiveness of reducing particulate matter is lost in the first hour. The overall efficiency is only 18.1% during the day, and water must be reapplied each day.

2. Apply 4 Inches of Gravel

The next step is to physically cover the unpaved road to trap dust particles. Applying 4 inches of gravel is 84% efficient at reducing PM_{10}. The cost for emission reduction is estimated at \$6,793-\$67,932/ton of PM_{10}.

3. Apply a Dust Suppressant

Dust suppressants cover a wide range of chemicals that have been used to bind fine particles on to larger ones. They fall into categories of petroleum-based, organic non-petroleum, electrochemical stabilizers and synthetic polymers. They have a wide range of prices and their effectiveness is quoted at anywhere between 41.4 – 90.6% at reducing PM_{10}. For this base case we assume that the annual cost to place a dust suppressant on a mile of road is \$10,000 and the efficiency is 60%.

4. Apply a Chemical Stabilizer

A chemical stabilizer is another form of a dust suppressant. In this case the base case calculations are derived from a study developed by Sierra Research which identified the annual cost of the chemical stabilizer to be \$16,480 per mile (2013 dollars) and found that a specific emulsion had an efficiency of 84%.

5. Limit Visible Dust Emissions to 20% Opacity

Limit visible dust emissions to 20% opacity in high dust areas and require stabilized surfaces on unpaved parking areas receiving up to 100 trips per day.*
This control is 85% efficient at reducing PM_{10}.
The cost for emission reduction is estimated at \$5,941-\$34,648/ton of PM_{10}.

6 Limit Vehicle Speeds to 25 mph*

This control is 1-24% efficient at reducing PM_{10}.
The cost for emission reduction is estimated at $1,227/ton of PM_{10}.

7. Paving Unpaved Roads and Parking Lots in Urban Areas*

Paving unpaved roads creates a seal and is provides the greatest reduction of particulate matter. Either a high quality asphalt or Portland concrete can be used. This approach is greater than 90% efficient at reducing PM_{10}. The cost for emission reduction ranges from $2,454-$6,725/ton of PM_{10}. These estimates originally made in 2003 assumed a cost of $400,000 per mile to pave an unpaved road. The road was assumed to last 25 years.

8. Identify Measures to Reduce Traffic Flow

No data is available for estimated efficiency or cost per ton of PM reduced.

Also note that in the San Joaquin Valley, California all new roads in urban areas are required to be paved according to Rule 8061.

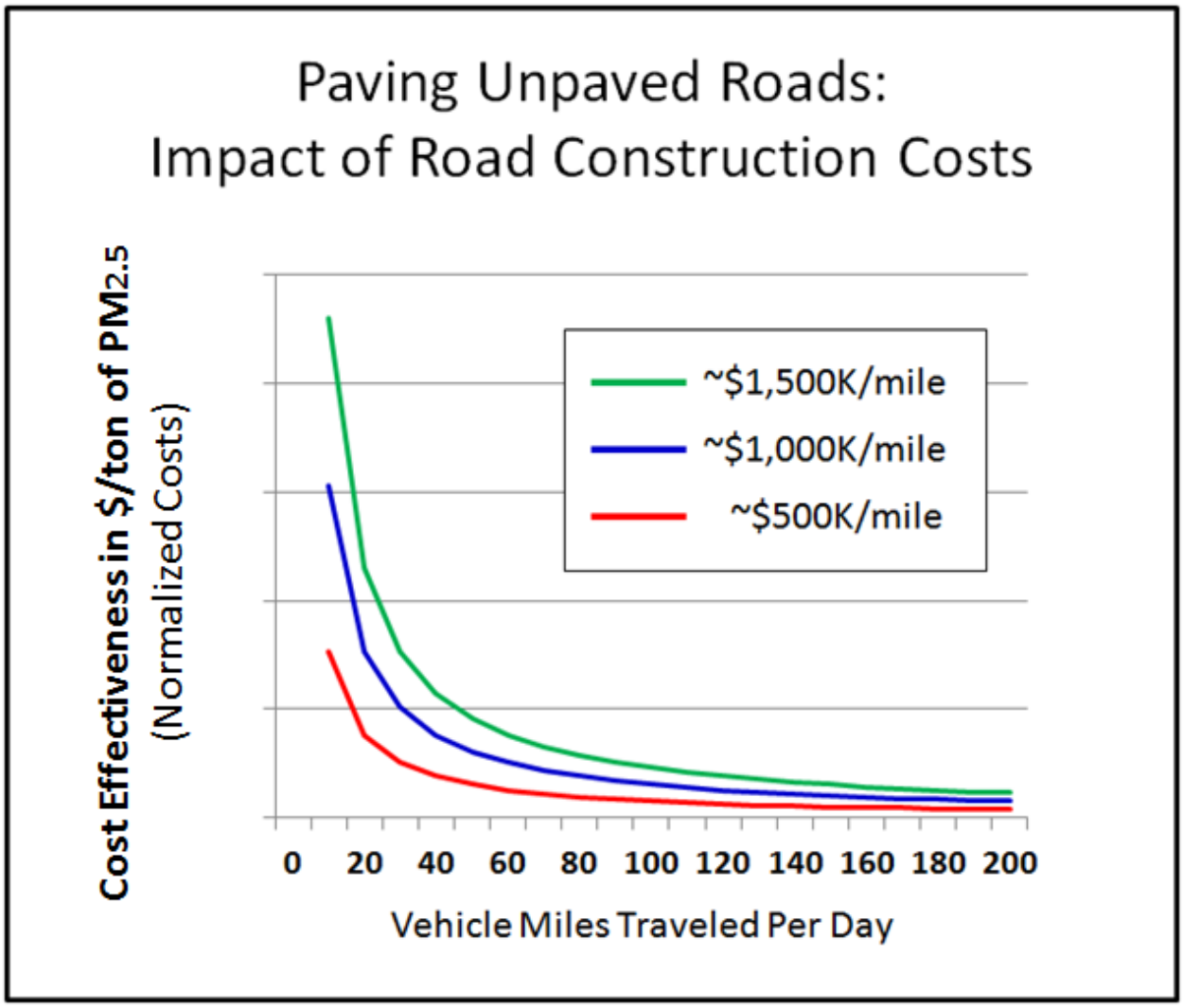
E. Cost Effectiveness

Cost effectiveness is impacted by a number of different factors. For example, one mile of unpaved road which has only one car traveling on it per day, generates relatively few emissions when compared to the same road with 100 cars traveling on it per day. If the road is paved, then there are substantial costs involved and relatively little benefit with one car per day when compared to the emissions reduced on the same road that has 100 cars per day. In general paved roads are more cost effective if they have more traffic because it costs less per ton of pollutant reduced.

There are other factors that must be considered. For example, paving a road is generally considered an expensive alternative, but paving can last for 25 years. Another method used to keep down unpaved road dust is to water the road, however watering is not as effective as paving, and it must be repeated daily (at least when it doesn't rain). If the road was watered every day for 25 years, it would cost much more than paving it. However, it might cost $500,000 to pave a mile of unpaved road, whereas watering a road would cost less than $100/day. Not every road can be paved due to budget constraints, but a decision might be made to water the roads at some frequency. Another consideration may be the impact of a drought conditions. These conditions will create more particulate matter, since the roads will be drier. On the other hand, water may be more expensive or needed for public and agricultural uses, etc. and that may influence whether or not to use it on unpaved roads.

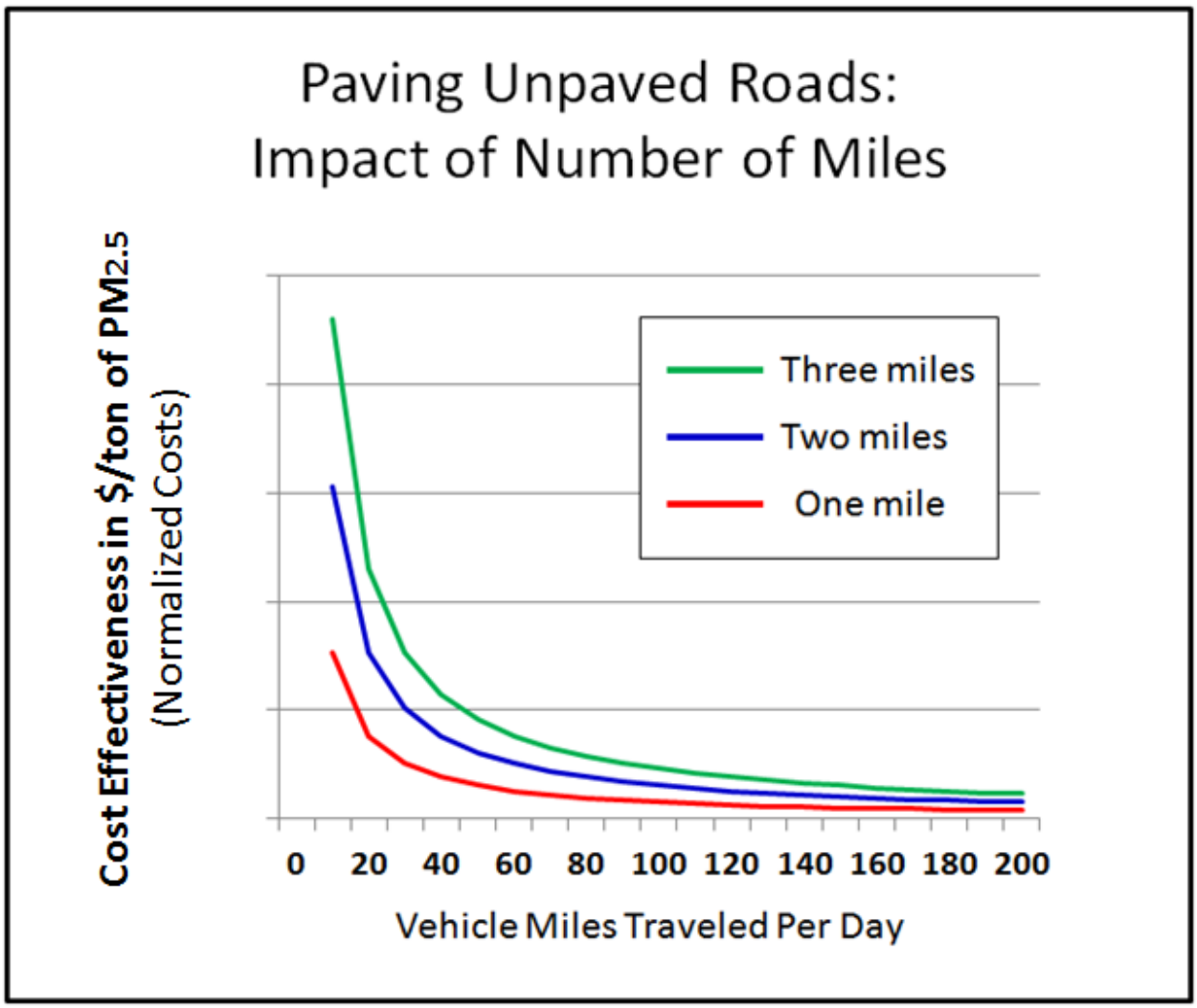
These and other issues are presented in the series of cost curves on the following pages in Figures 4 – 13, to demonstrate the variability of cost effectiveness based on a range of items. This variability shows how selecting the right control strategy is often very difficult.

Figure 4.



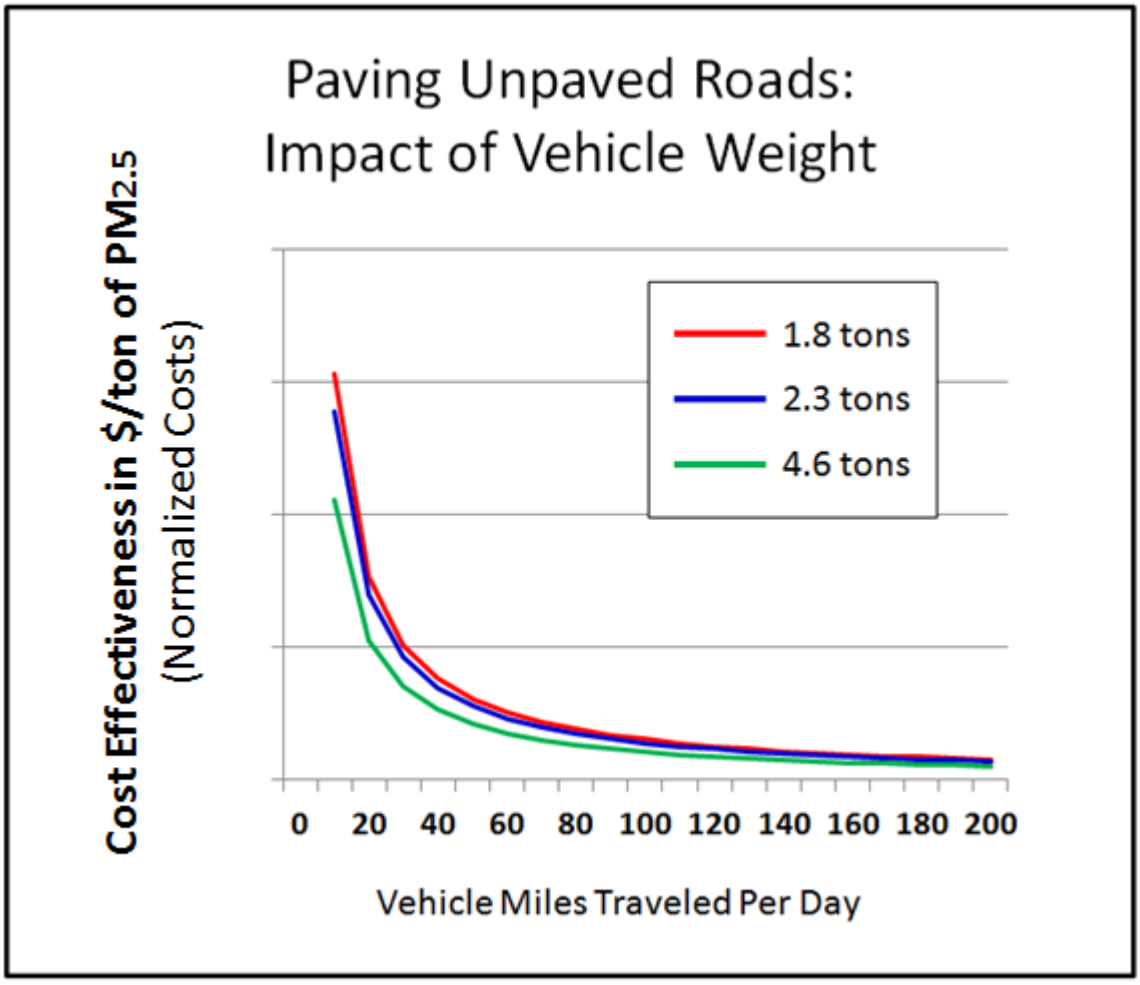
Road construction costs vary depending on local conditions. One source estimates approximately $500K to pave one mile of road. This plot shows how cost efficiency is impacted if the actual costs are 2 or 3 times that amount as a function of vehicle miles traveled per day.

Figure 5.



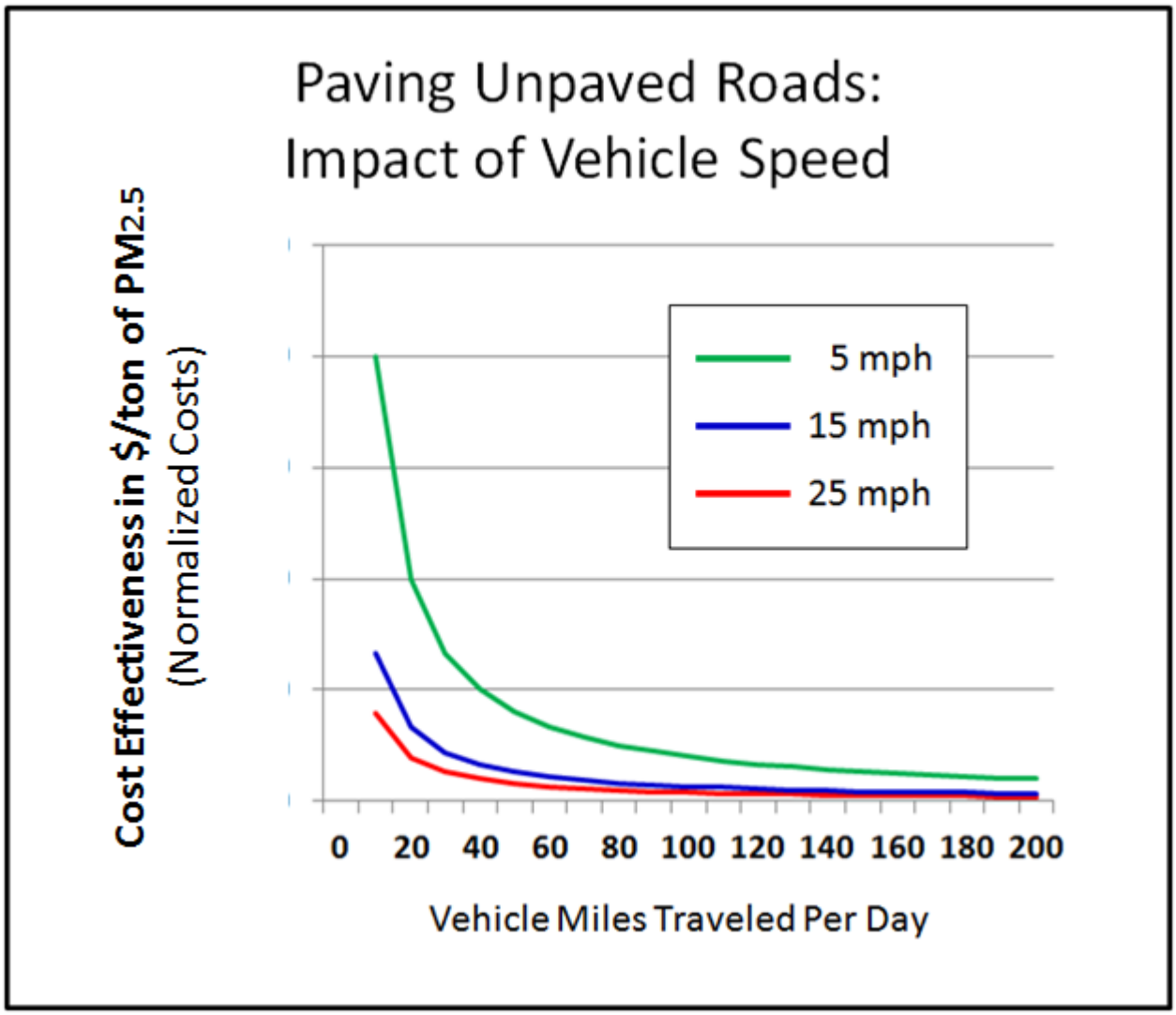
If 100 miles are driven on one mile of paved road, or 50 miles are driven on two miles of paved road, or 33 1/3 miles are driven on 3 miles of paved road, the VMT for each is 100 miles/day. They all save the same amount of emissions, however it costs much more to pave 3 miles than one mile, so it is most cost effective to pave the unpaved roads that are most travelled.

Figure 6.



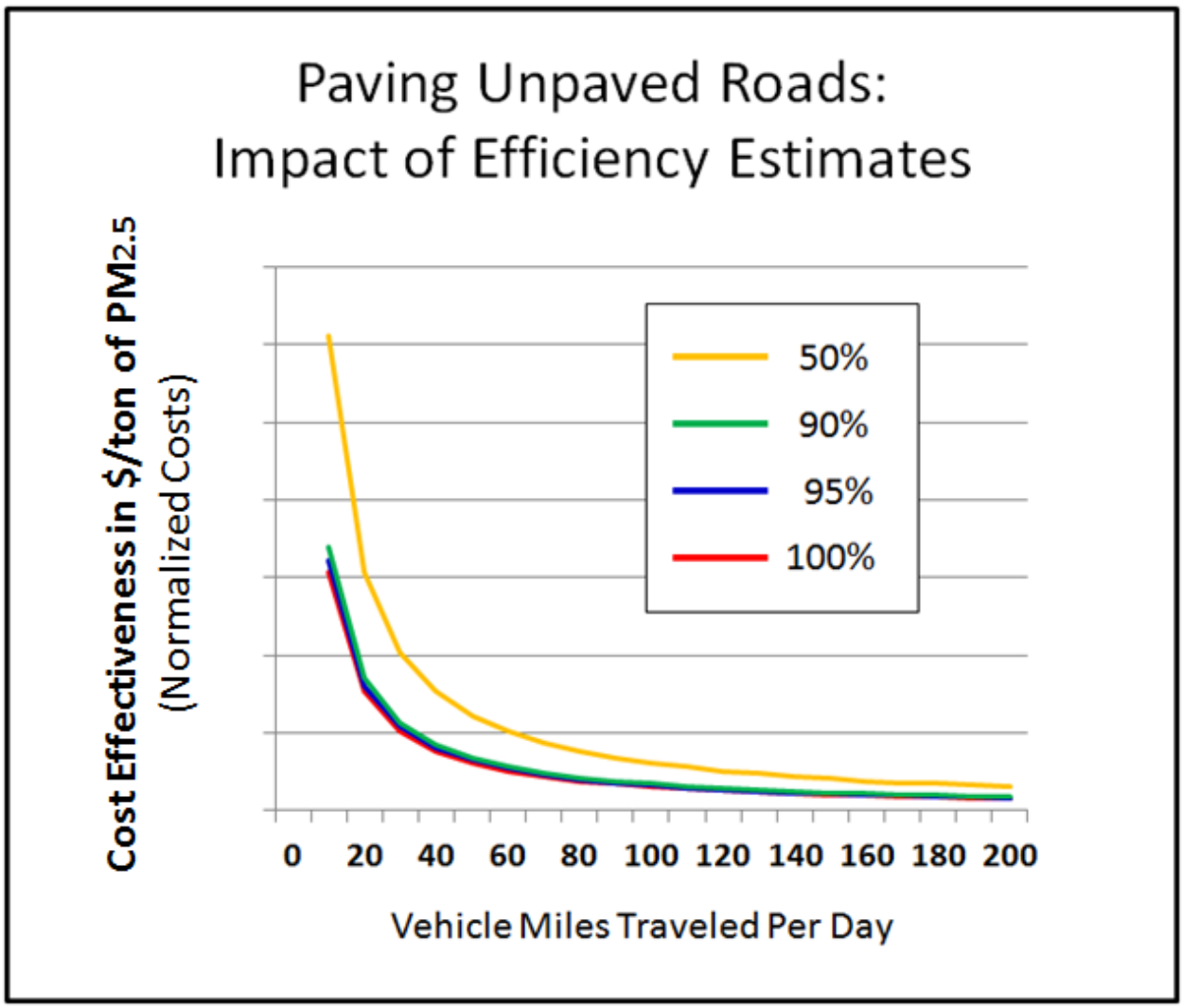
Larger, heavier vehicles kick up more dust/PM than lighter vehicles. A 1.8 ton vehicle is "typical" weight for traveling down a dirt road. A 2.3 ton vehicle is the lower end average for a 3 axle vehicle, and a 4.6 ton vehicle average is shown for comparison. Heavier vehicles create more dust, so paving the roads for them is more cost efficient. However, some vehicles/ equipment is so heavy that they require more robust – and expensive, paving.

Figure 7.



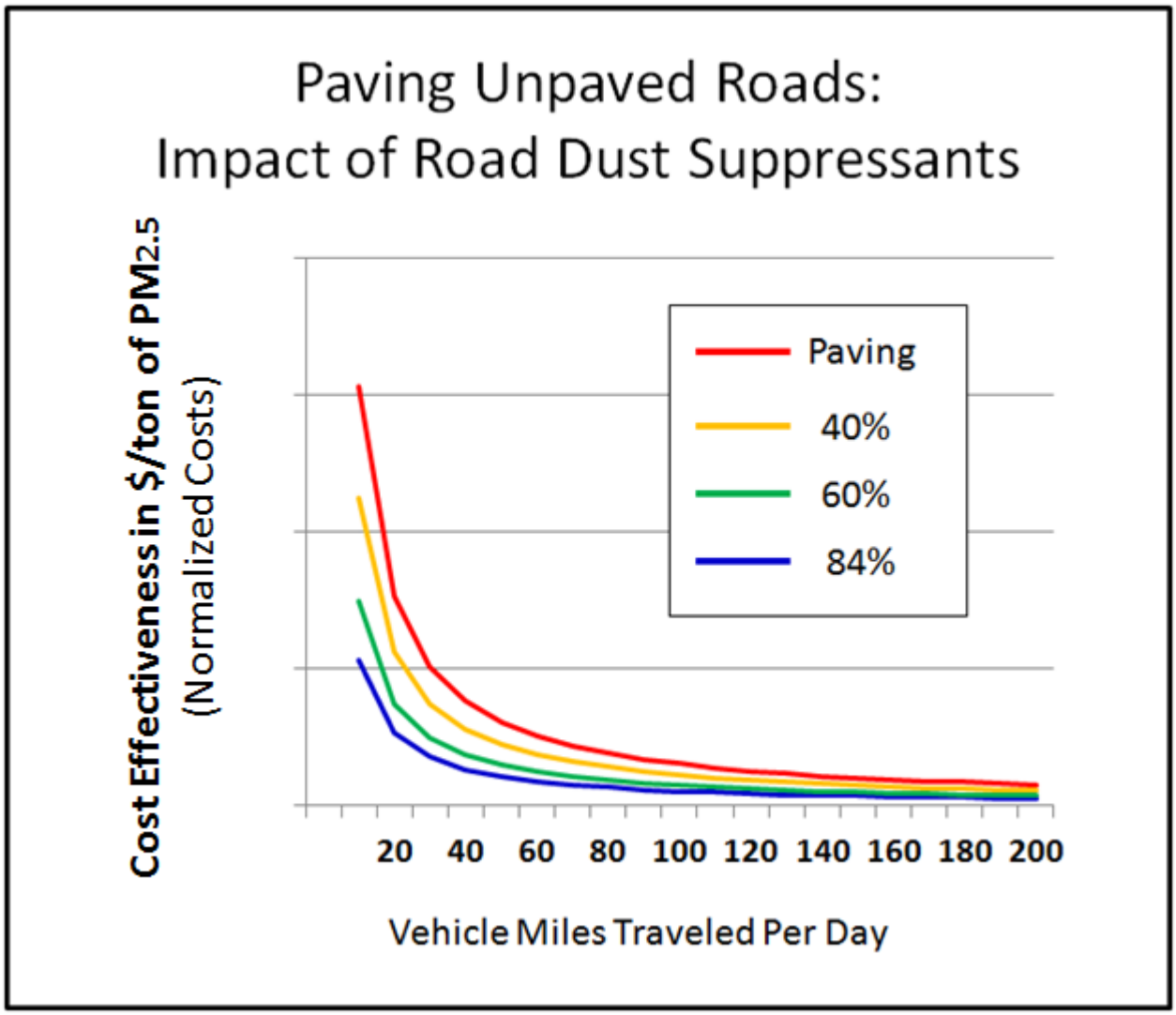
If the average speed is only 5 mph, less PM will be created than for vehicles traveling at 25 mph. Therefore paving those roads (or parking lots) will not reduce PM as much as paving unpaved roads where traffic flows at higher speeds.

Figure 8.



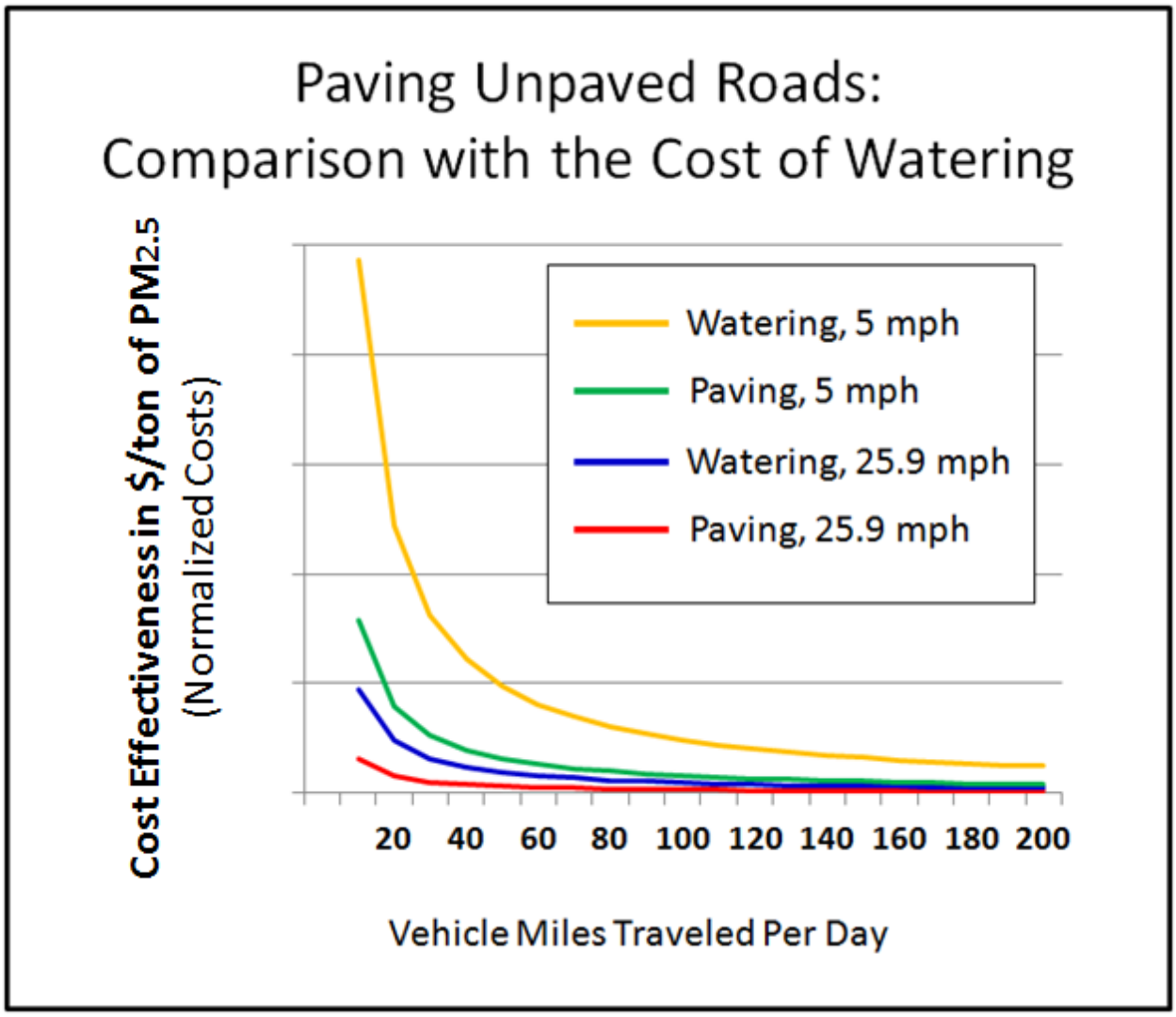
The published values for PM reduction efficiency by paving unpaved roads range from 90 to 100%. These curves indicate that different efficiencies quoted have a small price differential. A 50% efficiency case is shown to demonstrate how costs would increase, however none of the published literature indicates such a low PM reduction efficiency for paving unpaved roads.

Figure 9.



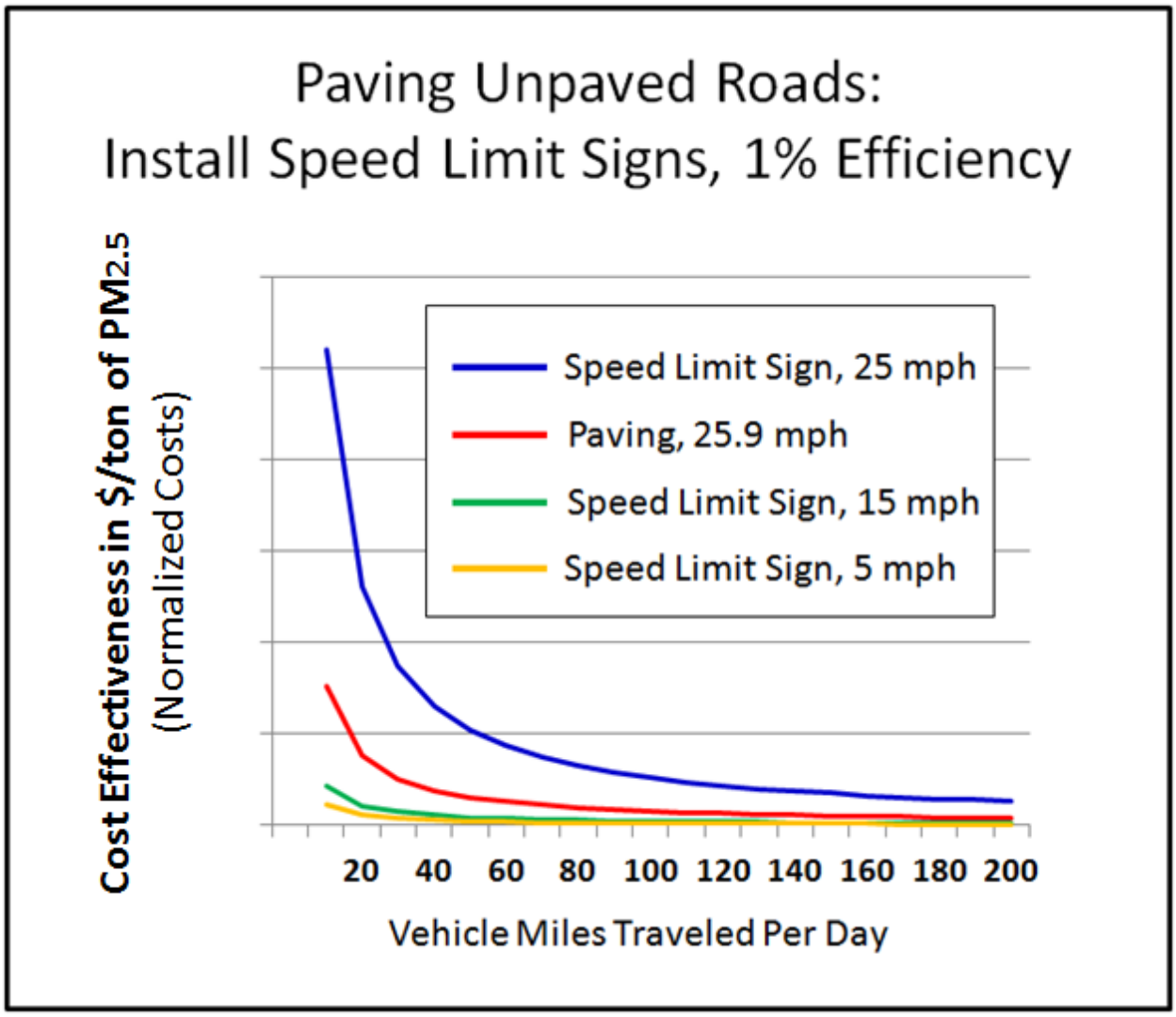
Paving roads has the highest efficiency in terms of reducing PM by somewhere between 90-100%, however chemical dust suppressants have been shown to have efficiencies reaching 84%. Other dust suppressants have lower efficiencies (40% and 60% efficient examples are shown here), but can still have lower costs than paving. However, the dust suppressants have to be reapplied at least annually.

Figure 10.



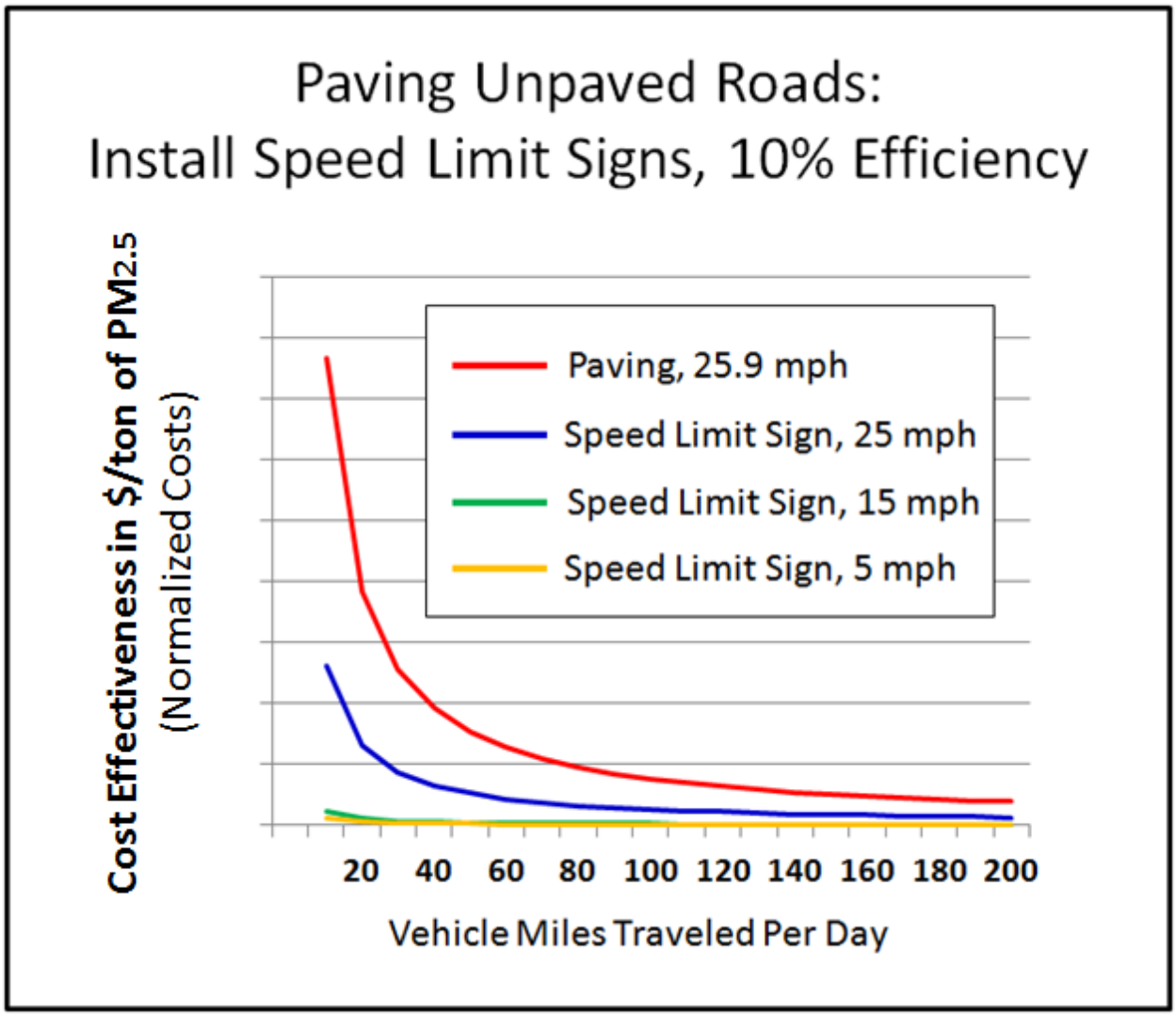
Watering is much less cost effective than paving and must be repeated every day; however paving requires a substantial upfront investment of at least $500K/mile. However, watering can be done selectively, on dry days, for less than $100/day. Paving or watering at lower speeds does not reduce PM as much as at higher speeds, and as a result is less cost effective.

Figure 11.



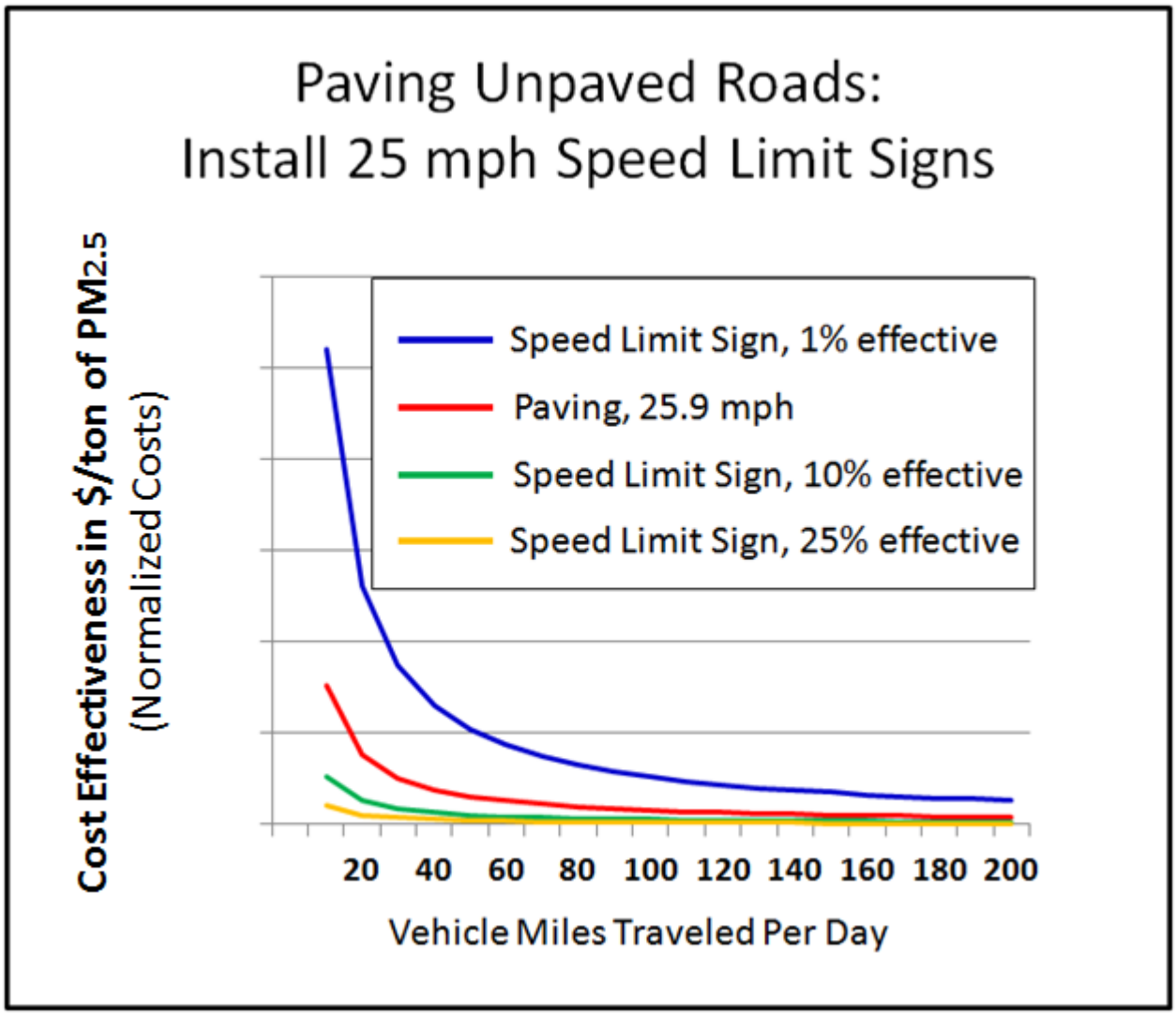
Installing speed limit signs is relatively cheap; however enforcing the posted speed limits is difficult. Literature cites anywhere from 1 – 25% effectiveness based on the level of compliance with the posted speeds. Lowering the speed from 25 mph to 15 mph or 5 mph can significantly reduce costs and improve the cost effectiveness.

Figure 12.



Installing speed limit signs is relatively cheap, however enforcing the posted speed limits is difficult. Literature cites anywhere from 1 – 25% efficiency based on the level of compliance with the posted speeds. Lowering the speed from 25 mph to 15 mph or 5 mph can significantly reduce costs and improve the cost effectiveness.

Figure 13.



Installing speed limit signs is relatively cheap; however enforcing the posted speed limits is difficult. Literature cites anywhere from 1 – 25% effectiveness based on the level of compliance with the posted speeds. As efficiency increases from 1 – 25%, the cost per ton of PM reduced goes down.

A table which provides the cost effectiveness in dollars/ton of $PM_{2.5}$ for some of the key control strategies is provided in Table 1. Details on how the calculations were derived from costs normally associated with PM10 controls are provided in Appendix C.

Table 1.

$PM_{2.5}$ Control Methods and Cost Effectiveness for Unpaved Roads

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Pave Roads	95%	$ 85,668
Chemical Stabilizer	84%	$ 29,545
Dust Suppressants	60%	$ 40,933
Apply 4" of Gravel	40%	$ 61,400
Apply Water	18.1%	$ 669,808

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

As indicated in the previous section, there are many variables to take into consideration when trying to identify the most cost effective means to reduce particulate matter. This section provides some suggestions based on selecting assumptions that may approximate what is seen in the field on average. Care should be taken not to apply the factors everywhere, and identify the cost effectiveness on a case by case review.

According to the most recent inventory completed as part of this project, unpaved roads are responsible for 48,354 tons of PM_{10} emissions and 4815 tons per year of $PM_{2.5}$ emissions. As noted previously, any reduction of PM_{10} (which is what these equations are based on) can be used to assume a similar percentage reduction in $PM_{2.5}$. Using the cost information provided above for each of the control measures listed yields the following results:

Table 2.

Cost to Reduce Unpaved Roads $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Pave Roads	95%	$41,249,142	$103,122,855
Chemical Stabilizer	84%	$14,225,918	$35,564,794
Dust Suppressants	60%	$19,709,240	$49,273,099
Apply 4" of Gravel	40%	$29,564,100	$73,910,250
Apply Water	18.1%	$322,512,552	NA

In addition to the assumptions for efficiency listed above, these calculations assumed that there were 30 vehicle miles traveled (VMT) per day on a mile of road and that the average speed was 25.9 mph. The cost to pave an unpaved road was based on estimates taken from the San Joaquin Valley Air Pollution Control District and updated in EPA's Menu of Control Measures. The updated values assume that in 2013 it would roughly $500,000 per mile to pave a road. Prices for paving roads are likely to vary considerably depending on local conditions.

Applying a chemical stabilizer or watering may be a better alternative in some cases, depending on the application and the severity of the problem. These are required by the San Joaquin Valley Air Control District (SJVAPCD) in high traffic areas. SJVAPCD is a nonattainment area for a number of pollutants, including $PM_{2.5}$. The Hot Asphalt case assumes application costs are similar to annual applications of a chemical stabilizer, and only 60% efficiency. Applying 4 inches of gravel is also assumed to have similar costs to an annual application of chemical stabilizer, but also assumes only 40% efficiency.

A "20% Maximum Opacity" allows for freedom to select whatever controls are needed to achieve the specified opacity. However there are drawbacks associated with keeping up with the monitoring and enforcement.

As indicated previously, applying water on a daily basis for long periods of time can be very expensive. This control method may be useful in some circumstances for a limited amount of time, but should be used judiciously. A 25% reduction is not considered possible because the efficiency for daily applications is estimated at 18.1%.

The speed limit control has been estimated at 1% efficient by some sources, which means that it could not obtain a 10% or 25% overall reduction even if all unpaved roads were set at 25 mph. However it is easy and fairly cheap to install speed limit signs. But at 30 VMT the cost efficiency is estimated to be$17.382/ton of PM reduced.

If a 10% or 25% reduction of $PM_{2.5}$ is needed, then it is likely that a mixture of the listed controls will be required.

Note that the discussions above for unpaved roads can be applied towards unpaved parking areas as well. Consideration should be given to how often the parking areas are used and the level of activity during use.

VIII. Construction



Photographed by Alex Cuclis

A. Source Definition

Construction emissions generally fall into the category of road construction and "other" construction related to building homes, offices or other infrastructure. Road construction includes all activities related to preparing the ground and building all types of roads, large and small. Typically roads are classified as arterials, collectors and local roads, depending on the amount of traffic flow. Roads vary according to surface type, lane width and location (urban or rural). The work can be new construction or lane widening. The work may be performed to address many different concerns related to expected traffic flow, vehicle weight, speed and safety issues. Emissions in this category are associated with dust that is generated with earth moving and other construction equipment and vehicles used to build roads. Particulate matter from diesel engine exhaust is not included in this category and is captured in the mobile off-road category.

B. Description of how the source emits $PM_{2.5}$

Construction particulate matter emissions are created by many different activities including land clearing, drilling, blasting, ground excavation, earth moving and paving. PM generated by construction varies substantially throughout the various stages of projects and depends on the level of activity and specific operations. Emissions estimates are based on the size of the area being worked, the level of activity and the length of time the activity lasts. Given the nature of

construction projects, emissions are expected to be more variable than PM emissions for other activities such as paved and unpaved roads. Most roadway work requires extensive earthmoving and heavy construction vehicle travel, creating PM emissions that are much higher than observed in other construction projects.[22] The $PM_{2.5}/PM_{10}$ ratio for fugitive dust from construction and demolition activities is 0.1 based on the analysis conducted by the Midwest Research Institute (MRI) on behalf of the Western Regional Air Partnership (WRAP).[20, 23] Note that emissions from diesel engines associated with construction work are included in mobile off-road emissions. It should also be noted that the San Joaquin Valley, which has substantial challenges with particulate matter, has found that construction dust is responsible for less than 5% of all $PM_{2.5}$ emissions and is considered "insignificant".[17]

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

Estimates that are used for construction on a state-wide basis and reported to EPA can vary substantially from county to county. EPA develops a National Emissions Inventory (NEI) based on some national averages that are applied to specific locations. Improved values can be obtained by collecting data from the state instead of using federal department of transportation numbers as well as other sources. It is always best to obtain local information whenever possible. In the most recent review the total $PM_{2.5}$emissions in Harris County from road and other construction were found to be 1843 tons.[11]

2. Capacity/Usage Rate/Duty Cycle

In this case "capacity," or the total amount of emissions, is related directly to the area that is used for the construction effort. The effort required to build a large superhighway with overpasses is substantially higher than paving a small rural road. The emissions estimates account for these differences by computing the total acres that are worked on in the project. Emissions will vary depending on the number and kinds of equipment to prepare and build each road; however emission estimates are generally based on emission factors proportional to the area that will be disturbed and the duration of activity of the construction project.

3. Condition

Construction occurs on very different terrains such as fields, forests, sandy beaches, level plains, rocky mountains, etc. The estimating techniques that have been developed assume that the contribution to PM will be related to the area of ground that is disturbed and the amount of time the activity lasts. For road construction the total area is estimated based on the amount of road to be paved including shoulders and other areas in which dirt is disturbed during construction.

4. Fluctuations due to time of day, day of week and time of year

Particulate matter emission fluctuations related to construction are dependent on the items mentioned above: area of land that is disturbed, level of activity, and duration of the construction project. Most of this activity occurs during normal working hours, when construction typically occurs.

5. How is the $PM_{2.5}$ emission factor determined?

MRI developed an average emission factor of 0.11 tons of PM_{10} per acre-month of activity in 1996. This number assumes that routine dust suppression such as watering is being applied. Emissions would have to be doubled if dust suppression methods were not used. The MRI report also uses a worst case scenario for large scale construction activities, providing an emission factor of 0.42 tons PM_{10}/acre-month.[16, 24] Typically road construction is considered to produce the highest amount of PM when compared to other construction projects because road building activities require a substantial amount of earth moving equipment.

D. Control Methods, Efficiencies and Costs

PM control efficiencies are reported in the literature in terms of PM_{10}, however, "It should be noted that Midwest Research Institute (MRI) found no significant differences in the measured control efficiencies for the $PM_{2.5}$ and PM_{10} size fractions of unpaved road emissions based on repeated field measurements of uncontrolled and controlled emissions. Thus, without actual published $PM_{2.5}$ control efficiencies, the user may wish to utilize the published PM_{10} values for both size fractions."[9] Some adjustments have to be made in the calculations because removing one ton of PM_{10} is not the same as removing one ton of $PM_{2.5}$. In a review of dust composition of particulate matter from paved roads, unpaved roads and construction it was found that the ratio of PM2.5/PM10 was 0.15 for paved roads and 0.10 for unpaved roads and construction.[22] Based on these finding it was assumed for every one ton of PM_{10} reduction, one-tenth of a ton $PM_{2.5}$ of would be reduced. The cost per ton $PM_{2.5}$ has been adjusted accordingly.

In the case of construction, the first step is to verify how much "routine" watering or other dust suppression techniques are actually employed at the construction sites. The calculations that follow assume that watering or dust suppression is being employed regularly.

In 2003 Sierra Research published the results from a number of studies on construction emissions.[16] The following control options were updated and evaluated for this project:

1. Apply a Dust Suppressant/Chemical Stabilizer

In this scenario Sierra Research determined the cost and emissions savings associated with placing a polymer emulsion around a two story building that was being demolished. The building had a footprint of 1000 square feet. The area to be treated with the polymer

emulsion/dust suppressant was 52,649 square feet. The cost to apply the treatment was estimated at $4,188 per demolition. The baseline emissions, which included the assumption that the area was being watered twice per day to keep dust down, were 77.54 lb PM_{10}/6 months. The control option efficiency for the polymer emulsion was cited as 84%. After making corrections for converting from PM_{10} to $PM_{2.5}$ and accounting for the transport factor adjustment and inflation, the cost effectiveness was calculated to be $2,698,614/ton $PM_{2.5}$.

2. Apply Water as a Dust Suppressant

In this scenario Sierra Research determined the cost and emissions savings associated with applying additional water to disturbed soils at the end of each day of demolition clean up. The cost to apply the water was estimated at $96.60/day. The baseline emissions were 0.26 lb PM_{10}/day. The control option efficiency for water application was cited as 10.4%. By making the same assumptions described in the previous option, the cost effectiveness was calculated as: $149,925,000/ton $PM_{2.5}$.

Since the cost of this option is so high, the control option efficiency is low and the application is limited to watering after hours and thus only reducing nighttime emissions, it has not been included as an option in the database. It should be noted that baseline emissions for construction typically assume that there is a routine watering plan in place that is being followed.

3. Prohibit Activity When Winds are Greater than 25 mph

In this scenario Sierra Research determined the cost and emissions savings associated with prohibiting construction activities when winds are greater than 25 mph. They used the demolition of a single story 1000 ft^2 residence as an example. The cost in this case includes lost capital for not being able use equipment, idle labor as well as additional watering required on the high wind day. The total cost of this measure was estimated at $1,690/day. The baseline emissions were 99.7 lb PM_{10}/high wind day. During high winds watering at a frequency of every 0.4 hours would normally have a control option efficiency of 94%. However, if earthmoving activities are stopped during high winds, the control option efficiency increases to 98%. The improvement gained by prohibiting activity is 4%. Making the same assumptions indicated previously, the cost effectiveness was calculated as: $17,728,855/ton $PM_{2.5}$.

Since the cost effectiveness of this option is high, the net control effectiveness is low (only 4%) and the applicability is limited to high wind days, it was not included in the list of control options in the database.

4. Dust Monitoring

This option estimated the cost and emissions savings associated with implementing dust control measures for construction projects where more than 40 acres of soil are disturbed. Sierra Research assumed that extra watering would be provided in such a project and that a trained on-site coordinator would direct the dust control activities to maintain compliance. The cost to apply the water and have a trained on-site coordinator at a 50 acre site was estimated at $67,639. The baseline emissions calculated were 17.6 tons. The extra watering associated with this scenario was said to reduce the emissions by 586 pounds or 0.29 tons. Reductions would only occur on the 5% of the days where the monitoring system would record instances of high opacity. The net control efficiency was calculated as 1.08%.
The cost effectiveness was calculated as $233,238/ton $PM_{10.}$

Because this cost effectiveness value is so high (and will be much higher when adjustments are made for $PM_{2.5}$, the control option efficiency was so low and the application so infrequent, it was not included as a default option in the database.

5. Monitor Soil Moisture

This scenario determined the cost and emissions savings associated with requiring soil to be 12% water before any earthmoving/construction begins. They assumed that a sprinkler system would have to be installed. They assumed that water trucks would be on site already, but that additional trucks would be needed. The cost to apply the water was estimated at $1,218 per 40 acre site if a sprinkler system was used. The cost to apply the water was estimated at $3,152 per 40 acre site if extra water from water trucks was used. The control efficiency was 68.6%. The sprinkler system had a cost effectiveness of $453,231/ton $PM_{2.5}$ and the water truck option had a cost effectiveness of $1,173,053/ton $PM_{2.5.}$

6. Limit on-site vehicle speeds to 15 mph

In this scenario Sierra Research determined the cost and emissions savings associated with limiting the speed of all vehicles at a construction site to 15 mph. This example is based on 40 acre residential construction site. The assumption is that there is a linear relationship between the emission factor and the speed. Also assumed is a 50% compliance rate. The cost to apply the water was estimated at $131.25/project for monthly inspections at on a 6 month project. The cost effectiveness was calculated as $17,833/ton $PM_{2.5.}$

Compliance rates of 50% may be difficult to achieve and the bulk of the emissions from construction is not from vehicles traveling at higher speeds, as would be expected for unpaved roads. Since there are uncertainties here and the application may be limited because of the fraction of PM generated by vehicles travelling greater than 15 mph, this was not included in the database. It can be entered as a “new control option” if the user so desires.

7. Post Speed Limit Signs for all sites larger than 10 acres

In this scenario Sierra Research determined the cost and emissions savings associated with posting 15 mph speed limit signs on unpaved areas. This example is based on 50 acre residential construction site and posting 4 signs at the site. The assumption is that there is a linear relationship between the emission factor and the speed. Also assumed is a 75% compliance rate. The cost to install the signs was estimated at $720/project. The control option efficiency for water application was cited as 18.74%. (Note: This is actually due to a change in emission factor from 2.0 to 1.35 lb PM_{10}/VMT based on the new lower speed.). The cost effectiveness was calculated as $52,220/ton $PM_{2.5.}$

Although according to this analysis posting speed limit signs is a very cost effective option, the compliance rate of 75% is very optimistic. Even at a lower compliance rate the option is appealing, however since vehicle speed is not as much of an issue in construction as it is in unpaved roads, this has not been included in the database. It can be entered as a "new control option" is desired by the user.

8. Require Dust Control Plans

In this scenario Sierra Research determined the cost and emissions savings associated with requiring dust control plans for a 10 acre or greater residential construction project. This scenario assumes training is provided for an on-site dust control coordinator and increased water application. The cost to apply the water was estimated at $32,552 per 10 acre project The control efficiency for water application was cited as 25%. The cost effectiveness was calculated as: $359,982/ton $PM_{2.5.}$

9. Require Notification of Earthmoving Operations

In this scenario Sierra Research determined the cost and emissions savings associated with notifying the district of earth moving activities. Sierra Research assumed additional watering and other dust control activities would occur as a result of the notification process. The cost to notify was estimated at $100 per10 acre project. The control option efficiency for district notification was cited as 5%. The cost effectiveness was calculated as $51,811/ton $PM_{2.5.}$

For comparison purposes the items chosen to place in the database were options 1 (chemical stabilizer), 5 (soil moisture with a sprinkler and with a truck), 8 (require dust plan) and option 9 (require notification of earthmoving operations). Option 9 is actually only 5% effective and thus cannot achieve the either 10 or 25% reductions alone. Other options can be entered into the database as desired by the user.

Some common other control methods mentioned in the literature include:

Use a water truck or sprinklers to moisten soil that is graded, dumped or hauled.
Minimize areas of clearing and grubbing.
Minimize time between PM creating activities (preparing the road) and completion (e.g. paving).
Minimize the drop height from tractors, cranes, etc.
Cover loads on haul trucks.
Pave haul roads and exit aprons.
Brush off mud from wheels, wheel wells, running boards and tail gates.
Wash wheels immediately prior to exiting. Consider a sedimentation basin.
Use fabrics or plastics for covering piles of soil and debris.[23]

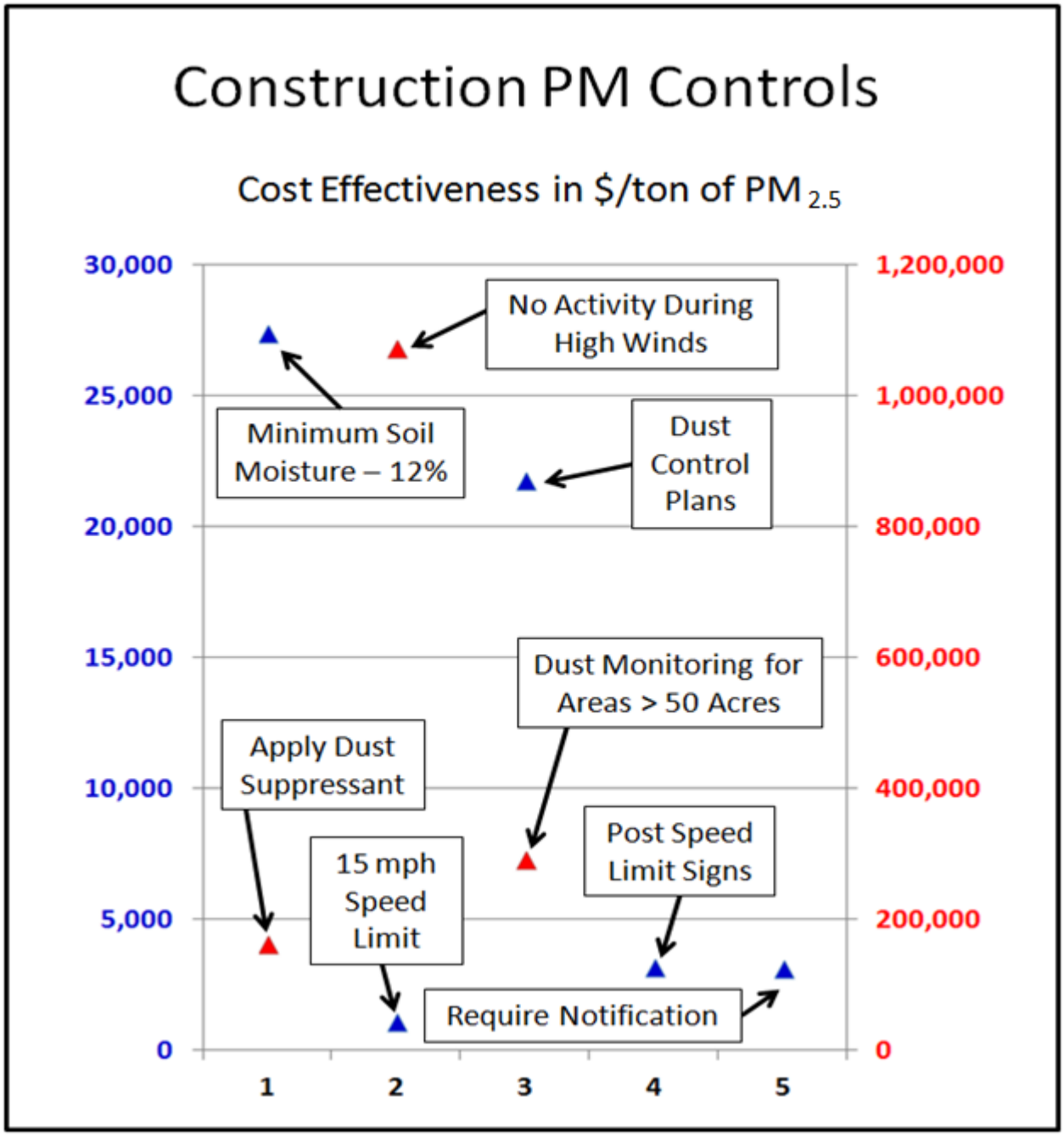


Picture taken from the Harris County Flood Control District's publication, "Riding the Ways of Change: 60 Years of Service," excavation of regional detention basin on White Oak Bayou, 1988. Used with permission.

E. Cost Effectiveness

There are a number of factors that impact the cost effectiveness of construction controls as has been indicated in the previous discussion. The cost effectiveness of various particulate matter controls vary widely, from under $5,000 to over $1,000,000, as is illustrated in the chart below.

Figure 14.



A table which provides the cost effectiveness in dollars/ton of $PM_{2.5}$ for some of the key control strategies is provided in Table 3. Details on how the cost effectiveness calculations were derived are provided in Appendix C.

Table 3.

$PM_{2.5}$ Control Methods and Cost Effectiveness for Construction

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Chemical Stabilizer	84.0%	$ 2,670,425
Soil Moisture/Sprinkler	68.6%	$ 453,231
Soil Moisture/Truck	68.6%	$ 1,160,842
Dust Control Plan	25.0%	$ 356,245
Earth Moving Notifications	5.0%	Not possible to reach 10%

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

There are a total of 1843 tons of $PM_{2.5}$ emissions associated with construction work in the most recent inventory.[11] The following table summarizes the cost to reduce emissions by 10% and 25%.

Table 4.

Cost to Reduce Construction $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Chemical Stabilizer	84.0%	$492,159,328	$1,230,398,319
Soil Moisture/Sprinkler	68.6%	$82,673,294	$206,683,235
Soil Moisture/Truck	68.6%	$213,943,181	$534,857,952
Dust Control Plan	25.0%	$65,655,954	$164,139,884
Earth Moving Notifications	5.0%	Not Possible	Not Possible

The most cost effective control option that can be applied everywhere is to implement a dust control plan, with a cost effectiveness value of $356,245/ton.

To reduce $PM_{2.5}$ emissions by 10% or 184.3 tons, the cost would be 184.3 tons * $356,245/ton = $65,657,612.

To reduce $PM_{2.5}$ emissions by 25% or 461 tons, the cost would be 461 tons * $359,986/ton = $165,953,546.

IX. Paved Roads



Picture taken from "Your Guide to Harris County Government: Winter 2013 Revision", Steve Radack, Commissioner, Harris County Precinct 3. Used with permission.

A. Definition

Paved roads are those emissions that come from road and tire wear or from re-suspension of loose material on road surfaces. In Harris County $PM_{2.5}$ emissions from unpaved roads is 4815 tons but $PM_{2.5}$ emissions from paved roads is only 2317 tons.[11] There are millions more paved roads in Harris County than unpaved roads and much more traffic on each mile of paved road. However the dust and resultant particulate matter from unpaved roads is far higher than the particulate matter created by traffic on all paved roads. This is why paving an unpaved road is such an effective way to reduce particulate matter.

B. Description of how the source emits $PM_{2.5}$

Area source PM_{10} and $PM_{2.5}$ comes from loose material on the road surface being lifted up, break wear and tire wear. Particulate emissions emanating from vehicle exhaust is categorized under mobile emissions and is controlled through federal standards for motor vehicles. Trackout is one contributing source to paved road dust and occurs when materials from unpaved roads and parking lots are carried onto paved road surfaces from other vehicles and then becomes airborne as more vehicles drive by the area that is impacted. The variables that have the greatest impact on emissions include the speed of the vehicles traveling on the road, the averaged daily traffic, the number of lanes, the fraction of heavy vehicles such as buses and trucks and the presence or absence of curbs, storms sewers and parking lanes. Note that the

EPA transportation model "MOVES" calculates the vehicle particulate emissions due to exhaust, brake wear and tire wear.[25]

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

The number of sources in measured by the total vehicle miles travelled (VMT). In Harris County the VMT is determined by the Texas Department of Transportation (TxDOT), the Houston Galveston Area Council (HGAC) and other contracted entities. HGAC enters the values into the EPA's MOVES model which converts the VMT information into pollutant emissions including particulates.

2. Capacity/Usage Rate/Duty Cycle

The emissions are impacted not only by the number of vehicles or traffic on the road, but also the size and weight of those vehicles. Another factor is the number of trackout points from construction sites, dirt roads, etc. More construction/roadway interface points will increase the amount of particulates on the paved roadways.

3. Condition

Particulate emissions are dependent on the "silt loading" (sL) of the road. Silt loading is the mass of the silt size material (equal to or less than 75 microns in physical diameter) per unit area of travel surface. The total road surface dust loading is total loose material that can be collected by sweeping of vacuuming. The silt fraction is determined by measuring the proportion of dry surface dust that passes through a 200 mesh screen. The silt loading is the product of the road surface dust loading and the silt fraction. Silt loadings are higher during early winter through spring months in parts of the country affected by snow and ice, due to the materials applied to the roads to reduce skidding. Another impact is due to rain. Areas that received more rain will have less road dust and therefore less particulate matter.[25]

4. Fluctuations due to time of day, day of week and time of year

There are changes during the day, week, and season in uses of unpaved roads due to changes in traffic. Activity and emissions are highest during morning and evening rush hours.

5. How is the $PM_{2.5}$ emission factor determined?

The particulate emission factor is represented by the following equation:

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

The particulate emission factor is a function of the silt loading, sL and the average weight of the vehicles, W. k is a particle size multiplier expressed in units such as lbs/VMT. Additional emission factors exist for break wear and tire wear and can be obtained from the MOVES model.

D. Control Methods, Efficiencies and Costs

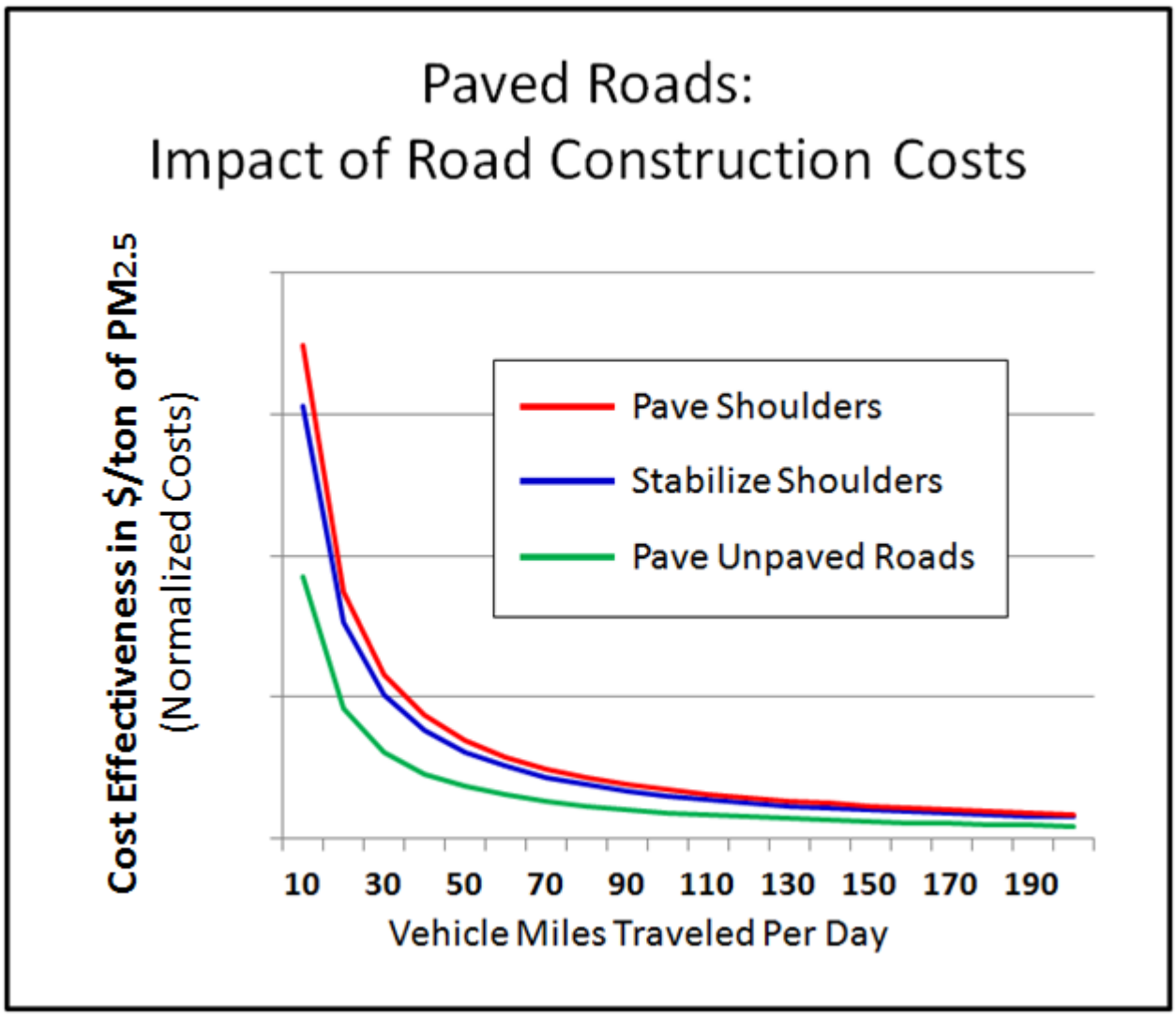
The best control methods for paved roads are those that can reduce silt loading. Note that street sweeping can actually increase silt loading and particulate matter. Some street sweepers are rated as "PM_{10} efficient sweepers", but they are generally considered to be ineffective for $PM_{2.5}$ materials, so these approaches have not been listed here. Although silt loading or re-entrainment of silt into the air can be reduced by reducing VMT, it is assumed that VMT is going to continue to increase in Harris County and that restrictions on traffic flow are not an option. The control methods identified below were selected because they have the best chance at reducing silt loading on paved roads at the lowest costs. These techniques were originally evaluated by Sierra Research.[16]

1. Pave New Shoulders

In this scenario all new or modified roads that have more than 500 vehicles traveling on them per day must have paved shoulders. It was assumed that 4 foot shoulders would be paved and that they would last for 20 years. We have selected an overall control efficiency of 60%, which is roughly midway between the efficiency estimated for truck wake (80%) and trackout (42%). Cost adjustments were made to convert the PM_{10} values to $PM_{2.5}$. Corrections were also made to adjust for 2014 dollars. Detailed calculations are provided in the Paved Road section of Appendix C. The resulting cost effectiveness was found to be \$282,001/ton $PM_{2.5}$

Paving shoulders is not as cost effective as paving unpaved roads as is shown in Figure 15.

Figure 15.



The cost effectiveness of paving the shoulders on paved roads (red) is shown in comparison to paving unpaved roads (green). The cost is higher for paving shoulders because fewer emissions are generated when compared to unpaved roads. Using a stabilizer or dust suppressant is slightly less expensive and has a much lower upfront costs than paving shoulders; however it must be reapplied at least once per year.

2. Pave Existing Shoulders

This control requires construction of 4 foot paved or stabilized shoulders on 50% of the highest traveled existing roads. Polymer emulsions often provide the best reductions for their cost. All of the variables regarding emissions and emission reductions were the same as shown in the previous option, Pave New Shoulders, including adjustments for particulate size and 2014 dollars. The resulting cost effectiveness was found to be $149,525/ton $PM_{2.5}$.

3. Install Trackout Control Devices

A trackout control device is a device that removes the mud, dust, silt and other particles from vehicles and construction equipment as it is leaving a construction area but before it enters a road. A number of trackout control devices are available but it is advisable to have one that is both wide enough and long enough to be effective. Assuming a control efficiency of 46% and correcting for the PM_{10} to $PM_{2.5}$ conversion and adjusting to 2014 dollars it was found that the cost effectiveness was \$288,221/ton $PM_{2.5}$.

4. Pave Interior Roads

Another option to reduce silt from trackout, especially if the site is permanent, is to require that 100 foot of paved road be installed. This allows for much of the silt to fall off prior to entering the main roadways. Using asphalt and assuming a control efficiency of 42% and correcting for the PM_{10} to $PM_{2.5}$ conversion and adjusting to 2014 dollars it was found that the cost effectiveness was \$166,372/ton $PM_{2.5}$.

5. Gravel Bed Trackout

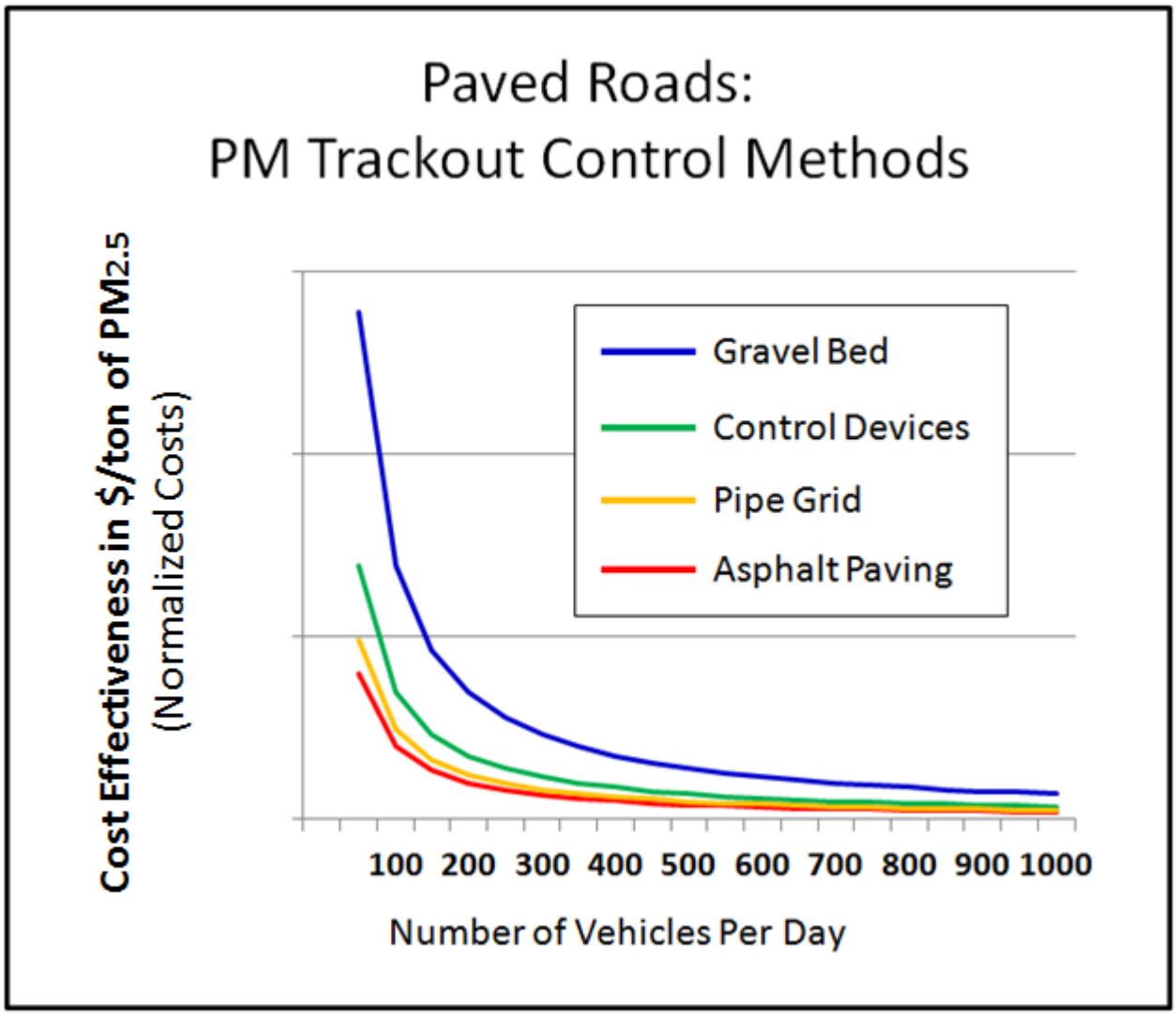
This control option is similar to the previous one except instead of using 100 foot of paved asphalt 50 foot of gravel that is 3 inches deep was used. Assuming a control efficiency of 46% and correcting for the PM_{10} to $PM_{2.5}$ conversion and adjusting to 2014 dollars it was found that the cost effectiveness was \$577,105/ton $PM_{2.5}$.

6. Pipe Grid Trackout

A pipe grid system for trackout shakes the accumulated dirt and mud from trucks leaving construction sites. The device is constructed with 2 inch diameter steel pipe welded in a ladder grid of 8-foot lengths. Three sections are linked together in each of two lanes and spaced over a 2 inch thick bed of 1 inch aggregate with dimensions of 100 feet by 18 feet at the exit of an unpaved area. Assuming a control efficiency of 80% and correcting for the PM_{10} to $PM_{2.5}$ conversion and adjusting to 2014 dollars it was found that the cost effectiveness was \$924,616/ton $PM_{2.5}$.

A comparison of cost effectiveness of different trackout controls is shown in Figure 16.

Figure 16.



Paving the entry and exits from a construction site to paved roads with asphalt is the most cost effective in this comparison. A pipe grid helps to remove dust and dirt from construction vehicles before they enter paved roads and is required in some cases by South Coast in Rule 8041. If there are additional control requirements, for example, if the roads must be 100 ft long and 25 ft wide, then the price increases as does the cost effectiveness. Placing gravel on the exits from unpaved construction areas can be expensive, unless the traffic through the exit is high. All calculations in this plot were done assuming light duty vehicles to place the comparisons on an equal basis.

E. Cost Effectiveness

The cost effectiveness of the options for reducing particulate emissions from paved roads as described above are summarized in Table 5.

Table 5.

$PM_{2.5}$ Control Methods and Cost Effectiveness for Paved Roads

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Pave New Shoulders	60%	$282,001
Pave Existing Shoulders	60%	$149,525
Trackout Control Devices	46%	$288,221
Pave Interior Roads	42%	$166,372
Gravel Bed Trackout	46%	$577,105
Pipe Grid Trackout	80%	$924,616

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

There are a total of 2317 tons of $PM_{2.5}$ emissions associated with paved roads in the most recent inventory.[11] The following table summarizes the cost to reduce emissions by 10% and 25%.

Table 6.

Cost to Reduce Construction $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Pave New Shoulders	60%	$65,339,632	$163,349,079
Pave Existing Shoulders	60%	$34,644,943	$86,612,356
Trackout Control Devices	46%	$66,780,806	$166,952,014
Pave Interior Roads	42%	$38,548,392	$96,370,981
Gravel Bed Trackout	46%	$133,715,229	$334,288,071
Pipe Grid Trackout	80%	$214,233,527	$535,583,818

The most cost effective control option that can be applied everywhere is to pave existing shoulders, with a cost effectiveness value of $149,525/ton.

To reduce $PM_{2.5}$ emissions by 10% or 232 tons, the cost would be 232 tons * $149,525/ton = $34,644,943.

To reduce $PM_{2.5}$ emissions by 25% or 579 tons, the cost would be 579 tons * $149,525/ton = $86,612,356.

Note that there are not likely to be enough existing shoulders to achieve 10 and 25% reductions, at least not at the cost that was premised. If that is the case, the next choice would be to pave interior roads. As is always the case, individual studies on specific locations and controls can identify the optimal solutions. For the purposes of the descriptions for overall estimates in the conclusion of this report, we assume that 50% of the emission reductions are achieved by paving existing shoulders and another 50% is achieved by paving interior roads.

X. Commercial Cooking

A. Definition

Restaurants which use certain types of equipment for cooking meat such as underfired charbroilers, chain driven or conveyorized charbroilers, deep fat fryers, and griddles emit a disproportionate amount of $PM_{2.5}$ when compared to other restaurants. Chain driven charbroilers are partially enclosed and have mechanical devices that move the food through the broiler. Underfired charbroilers are open and resemble a backyard barbeque. Underfired charbroilers are responsible for most of the $PM_{2.5}$ emissions from commercial cooking. Deep fat fryers and griddles also emit $PM_{2.5}$ but at much lower rates than charbroilers.

B. Description of how the source emits $PM_{2.5}$

When meat is grilling it gives off water, steam, volatile organic compounds and particulate matter. The grease filter located inside the ventilation hood will capture larger particles however smaller particles including the remaining $PM_{2.5}$ will pass out the exhaust system if no controls have been put into place.[17]

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

Emissions of $PM_{2.5}$ from cooking largely come from one of four sources: underfired charbroiling, chain driven/conveyorized charbroiling, flat griddle frying and clamshell griddle frying. In 2002 EPA developed emissions estimates from these sources based on the number of restaurants, the type of cooking equipment inside the restaurants, the number of pieces of cooking equipment which create $PM_{2.5}$ emissions in each restaurant, the amount of food, especially meet prepared in each restaurant and specific emission factors related to the cooking equipment and the type of meat cooked. Later EPA converted this information using population as a surrogate to obtain emission rates. In a recent update of TCEQ's 2011 $PM_{2.5}$ inventory a more detailed review of restaurants in Harris County was performed by SC&A. SC&A found that in Harris County a larger fraction of the restaurants use cooking equipment that creates $PM_{2.5}$ than the numbers reflected by EPA's 2002 analysis and as a result SC&A revised the TCEQ 2011 annual $PM_{2.5}$ emissions estimate for commercial cooking from 1071 tons to 2088 tons.[11]

Nationwide charbroiling is responsible for about 80% of all commercial cooking $PM_{2.5}$ emissions, but in Harris County the number is closer to 85%.[11, 26] There are two types of charbroilers – underfired and conveyorized or chain driven. Underfired broilers are responsible for 74% of all charbroiling $PM_{2.5}$ emissions. The SCAQMD requires catalytic oxidizers or

equivalent control methods to reduce $PM_{2.5}$ emissions from chain driven charbroilers. There are more emissions from underfired charbroilers; however, they are more expensive to control.[19]

PM emissions from meat cooking are primarily in the $PM_{2.5}$ range. Meats with higher fat content produce higher amounts of $PM_{2.5}$.[27]

2. Capacity/Usage Rate/Duty Cycle

Restaurants with more equipment that is likely to create $PM_{2.5}$ emissions and that cook more food, especially meat, are more likely to create higher $PM_{2.5}$ emissions. For example, Harris County has a higher proportion of restaurants that charbroil food than the national average[11] so they have higher $PM_{2.5}$ emissions per capita.

3. Condition

Although there are several controls available to reduce $PM_{2.5}$ emissions associated with commercial cooking including replacing old units with newer designs that emit less, it is difficult to say conclusively whether the emissions are higher for older units, simply because data on $PM_{2.5}$ emissions from cooking on equipment of different ages and condition is not readily available. However some devices which use control methods such as oxidizing catalyst or ceramic filters must be kept clean to maintain their specified emission reduction efficiencies.[28]

4. Fluctuations due to time of day, day of week and time of year

Since meat cooking is the source of the majority of these emissions, they can occur anytime, but the majority of meat cooking will occur in restaurants in preparation for meals. The hours prior to and during the heaviest activity in restaurants is likely be when most of these emissions occur.

5. How is the $PM_{2.5}$ emission factor determined?

There are five categories of commercial cooking: chain driven (or conveyorized) charbroilers, underfired charbroilers, deep fat fryers, flat griddle fryers, and clamshell griddle fryers. Emission factors are based on the type of equipment used and the food that is prepared. Different equipment and different meats will have different emission factors.[19] However the most common method for developing emissions inventories is to use emission factors based on population as a surrogate as discussed above.[11]

D. Control Methods, Efficiencies and Costs

Control methods vary depending on the type of cooking used.

In chain driven charbroilers grease from falls onto a radiant heating element or flame and combusts creating $PM_{2.5}$. The emissions can be controlled with catalytic oxidizers.[29] The exhaust of the charbroiler is directed through the catalytic oxidizer and the heated catalyst converts the VOCs and PM into water and carbon dioxide.[17] Chain driven charbroilers are often used in fast food hamburger restaurants. They are the most cost effective type of charbroilers to control because charbroiling occurs inside a metal cabinet and their exhausts can be easily captured and controlled.[30] Catalytic oxidizers have been found to be 83% efficient in removing $PM_{2.5}$.[31, 32]

The use of a catalytic oxidizer above the charbroiler in the stack and activated by the heat from the cooking, appears to be the best and most cost effective emission control device for chain driven charbroilers. Regulations for these controls have been adopted by the South Coast Air Quality Management District (SCAQMD) in 1997 (Rule 1138), the San Joaquin Valley in 2002 (Rule 4692) and Ventura County in 2004 (Rule 74.31).[33, 34, 35]

Underfired charbroilers create four times as much $PM_{2.5}$ emissions as do chain driven charbroilers, however catalytic oxidizers do not work on underfired charbroilers because the exhaust loses too much heat before reaching the catalyst.[29] Other options for underfired charbroilers are high efficiency particulate arresting (HEPA) filtration systems, electrostatic precipitators (ESPs) and wet scrubbers. HEPAs are easy to maintain but require frequent changing of filters. ESPs ionize the exhaust particles and then gather them using two charge plates. Filters are required ahead of the ESPs to remove grease and other particles. Wet scrubbers use a fine stream of water and detergent to wash out the particles.[17, 19]
The SCAQMD found that HEPA filters had control efficiencies between 95-99%, and wet scrubbers and ESP's each had control efficiencies greater than 90%.[34]

More information about the cost of the various techniques is provided below.

1. Catalytic oxidizers are the most common control option for conveyor chain driven charbroilers. EPA determined the control efficiency of catalytic oxidizer to be 83%.[14] These controls are not effective with underfired charbroilers, deep fat fryers, griddles or other cooking devices because the temperatures of the exhaust heat are too low to create the catalytic process required.

According to email conversations with SC&A Inc who prepared the Harris County emissions inventory report, [11] the initial cost of an oxidizer retrofit is $4000 and the installation cost is $1000.[14] The replacement cost is $4,000 and the operating and maintenance costs every year is $750.

Underfired broilers emit approximately 82% of the PM emissions. But control technologies available are very expensive. According to the Bay Area Air Quality Management District, if the top 40% of under-fired broilers are regulated, it would reduce PM emissions by 36%. The filterable $PM_{2.5}$ can be reduced by adding HEPA filters which have high control efficiency.[35]

2. High Efficiency Particulate Arresting (HEPA) filters are a series of filters that capture particles by interception, impaction or diffusion. The pre-filter takes out the coarser particles, the second filter is a disposable bag that collects smaller particles and the final filter collects finest particles.

SC&A determined the control efficiency to be 90% for capturing filterable $PM_{2.5}$.[11] The cost per retrofit was estimated to be $37,000 (installation and labor) according to San Joaquin Valley's control district. The operating and maintenance cost is $ 3,000. The total annualized cost over 10 years at 7% discounting is $8,269.[35]

3. Electrostatic Precipitators (ESPs) can also be used to control $PM_{2.5}$ emissions. An ESP consists of a two stage process: First, the exhaust stream gets charged in the first stage; then the charged particles are then collected in second stage. The South Coast Air quality Management District provides detailed guidance on using ESP's.[35]

The cost of an ESP for all charbroilers is averaged as $40,000 for both types of charbroilers from the San Joaquin valley report.[30] The operating and maintenance cost is expected to be $2,000 per year. The total annualized cost is $7,696 at 7% interest over 10 year's life.

EPA estimates control efficiency of a standard Smog–Hog ESP system (manufactured by United Air Specialist) to be 99%.[19]

4. Wet scrubbers are capable of $PM_{2.5}$ removal efficiencies of 90% or higher depending on load. They rely on an atomized stream of liquid to capture particulate pollutants from an exhaust stream. The South Coast Air quality district has several wet scrubbers permitted in restaurants.[35]

The cost of the Wet scrubber was averaged to be $33,000 according to the San Joaquin Air Quality District report.[30] The operating and maintenance cost is average out to be $ 7,000. The total annualized cost at 7% interest rate over a life of 10 years is $ 11,700.

5. The smokeless broiler is an alternative to traditional underfired broiler. Since it is not a direct flame broiler, it has fewer emissions. Vendors may not desire this approach because of the impact on the taste of the food.

The cost from the $PM_{2.5}$ Clean Air report by STAPPA /ALAPCO[19] estimated smokeless broilers to be around $5,500 just for installation. Assuming a labor cost of $1,500, we determined total cost to be around $7,000. The operating and maintenance cost is assumed to be $2,000 per year. The total annualized cost over 10 years is $2,996.

From the South Coast Air quality district reports, we determined control efficiencies to be 75% for a smokeless broiler.[35]

6. Add-on scrubbers can be placed on the exhaust vents of underfired broilers. There are approximately 12 CAST scrubbers installed in the US and the system has been improved over the past to increase effectiveness. The cost of the add-on scrubber was $32,350 according to SCAQMD reports. The labor cost is $1,300 and the operating and maintenance cost is $3,300. The total annualized cost over 10 years life at 7% discounting is $8,091. The control efficiency is assumed as 85% according to the SCAQMD.[30]

E. Cost Effectiveness

It must be remembered that cost effectiveness is always very dependent upon the variables including amount of food cooked per week, location, equipment type, equipment age and costs associated with retrofitting or replacing equipment. It is assumed that essentially all of the particulate matter is $PM_{2.5}$. In the case of commercial cooking, catalytic oxidizers can only be used as a control for conveyorized charbroilers, and will be ineffective for other types of charbroilers. The controls that work for underfired charbroilers may work on conveyorized charbroilers, but may be too expensive to be practical. Stakeholders (in this case restaurant owners) have provided some input to the development of these costs and cost effectiveness, but may not agree with the values that are published in the literature.

The cost effectiveness values developed here are based on the types of restaurants found in Harris County and their predicted emissions and are in line with other published values of cost effectiveness for commercial restaurants when adjusted for inflation. Detailed calculations can be found in Appendix C of this document.

Table 7.

Control Methods and Cost Effectiveness for Commercial Cooking

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Catalytic oxidizer	83%	$7,134
High Efficiency Particulate Arresting (HEPA) filter	90%	$13,227
Electrostatic Precipitator (ESP)	99%	$12,123
Wet scrubber	90%	$18,715
Smokeless broiler	53%	$7,275
Add-on scrubbers	85%	$12,459

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

In these calculations we assume that 10% of the emissions are from deep fryers or griddles, which are not addressed by these control methods, hence we must make up the difference by placing controls on a larger number of underfired and conveyorized charbroilers.

According to the SC&A report there are 2088 tons per year of $PM_{2.5}$ from commercial cooking in Harris County.[11] To achieve a 10% reduction we would need to reduce the emissions by 209 tons, and to reduce by 25% we would need to eliminate 0.25 * 2088 = 522 tons.

The catalytic oxidizer is the most cost effective route, and so we assume that catalytic oxidizers will be installed everywhere possible. However this control is only effective on conveyorized charbroilers. In Harris County conveyorized charbroilers are responsible for 169 tons of $PM_{2.5}$ emissions. Since catalytic oxidizers are 83% efficient, they could remove 0.83 * 169 tons = 140 tons. The cost would be $7,134 * 140 = $998,760.

To hit the 10% reduction target we still must remove another 209 – 140 = 69 tons. The next control that is lowest in price is the Smokeless broiler, however since that broiler may have negative impacts on taste, many restaurants may not see this as an option. So the next likely choice is an ESP. ESP's are 99% efficient so they can be used to reach the reduction targets based on the remaining available underfired charbroilers.

To reduce the 69 tons need to reach the 10% target, it will cost $12,123 *69 = $836,487. The total cost for the 10% target will be $998,760 + $836,487 = $1,835,247.

To reach the 25% target an additional 522 – 140 = 382 tons will be needed. Again, using the ESP to complete the reductions, the price will be $12,123 * 382 = $4,630,986.

The total cost for a 25% reduction will be $998,760 + $4,630,986 = $5,629,746.

Note that from the inventory 1603 tons of $PM_{2.5}$ come from conveyorized charbroiling. These devices can use ESP's, which are 99% efficient and could reduce a total of 0.99 * 1603 = 1587 tons of $PM_{2.5}$.

For consistency sake we have included a table that lists the costs to reduce commercial cooking emissions by 10% and 25%, however, it must be kept in mind that in practice this cannot work because some control measures only work on a small part of the commercial cooking emission inventory.

Table 8.

Cost to Reduce Commercial Cooking $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Catalytic oxidizer	83%	$1,489,579	$3,723,948
High Efficiency Particulate Arresting (HEPA) filter	90%	$2,761,798	$6,904,494
Electrostatic Precipitator (ESP)	99%	$2,531,282	$6,328,206
Wet scrubber	90%	$3,907,692	$9,769,230
Smokeless broiler	53%	$1,519,020	$3,797,550
Add-on scrubbers	85%	$2,601,439	$6,503,598

XI. Residential Wood Combustion



Photographed by Alex Cuclis

A. Source Definition

Residential wood combustion can occur from wood stoves, fireplaces, outdoor wood burning furnaces or boilers (used for heating) and open burning for the disposal of tree trimmings, leaves, etc.[19] Wood stoves are not common in Harris County due to the temperate climate. They are free-standing space heating appliances used either as the principal source of heat for a home or to supplement conventional heating systems. A typical wood stove will hold a fuel load that results in 4 to 12 hours of operation between refueling. On the other hand fireplaces have typically been identified as wood burning structures built into the living area, however changes in design has created some overlap between fireplaces and wood stoves.[36] In the most recent $PM_{2.5}$ emission inventory (2011) for Harris County[11], Fireplaces and Woodstoves respectively comprise 61.9% and 30.2% of the total Residential Wood Combustion $PM_{2.5}$ emissions.

B. Description of how the source emits $PM_{2.5}$

The combustion from burning wood creates small particles including ultrafine particulate matter which has an equivalent diameter of 0.1 microns or less. In addition to immediately forming $PM_{2.5}$, wood burning also creates secondary organic aerosols, which can create additional $PM_{2.5}$. Higher levels of air pollutants are generated during fire start-up and when wood is smoldering. This is usually evident by white or gray visible smoke exiting the chimney. Higher than normal air pollutant emissions can also occur when a wood burning appliance is performing poorly, where fuel quality is suboptimal, or where treated wood or wood with high moisture content (typically greater than 20%) is used.[36]

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

According to surveys performed in the early 2000's there are 40-45 million wood burning appliances and more than 27 million fireplaces.[19] In Harris County residential wood burning is responsible for 6.4% of all primary $PM_{2.5}$ emissions. Most of those emissions (70%) come from wood burning fireplaces. The remaining emissions come from woodstoves and firelogs.[11]

2. Capacity/Usage Rate/Duty Cycle

The highest usage rates occur during the winter when residents are seeking warmth. Otherwise there is not a significant usage rate identified in the literature.

3. Condition

Older fireplaces do not burn as efficiently, which is why one of the control measures is to upgrade to an "EPA Phase 2 fireplace" or qualified retrofit devices. Older wooden stoves have similar problems. In general providing more efficient combustion reduces the amount of particulate matter. Routine maintenance of all wood burning devices, including new technology stoves is required to ensure continued low emission performance over the life of the appliance.[37]

4. Fluctuations due to time of day, day of week and time of year

The highest use of wood burning stoves, fireplaces and outdoor furnaces and boilers occurs in the winter months. Some regulators have instituted "no burn days" when the particulate matter levels are high. In some locations during the winter over half of the particulate emissions were identified from wood burning sources.[19] However, in Harris County the temperate climate does not encourage those activities very frequently.

5. How is the $PM_{2.5}$ emission factor determined?

The emissions are determined by identifying the different types of wood burning equipment and the emission factor assigned for each one and multiplying by the number of hours of operation. The usage rate is determined by using a factor that considers the temperature of the location.[38] Residential wood remains one of the five largest categories of PM emissions according to the 2008 National Emissions Inventory. However residential demand for wood as a fuel source has been declining since 1989.[39]

D. Control Methods, Efficiencies and Costs

Control methods are divided into the two major categories of fireplaces and wood stoves. Example calculations and assumptions for a variety of the recommended control measures can be found in the Control Efficiency and Cost Effectiveness of Certain Residential Wood Combustion Control Measures (June 2013)(Microsoft Excel), developed by EPA.[40] Also, EPA's Wood Stove and Fireplace Emission Calculator (October 2009) was used to estimate emission reduction by wood stove and fireplace change outs.[41]

1. Install EPA Phase 2 Qualified Fireplaces

In this scenario EPA determined the cost and emissions savings associated with installing new EPA phase 2 qualified wood-burning fireplaces. If new wood-burning fireplace construction is in place, only EPA Phase 2 qualified models will be allowed. A Partnership Agreement (PA) is currently in place between EPA and wood-burning fireplace manufacturers. Under this PA, cleaner wood-burning fireplaces are qualified when their $PM_{2.5}$ emissions are at or below the Phase 2 $PM_{2.5}$ emissions level.

The calculation of the cost effectiveness of an individual fireplace is based on the incremental cost of installing a Phase 2 qualified fireplace instead of a non-Phase 2 fireplace.

The total annualized incremental cost calculation was based on EPA's communication with FMI fireplace manufacturers on August, 2012. It included the incremental cost of the new EPA Phase 2 fireplace plus an installation charge of $630 beyond an existing non-Phase 2 fireplace. The control efficiency for the new phase 2 fireplace was reported as 70%. The cost effectiveness was calculated as $9,775/ton.[40, 41]

2. Install Retrofit Device into Fireplaces

In this scenario EPA determined the annualized cost and emissions savings associated with installing qualified retrofit devices into wood-burning fireplaces. Incentives need to be provided to encourage the installation. Under the EPA Wood-burning fireplace PA, a retrofit device is qualified when it lowers fireplace $PM_{2.5}$ emissions to a level at or below the program Phase 2 $PM_{2.5}$ emissions level.

The annualized cost of the retrofit device plus installation was assumed to be the same as the annualized incremental cost of the first option: Install EPA Phase 2 Qualified Fireplace, and the cost effectiveness is the same at $9,775/ton. [40, 41]

3. Install Gas Logs in Existing Fireplaces

In this scenario EPA determined the cost and emissions savings associated with retrofit wood-burning fireplaces to gas log sets. Incentives need to be provided for the retrofit program.

The total annualized cost was based on EPA's communication with Rod Tinnamore, WA State in October 2012.[42] The calculation of annualized cost of the gas log set and installation was based on the cost of the gas log set plus installation charges of $1,483, the 18 years' lifetime of the gas log set and the capital cost of 7%. The baseline emissions were 0.0135 tons/year for wood-burning fireplaces as determined by using EPA's Wood-burning emissions reduction calculator. The gas log set control efficiency is 100%. The cost effectiveness was calculated as $11,402/ton.[40, 41]

4. Wood to Wood Replacement Program – Wood Stove

In this scenario EPA determined the cost and emissions savings associated with replacing old uncertified wood stoves with new EPA-certified wood stoves. An incentive program is required to provide to make this work.

The total annualized cost included the cost of replacement plus installation of an EPA certified wood stove and the cost of catalyst replacement in certified catalytic wood stoves in the RWC MANE-VU Report, page 61, 2006.[42] EPA assumed that the replacement and installation of EPA uncertified wood stove with EPA certified wood stove would cost $3,550, with a lifetime of 20 years. The cost recovery factor at 7% interest was 0.0944. Also with the assumption, that 24% of wood stoves are catalytic, the cost of catalyst replacement was assumed to be $10.32/year.

The baseline emissions calculated were 0.056 tons by using EPA's Wood Stove emission reduction calculator, assuming wood density of 1.22 tons/cord and 3 cords of wood burned per year. The emissions after the controls are implemented were 0.0386 tons.

The cost effectiveness was calculated as $10,827/ton.[40, 41]

5. Wood to Gas Replacement Program – Wood Stove

In this scenario EPA determined the cost and emissions savings associated with replacing old uncertified wood stoves with new gas stoves. Incentives need to be provided for the gas replacement program to work.

The total annualized cost included the cost of replacement plus installation of a gas stove and annual electricity cost as reported in the RWC MANE-VU Report, page 61, 2006.[42] EPA assumed that the replacement plus installation of an EPA uncertified wood stove with an EPA certified wood stove will cost $3,400, with a lifetime of 18 years. The cost of capital was assumed to be 7%.

The baseline emissions calculated were 0.056 tons by using EPA's Wood Stove emission reduction calculator, assuming wood density of 1.22 tons/cord and 3 cords of wood burned per year. And the control efficiency was 100%, assuming 100% conversion to gas.

The cost effectiveness was calculated as $7,841/ton.[40, 41]

6. Remove Old Wood Stoves for Money or "Bounty"

In this scenario, EPA based their calculations on the "woodstove roundup" program in the Methow Valley of Washington State in June 2012.[43]

The control efficiency of wood stoves that are actually used was 70%, according to an estimate provided by Washington State Department of Ecology.

Up to $250 was offered for an old EPA uncertified woodstove to be turned in. Around $16,000 was paid out for 69 old uncertified wood stoves. The $PM_{2.5}$ emissions reduction from these wood stoves is estimated at 3 tons per year. Thus, the cost-effectiveness of this bounty program was:

Cost Effectiveness = $16,000/3 tons = $5,333/ton (2012 dollars)

Converting to $2014 gives the a cost effectiveness of $5,483/ton

7. Curtailment program or Burn Ban

The curtailment measure employed here reflects a second stage program that requires a ban on wood-burning from all wood-burning appliances, not just uncertified appliances (which would be a first-stage program).

A public awareness campaign and enforcement are critical to accomplish 75% control efficiency. The control efficiency applies to the entire local area where the curtailment program is implemented.

EPA estimated the cost of this control option from Sacramento Metro Air District staff report for Rule 421, Sept. 9, 2009, and that report contains the details behind the program's cost estimate.[38]

Cost-effectiveness of the curtailment program is estimated using the lost sales for wood suppliers from reduced wood burning. Emission reductions are based on their being No Burn days attributable to the curtailment program.

The total annualized cost of the curtailment program is estimated in the report at $577,781.[44]

The emission reductions are estimated to range from 52.0 to 91.7 tons of $PM_{2.5}$ annually, with all reductions occurring in the winter season (when the curtailment program is effective). When the average emissions reductions are taken and corrections are made to place the values in 2014 dollars the cost effectives comes to $9483/ton.

It should be noted that households may have reduced heating costs due to switching to natural gas or electricity from wood, but these savings were not calculated for inclusion in the cost estimate for the curtailment program. Businesses with wood burning devices other than for cooking would have a cost savings from reduced wood use, but no information was available to quantify this impact.

E. Cost Effectiveness

Cost effectiveness varies not only depending on the control option selected but also on the individual piece of equipment. The table that follows shows average values. Also recognize that in Harris County about 62% of the residential wood burning emissions come from fireplaces and 30% come from wood stoves. Finally, although removing old wood stoves is the most cost effective, it will not be practical in many cases. Similarly options like Wood to Gas may not work for some residents. Consideration must be given not only to price but also to the practicality and likelihood of being able to make the change.

Table 9.

Control Methods and Cost Effectiveness for Residential Wood Combustion

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Phase 2 Qualified Fireplaces	70%	$9,777
Retrofit Device for Fireplaces	70%	$9,777
Install Gas Logs for Fireplaces	100%	$11,399
Wood to Wood Replacement Program – Wood Stove	69.93%	$10,561
Wood to Gas Replacement Program – Wood Stove	100%	$7,649
Remove Old Wood Stoves for Money or “Bounty”	100%	$5,495
Curtailment/Burn Ban	75%	$9,483

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

According to the SC&A report there are 735 tons per year of $PM_{2.5}$ from residential wood burning in Harris County.[11] We need to reduce the total by 73.5 tons to achieve a 10% reduction and 184 tons to achieve a 25% reduction.

If we assume that all reductions are to come from fireplaces using either Phase 2 qualified fireplaces or a retrofit device, then the costs would be $9,775/ton * 73.5 tons = $718,462 for a 10% reduction and $9,775/ton * 184 tons = $1,798,600 for a 25% reduction. Note that according to the 2011 inventory fireplaces are responsible for 515 tons per year. Since the Phase 2 fireplaces are 70% effective theoretically up to 515 * 0.7 = 360 tons of $PM_{2.5}$ can be reduced.

Wood stoves in Harris County contribute a total of 220 tons per year of emissions. Theoretically, if enough people were willing to turn in their wood stoves for a bounty of $250 each, then the cost effectiveness would drop to $5,483/ton. The cost for reducing emissions would be $5,483/ton * 73.5 tons = $403,000 for a 10% reduction and $5,483/ton * 184 tons = $1,008,872 for a 25% reduction. This would be a considerable savings over approaches to reduce fireplace emissions.

The reality is that different people will respond differently to the various regulations and incentives offered for the controlling particulate matter from wood burning. The right balance of controls must be explored to achieve optimal results.

Once again for consistency we have built a table with all of the control measures discussed and the costs it would take to reduce emissions by 10% and 25% assuming each of the controls could achieve the full reduction amount. However, as indicated previously, many of these controls only apply to a portion of these emissions and a combination of controls will be required.

Table 10.

Cost to Reduce Residential Wood Combustion $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Phase 2 Qualified Fireplaces	70%	$718,610	$1,796,524
Retrofit Device for Fireplaces	70%	$718,610	$1,796,524
Install Gas Logs for Fireplaces	100%	$837,827	$2,094,566
Wood to Wood Replacement Program – Wood Stove	69.93%	$776,234	$1,940,584
Wood to Gas Replacement Program – Wood Stove	100%	$562,202	$1,405,504
Remove Old Wood Stoves for Money or "Bounty"	100%	$403,883	$1,009,706
Curtailment/Burn Ban	75%	$697,001	$1,742,501

XII. Other Area Sources

In the revised emissions inventory for Harris County there were a total of 20,468 tons of $PM_{2.5}$ per year. Area sources accounted for 11,942 tons of $PM_{2.5}$ in the revised inventory. The area emissions were broken down as follows:

Table 11.

Summary of Harris County Area Source $PM_{2.5}$ Emissions[11]

Category	$PM_{2.5}$ (tons)
Unpaved Roads	4815
Construction	1843
Paved Roads	2317
Commercial Cooking	2087
Residential Wood Combustion	735
Other	145

The "Other" remaining sources contributing to this category were Industrial Fuel Combustion, Commercial/Residential Fuel Combustion, Agriculture, Other Combustion – Structure Fires, and On-shore Oil and Gas. Because the combination of all of the "Other" categories represents less than 1% of the total primary $PM_{2.5}$ emissions they were not considered in this control strategy analysis. Part of the consideration of the effectiveness of any control will include how many opportunities exist to use it and how many total emissions would be reduced due to the implementation of those controls. In the case of the Area "Other" category there were not enough opportunities to use it and not a substantial amount of emissions that could be eliminated. Therefore we have not attempted to evaluate control for this category.

XIII. Cooling Water Towers



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A. Source Definition

Cooling water towers are used to remove heat from industrial processes. Before arriving at the cooling water tower, water is circulated through metal heat exchangers where the cooling water absorbs heat from process fluids. The heated water is routed to the top of a cooling water tower where it is released. As the water falls through the air some heat is removed through evaporation and other heat is removed through cooling of the water as it makes contact with the ambient air. There are two common types of cooling water towers, induced or forced draft which typically uses a fan to drive the air upward and natural draft. The induced draft cooling water towers are most common because they provide the most cooling but they also create higher amounts of particulate matter.

According to the TCEQ's 2011 inventory for Harris County various point sources reported that 170 cooling water towers emitted 1714.4 tons of $PM_{2.5}$, making it the highest source of $PM_{2.5}$ emissions reported for all categories of point sources. (Note: There were more than 130 other cooling water towers in the inventory that reported other emissions such as PM_{10} and VOCs, but no $PM_{2.5}$). However, there is considerable controversy and uncertainty in the reported emissions for cooling water tower $PM_{2.5}$. The reporting requirements for $PM_{2.5}$ are relatively new and industry has the option of reporting all of its $PM_{2.5}$ emissions as equal to their PM_{10} emissions to avoid the cost more complex analyses and modeling for identification of the $PM_{2.5}$

portion of the particulate emissions. As a result many consider the reported $PM_{2.5}$ numbers to have a high bias.

B. Description of how the source emits $PM_{2.5}$

In a cooling water tower the water that has been heated by process fluids in heat exchangers is released at the top and falls downward as air passes upward. The cooled water is re-circulated through process heat exchangers to absorb more heat. The total particulate matter (TPM) released by a cooling water tower is estimated using the following equation[45]:

$$TPM\ [g/h] = TDS\ [ppmw] \times Drift\ Loss\ [\%] / 100\% \times Circulating\ Water\ Rate\ [m^3/hr]$$

TDS is the total dissolved solids. The "drift" is the water that is entrained with the air that blows out of the cooling water tower. It can vary depending on the cooling water design, atmospheric conditions and other issues. "Tower maintenance and operation levels also can influence the formation of drift droplets. For example, excessive water flow, excessive airflow, and water bypassing the tower drift eliminators can promote and/or increase drift emissions."[46]

There is controversy in determining the fraction of particulate matter that falls into PM_{10} and $PM_{2.5}$. Reisman[47] calculates that that $PM_{2.5}$ is less than 1% of the total PM_{10}, however Ron Meyers at EPA in a report by Jim Wilson at SC&A identifies a number of problems with the analysis and suggests that a 1998 report performed by Entropy Environmentalists indicates that emissions are much higher. After reviewing the Reisman report and EPA comments, the SC&A report indicated that 60% of cooling water tower PM_{10} emissions are $PM_{2.5}$.[11, 48]

Further complicating the issue is that most refineries and chemical plants in Harris County report that all of their PM_{10} is actually $PM_{2.5}$ because it simplifies their reporting process.

As a compromise the Harris County inventory for $PM_{2.5}$ was set at 60% of the reported values of PM_{10} for all cooling water towers in TCEQ's 2011 inventory for Harris County. Changes in the assumed percentage can dramatically change the cost of reducing the emissions.

We assumed that the average cooling water tower was 5000 square feet. The installation cost for a high efficiency drift eliminator based on the numbers quoted above would be $100,000[49]. We assume in this option that the cooling water did not have an existing drift eliminator, so there are no disposal costs. Installing a drift eliminator will increase the drag or resistance on the system, requiring more power and more water, which will increase the operating costs.

There are additional costs associated with shutting down a cooling water tower that are difficult to quantify. If no other cooling water tower exists to route the hot process water during operation, then the installation process may have to wait until a shutdown occurs. There are other costs associated with shutting down a cooling water tower that are not incorporated here. To account for the costs associated with lost business associated with

shutting down a cooling water tower and the associated process units as well as increased operating costs, we have assumed a loss of $1,000,000 bringing the total installation costs to $1,100,000. Similar assumptions are made for replacing an existing drift eliminator and performing maintenance or cleaning on drift eliminators.

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

There are approximately 170 forced draft cooling water towers in Harris County, mostly located in the Houston Ship Channel area.

2. Capacity/Usage Rate/Duty Cycle

Cooling water towers are in use continually all year round, unless they are down for maintenance. Usage may drop to some extent when some of the individual process units that rely on the cooling water towers are down for maintenance. Usage may increase in the summer when more evaporation occurs, requiring more make up water as well as higher flow rates through the tower to achieve the desired levels of cooling.

3. Condition

Cooling water towers vary substantially in age. Many were installed many years ago and it is difficult to determine how many cooling water towers had drift eliminators installed originally and the level of maintenance that has occurred since their installation. In part due to the emphasis and concern about particulates new cooling water towers are generally installed with drift eliminators.

4. Fluctuations due to time of day, day of week and time of year

Cooling water towers are under more stress during the summer since the ambient temperatures are higher. This means more water must be circulated through the towers, and because the temperatures are higher more evaporation will take place, leading to higher emissions of particulates.

5. How is the $PM_{2.5}$ emission factor determined?

EPA's AP-42 document lists the "standard drift" at 0.02%, but drift eliminators installed on cooling water towers can reduce drift down to 0.001 – 0.0005%.[46]

Cooling water towers provide unique challenges in regards to $PM_{2.5}$ reduction because of all of the significant discrepancies in $PM_{2.5}$ emission estimation techniques. The 2004 paper by Reese and Frisbie[47] claims that cooling water tower $PM_{2.5}$ emissions have been over-estimated and says the emissions should be someplace near or less than 1% of the total PM_{10} emissions. However a 2013 document published by the New Mexico Environment Department Air

Bureau[44] claims that there is no scientific basis for some of the assumptions made by Reese and Frisbie and provides calculations that give higher numbers. Similarly, discussions with EPA suggest that their belief is that the cooling water tower $PM_{2.5}$ much higher.[11, 48] Finally, in order to address some permit issues many companies simply report all of their PM_{10} as $PM_{2.5}$.

For the purposes of this analysis we have assumed that the $PM_{2.5}$ is 60% of the PM_{10}.

There were 170 water towers in Harris County that report PM_{10} and $PM_{2.5}$ emissions in 2011. The most often cited control for reducing PM emissions on a cooling water tower is to install a drift eliminator. While many drift eliminators are currently in place, it is not clear how many of the cooling water towers are equipped with them. Also, drift eliminator manufacturers claim that they must be replaced every 12-15 years. It is also not clear how often drift eliminators are replaced in practice.

D. Control Methods, Efficiencies and Costs

Installing a drift eliminator can add drag to the air flow through the cooling water tower, reducing its efficiency and increasing cost. If a new drift eliminator is installed to replace an existing drift eliminator that is fouled and partially plugged it can increase air flow and the efficiency of the cooling water tower.

According to Brandon Rees, Regional Director for Cooling Water Depot, "$15-$20 per square foot would be a conservative estimate of cost of replacement. This number includes material, removal and installation labor."[43] There is an additional charge associated with disposal of the old drift eliminator.

Based on an informal survey using Google Maps to identify and size a number of cooling water towers we assumed that the average cooling water tower was 5000 square feet. The installation cost for a high efficiency drift eliminator based on the numbers quoted above would be $100,000[49]. We assume in this option that the cooling water did not have an existing drift eliminator, so there are no disposal costs.

There are additional costs associated with shutting down a cooling water tower as well as an increase in operating costs with a new drift eliminator. As indicated previously we have selected a value of $1,100,000 as the total cost for installing a drift eliminator.

In an analysis performed by TRC for the Entergy Indian Point Energy Center in Westchester County, New York based on EPA and New York State Department of Environmental Conservation (NYSDEC) approved air quality modeling "AERMOD", several variables were reviewed to reduce the particulates from the proposed cooling water tower. These included:

Cooling tower height
Air flow rate

Water flow rate
Total dissolved solids content (determined by the either the cycles of concentration/the amount of make-up water required or water treatment chemicals).
Drift eliminators with drift rates of either 0.001% or 0.0005%.
Cooling water tower size/geometry.

The conclusion of this 2009 study was that the cooling water towers would emit more than 100 tons per year of $PM_{2.5}$ and would have an adverse impact on the surrounding communities. Furthermore, TRC found that mitigating the emissions to a level that would satisfy the permitting requirements was not feasible.[51]

In a permit application Dominion Energy Brayton Point, LLC planned to install new cooling water towers and looked at the following options for reducing particulates:

Air Cooled Condensers

Once-Through Cooling (existing configuration)

Fresh Water

Mechanical Draft Cooling Towers.

Reduction in Cycles of Concentration.

Reduction in Air Velocity

Drift Eliminators

Dominion determined that three of these items: Once-Through Cooling, Fresh Water and Reduction of Cycles of Concentration were technically infeasible due to limits on the amount of water that is available for circulating or the amount of discharge water that is allowable into the bay.

Dominion also determined that air cooled condensers would not work due to their high installation costs, high energy use as well as significant land use requirements. Dominion also rejected using mechanical draft cooling water towers with drift eliminators due to their high installation and operating costs with no significant benefit in reducing particulates. According to Dominion reducing air velocity would require building taller towers without a significant improvement in emissions.

Dominion reviewed drift eliminators with different efficiencies and found that drift rates lower than 0.0005% would create back pressure that could not be overcome in a natural draft tower. As a result Dominion proposed natural draft cooling water towers with a drift eliminator that

created a drift rate of 0.0005%. The EPA reviewed Dominion's analysis and agreed with their conclusions.[52]

E. Cost Effectiveness

We have used the data described above as the basis to calculate cost effectiveness of several different options including installing a new drift eliminator, replacing an existing drift eliminator and performing a tune-up/maintenance plan on an existing drift eliminator.

Table 12.

Control Methods and Cost Effectiveness for Cooling Water Towers

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Cooling Water Tower Research	100%	$1,000,000
Install New Drift Eliminator	79%	$4,170
Replace Existing Drift Eliminator	74%	$5,628
Implement Maintenance Plan	36.9%	$11,461

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

Installing and replacing drift eliminators is the best way to reduce emissions from this category. There is a large disagreement in the amount of $PM_{2.5}$ emitted from cooling water towers, and depending on the values selected the costs could change dramatically.

According to the most recent inventory cooling water towers emit 1639 tons of $PM_{2.5}$ per year in Harris County. In order to get 10% and 25% reductions emissions must be reduced by 164 tons and 410 tons respectively. Table 13 shows the expected costs.

Table 13.

Cost to Reduce Cooling Water Tower $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Cooling Water Tower Research	100%	$164,000,000	$410,000,000
Install New Drift Eliminator	79%	$683,463	$1,708,658
Replace Existing Drift Eliminator	74%	$922,429	$2,306,073
Implement Maintenance Plan	36.9%	$1,878,458	$4,696,145

As mentioned previously, the uncertainties which exist may require some extensive research before other options are proven viable. Also, more research must be done to identify how many cooling water towers do not have drift eliminators or need to have existing drift eliminators to be replaced. However, in order to provide an estimate we assume that 10% of the cooling water tower emissions can be improved with the installation of a new drift eliminator, another 10% can be improved by replacing an existing drift eliminator with a new drift eliminator and another 10% can be improved by implementing a maintenance plan. The remaining 70% will require "research".

To achieve a 10% reduction we can calculate

0.1 * 164 * $4,170 + 0.1 * 164 * $5,628 + 0.1 * 164 * $11,461 + 0.7 * 164 * 1,000,000 or

$68,388 + $92,299 + $187,960 + $114,800,000 = $115,148,647.

Repeating the process for a 25% reduction yields,

$170,970 + $230,748 + $469,900 + $287,000,000 = $287,871,518.

XIV. Boilers

A. Source Definition

Boiler is a term used to describe industrial point source equipment that heats water and uses the resulting hot water or steam to provide heat to other processes, to create electricity or to for use to power equipment such as turbines, compressors and pumps. Boilers use a variety of different fuel sources including coal, wood, oil, biofuels, natural gas and fuel gas. In Harris County about 98% of all point source boilers run on either natural gas or process gas.

B. Description of how the source emits $PM_{2.5}$

$PM_{2.5}$ is produced by the combustion of the boiler's fuel source. Solid fuel sources like coal and wood as well as liquid sources, like oil, produce much higher amounts of $PM_{2.5}$ than does natural gas. EPA estimates greater than a 90 percent reduction in $PM_{2.5}$ emissions can be achieved when switching from residual oil to natural gas. Fabric filters or baghouses, electrostatic precipitators (ESPs), wet scrubbers and venture scrubbers are all suggested controls for boilers that use wood, coal or oil as a fuel, but these techniques are not considered effective for boilers using natural gas or fuel gas because of the relatively high cost of those techniques and the relatively low emission rates from natural gas/process gas boilers.[19] Optimal combustion reduces $PM_{2.5}$ levels regardless of the fuel source. Combustion can be optimized in large boilers by continuously monitoring oxygen and carbon monoxide levels. The most effective control of particulate matter is to move away from solid and liquid fuels and use natural or process gas instead.

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

There are 548 boilers used by point sources in Harris County based on queries of the self-reported data in TCEQ's 2011 emissions inventory database. These boilers emit a total of 637.8 tons of $PM_{2.5}$ per year. Of the 548 boilers, 97% use natural gas or fuel gas, 1% use oil and the remaining 2% do not specify their fuel source.

2. Capacity/Usage Rate/Duty Cycle

Boilers vary widely in size and application. Their usage is dependent upon the needs for heat, steam and electricity. It is common for boilers to run continuously. Higher emissions can be seen during start up and shutdowns when boilers are taken out for maintenance.

3. Condition

Boilers have been part of industrial processes in Harris County for most of the last century. As a result some boilers are very old whereas others are fairly new. Boilers must meet specifications set by the EPA based on their fuel type and their size. For some boilers that have solid or liquid fuels this might mean adding a baghouse, an ESP or a wet scrubber to remove particulates. Other boilers have installed low NOx burners to meet more stringent NOx requirements. However, 98% of boilers in Harris County are fueled by natural gas or process gas.

4. Fluctuations due to time of day, day of week and time of year

Boilers typically run continuously. Fluctuations can happen when demand changes or when maintenance occurs, but these items are generally not dependent on the time of day or the season.

5. How is the $PM_{2.5}$ emission factor determined?

Emissions are very dependent on the type of fuel used by the boiler and to a lesser degree the type of burner. Burner manufacturers publish emission factors for their burners based on testing. However emission rates can vary significantly depending on what kind of controls are added. Although boilers may have continuous emissions monitoring systems on their stacks to measure actual emissions of NOx, SO2 and CO, they do not continuously measure particulates due to the complexities of measuring the condensable portion. Typically the emission factor calculation is made simply by measuring the total $PM_{2.5}$ and dividing it by the fuel input rate. The combustion of only natural gas is expected to achieve an emission rate of 0.0076 lb/MMBtu for both $PM_{2.5}$ and PM_{10}. This is the most effective level of control.[53, 54]

D. Control Methods, Efficiencies and Costs

The "work standard practice" is an annual tune up. All boilers and process heaters are subject to a work practice standard. Large units (greater than or equal to 10 MMBtu per hour) are required to conduct an annual tune-up. All small boilers (less than 10 MMBtu per hour) combusting any fuel, and limited use boilers (less than 876 hours of operation per year) are required to conduct a biennial boiler tune-up. Very small units designed to burn gaseous fuels or light liquid fuels (less than 5 MMBtu per hour) are required to conduct a tune-up every 5 years. The annualized cost for an annual tune-up was $2,875 per boiler in 2008 dollars.[55, 56]

A Tune-up requires the following steps:

1. Inspect the burner, and clean or replace any components of the burner as necessary.
2. Inspect the flame pattern and adjust the burner as necessary to optimize the flame pattern. The adjustment should be consistent with the manufacturer's specifications, if available.
3. Inspect the system controlling the air-to-fuel ratio and ensure that it is correctly calibrated and functioning properly.

4. Optimize total emissions of carbon monoxide. This optimization should be consistent with the manufacturer's specifications, if available, and with any nitrogen oxide requirement.
5. Measure the concentrations in the effluent stream of carbon monoxide in parts per million, by volume, and oxygen in volume percent, before and after the adjustments are made.
6. Maintain onsite and submit, if requested by the Administrator, biennial or five year report.
7. If the unit is not operating on the required date for a tune-up, the tune-up must be conducted within 30 days of startup. You must conduct the tune-up while burning the fuel that provided the majority of the heat input to the boiler in the last 12 months before the tune-up.[57]

In contrast, an energy assessment must include the following items:
1. A visual inspection of the boiler system (e.g. cracks, corrosion, leaks, insulation).
2. An evaluation of operating characteristics of the affected boiler systems, specifications of energy systems, operating and maintenance procedures, and unusual operating constraints.
3. An inventory of major systems consuming energy (i.e., energy use systems).
4. A review of available architectural and engineering plans, facility operation and maintenance procedures and logs, and fuel usage.
5. A list of major energy conservation measures that are within the facility's control.
6. A list of the energy savings potential of the energy conservation measures identified.
7. A comprehensive report detailing the ways to improve efficiency, the cost of specific improvements, benefits, and the time frame for recouping those investments.[57]

According to the EPA's Boiler MACT rule in 2011, for all new and existing natural gas and refinery gas-fired units, the operator must perform an annual tune-up instead of emission limits to comply with regulations. Other gases can qualify for tune-ups by demonstrating that they burn cleanly, with contaminant levels similar to natural gas.[58, 59]

The first control option recommended for natural gas and process gas fueled boilers is to perform annual tune-ups. EPA tests yielded a maximum potential of 34% emission reduction through best combustion practices and annual tune ups.[54]

The options for addressing emissions from boilers are as follows:

1. Research

EPA's advice to reduce emissions from boilers is first to convert coal, wood and oil boilers to natural gas or fuel gas boilers. Gas fired boilers are subject to additional rules related to tune-ups and energy assessments depending on size as described above. Ron Myers at EPA indicated that further improvements on boiler emissions are not likely to be seen because the current measurement practices and not distinguish signal from the noise level of the measurement.[60] Therefore if additional reductions are to be made they would require significant research and development to achieve. We have entered $1,000,000/ton as a default to accommodate all of the costs associated with potentially finding other means of reducing particulate emissions.

2. Annual Tune-ups

Note as indicated above, all boilers that are larger than 10 MMBtus/hour are subject to annual tune-ups. These tune-ups would apply to smaller boilers. There may be an opportunity to reduce emissions by confirming that these tune-ups are occurring on a regular basis. The efficiency for performing a tune-up is 34% and the cost effectiveness is $ 7,271 per ton $PM_{2.5.}$ Detailed calculations are provided in Appendix C.

3. Biennual Tune-ups

This is a duplicate of option 2, except performed every 2 years instead of annually. Reducing this requirement drops the efficiency to 22%, but also drops the cost to $ 5,620 per ton $PM_{2.5.}$

4. Energy Assessment

An energy assessment, as described previously, would be applied to any boilers that are not regulated. The efficiency is estimated at only 15% and the cost effectiveness is $ 11,465 per ton $PM_{2.5}$.

5. Oil to Gas Conversion

Only 2% of the boilers in Harris County point sources are fueled by oil. If they were converted to gas fired boilers the efficiency of particulate reduction would be 90%. The cost to upgrade from an oil to gas fired process heater must consider many things including:

- The cost of the fuel
- The need to comply with the maximum available control technology (MACT) standard
- Adjustments that need to be made to the controls in order comply with annual tune-ups associated with industry standards.
- Changes that impact the facility outside of the boiler, such as delivery of the new fuel to the heater.
- Equipment (e.g. baghouse, scrubber, ESP) that must be removed.
- Adjustments to account for differences in the heat transfer that occurs with gas.
- Downtime can be 6 months to a year.[61]

Cost effectiveness has not been estimated since this represents a small portion of the emissions and the costs are likely to be highly variable depending on the age and characteristic profile of the boilers to be converted.

E. Cost Effectiveness

Below is a summary of the cost effectiveness of the various options for particulate control on boilers.

Table 14.

Control Methods and Cost Effectiveness for Boilers

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Boiler Research	100%	$1,000,000
Annual Tune-up	34%	$ 7,271
Biennial Tune-up	22%	$ 5,620
Energy Audit	15%	$ 11,465
Oil to Gas Conversion	90%	Not estimated

The Oil to Gas Conversion was not estimated because less than 2% of the boilers fall into this category.

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

According to the most recent inventory[11] the boiler emissions are 638 tons per year. This means that a 10% reduction requires 63.8 tons be eliminated and a 25% reduction requires that a 160 tons be eliminated.

If we assume that each of these measures can be applied enough to achieve these results, we obtain the following:

Table 15.

Cost to Reduce Boiler $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Boiler Research	100%	$63,800,000	$159,000,000
Annual Tune-up	34%	$463,890	$1,159,725
Biennial Tune-up	22%	$358,556	$896,390
Energy Audit	15%	$731,467	$1,828,668
Oil to Gas Conversion	90%	Not Possible	Not Possible

However, if assume that the annual tune-up, the biennial tune-up and the energy audit can each apply to no more than 25% of the boilers. In that case, with efficiencies of 34%, 22% and 15% respectively the most reductions each can obtain is

Annual Tune-up - 0.25 * 638 *0.34 = 54 tons
Biennial Tune-up - 0.25 * 638 *0.22 = 35 tons
Energy Assessment - 0.25 * 638 *0.15 = 24 tons

Then none of these approaches can achieve a 63.8 ton or 10% reduction, much less a 25% reduction. For the purposes of this project we have assumed that each of these three approaches can achieve 1% or 6.4 tons worth of reductions and the remainder will have to be achieved through “research”.

The Oil to Gas Conversion is not possible because although it is 90% efficient, it can only be applied to 2% of the boilers.

XV. Process Heaters

A. Source Definition

Process heater is a term used to describe industrial point source equipment that heats fluids other than water for a variety of purposes including to boil off or distill different fractions of the fluid in a separator or distillation tower or to bring the fluid to a temperature required for a chemical reaction. Like boilers, process heaters use a variety of different fuel sources including coal, wood, oil, biofuels, natural gas and fuel gas. In Harris County about 90% or more of all point source process heaters run on either natural gas or process gas.

B. Description of how the source emits $PM_{2.5}$

$PM_{2.5}$ is produced by the combustion of the process heater's fuel source. Solid fuel sources like coal and wood and liquid sources, like oil, produce much higher amounts of $PM_{2.5}$ than does natural gas. EPA estimates greater than a 90 percent reduction in $PM_{2.5}$ emissions can be achieved when switching from residual oil to natural gas. Fabric filters or baghouses, electrostatic precipitators (ESPs), wet scrubbers and venture scrubbers are all suggested controls for process heaters that use wood, coal or oil as a fuel, but these techniques are not considered effective for process heaters using natural gas or fuel gas because of the relatively high cost of these techniques and relatively low emissions of natural gas/process gas process heaters.[19] Optimal combustion reduces $PM_{2.5}$ levels regardless of the fuel source. Combustion can be optimized in large process heaters by continuously monitoring oxygen and carbon monoxide levels. The most effective control of particulate matter is to move away from solid and liquid fuels and use natural or process gas instead.

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

There are 660 process heaters used by point sources in Harris County based on queries of the self-reported data in TCEQ's 2011 emissions inventory database. These process heaters emit a total of 1083.5 tons of $PM_{2.5}$ per year. Approximately 90% of the $PM_{2.5}$ emissions come from boilers in Harris County use either natural gas or process gas as a fuel source. About 1.4% of the emissions come from process heaters that are oil fired. The remaining emissions come from process heaters that do not specify their fuel source in the inventory.

2. Capacity/Usage Rate/Duty Cycle

Process heaters vary widely in size. Their usage is dependent upon the needs for heat. It is common for process heaters to run continuously. Higher emissions can be seen during start up and shutdowns when process heaters are taken out for maintenance.

3. Condition

Process heaters have been part of industrial processes in Harris County for most of the last century. As a result some heaters are very old whereas others are fairly new. Process heaters must meet specifications set by the EPA based on their fuel type and their size. For process heaters that have solid or liquid fuels this might mean adding a baghouse, an ESP or a wet scrubber to remove particulates. Other process heaters have installed low NOx burners to meet more stringent NOx requirements. However, about 90% of process heaters in Harris County operate on natural gas or process gas.

4. Fluctuations due to time of day, day of week and time of year

Process heaters typically run continuously. Fluctuations can happen when demand changes or when maintenance occurs, but these items are generally independent of time of day or season.

5. How is the $PM_{2.5}$ emission factor determined?

Emissions are very dependent on the type of fuel used by the boiler and to a lesser degree the type of burner. Burner manufacturers publish emission factors for their burners based on testing. However emission rates can vary significantly depending on what kind of controls are added. Although process heaters often have continuous emissions monitoring systems on their stacks to measure actual emissions of NOx, SO2 and CO, they do not continuously measure particulates due to the complexities of measuring the condensable portion. Measurements indicate the $PM_{2.5}$ emission factors for process heaters are similar to the factors found for boilers.[62, 63]

D. Control Methods, Efficiencies and Costs

The "work standard practice" is an annual tune up. All boilers and process heaters are subject to a work practice standard. Large units (greater than or equal to 10 MMBtu per hour) are required to conduct an annual tune-up. All small boilers (less than 10 MMBtu per hour) combusting any fuel, and limited use boilers (less than 876 hours of operation per year) are required to conduct a biennial boiler tune-up. Very small units designed to burn gaseous fuels or light liquid fuels (less than 5 MMBtu per hour) are required to conduct a tune-up every 5 years. The annualized cost for an annual tune-up is $2,875 per boiler in 2008 dollars. [55, 56]

A Tune-up requires the following steps:
1. Inspect the burner, and clean or replace any components of the burner as necessary.
2. Inspect the flame pattern and adjust the burner as necessary to optimize the flame pattern. The adjustment should be consistent with the manufacturer's specifications, if available.
3. Inspect the system controlling the air-to-fuel ratio and ensure that it is correctly calibrated and functioning properly.

4. Optimize total emissions of carbon monoxide. This optimization should be consistent with the manufacturer's specifications, if available, and with any nitrogen oxide requirement.
5. Measure the concentrations in the effluent stream of carbon monoxide in parts per million, by volume, and oxygen in volume percent, before and after the adjustments are made.
6. Maintain onsite and submit, if requested by the Administrator, biennial or five year report.
7. If the unit is not operating on the required date for a tune-up, the tune-up must be conducted within 30 days of startup. You must conduct the tune-up while burning the fuel that provided the majority of the heat input to the boiler in the last 12 months before the tune-up.[57]

In contrast, an energy assessment must include the following items:
1. A visual inspection of the boiler system (e.g. cracks, corrosion, leaks, insulation).
2. An evaluation of operating characteristics of the affected boiler systems, specifications of energy systems, operating and maintenance procedures, and unusual operating constraints.
3. An inventory of major systems consuming energy (i.e., energy use systems).
4. A review of available architectural and engineering plans, facility operation and maintenance procedures and logs, and fuel usage.
5. A list of major energy conservation measures that are within the facility's control.
6. A list of the energy savings potential of the energy conservation measures identified.
7. A comprehensive report detailing the ways to improve efficiency, the cost of specific improvements, benefits, and the time frame for recouping those investments. [57]

According to the EPA's Boiler MACT rule in 2011, for all new and existing natural gas and refinery gas-fired units, the operator must perform an annual tune-up instead of emission limit to comply with regulations. Other gases can qualify for tune-ups by demonstrating that they burn cleanly, with contaminant levels similar to natural gas.[59]

The first control option recommended for natural gas and process gas fueled process heaters is to perform annual tune-ups. EPA tests conducted on four gas fired process heaters yielded a maximum potential of 34% emission reduction through best combustion practices and annual tune ups.[55]

1. Research

EPA's advice to reduce emissions from boilers is first to convert coal, wood and oil process heaters to natural gas or fuel gas process heaters. Gas fired heaters are subject to additional rules related to tune-ups and energy assessments depending on size as described above. Ron Myers at EPA indicated that further improvements on boiler and process heater emissions are not likely to be seen because the current measurement practices and not distinguish signal from the noise level of the measurement.[60] Therefore if additional reductions are to be made they would require significant research and development to achieve. We have entered $1,000,000/ton as a default to accommodate all of the costs associated with potentially finding other means of reducing particulate emissions.

2. Annual Tune-ups

Note as indicated above, all boilers that are larger than 10 MMBtus/hour are subject to annual tune-ups. These tune-ups would apply to smaller boilers. There may be an opportunity to reduce emissions by confirming that these tune-ups are occurring on a regular basis. The efficiency for performing a tune-up is 34% and the cost effectiveness is $ 5,153 per ton $PM_{2.5.}$ Detailed calculations are provided in Appendix C.

3. Biennual Tune-ups

This is a duplicate of option 2, except performed every 2 years instead of annually. Reducing this requirement drops the efficiency to 22%, but also drops the cost to $ 3,983 per ton $PM_{2.5.}$

4. Energy Assessment

An energy assessment, as described previously, would be applied to any boilers that are not regulated. The efficiency is estimated at only 15% and the cost effectiveness is $ 8,125 per ton $PM_{2.5}$.

5. Oil to Gas Conversion

Less than 10% of the process heaters in Harris County point sources are fueled by oil. If they were converted to gas fired boilers the efficiency of particulate reduction would be 90%. The cost to upgrade from an oil to gas fired process heater must consider many things including:

- The cost of the fuel
- The need to comply with the maximum available control technology (MACT) standard
- Adjustments that need to be made to the controls in order comply with annual tune-ups associated with industry standards..
- Changes that impact the facility outside of the boiler, such as delivery of the new fuel to the heater.
- Equipment (e.g. baghouse, scrubber, ESP) that must be removed.
- Adjustments to account for differences in the heat transfer that occurs with gas.
- Downtime can be 6 months to a year.[61]

Because the many variables and the scale of a project like this the costs will be variable and high, and since the contribution of oil fired process heaters is relatively small, a cost effectiveness has not been estimated for this option.

E. Cost Effectiveness

In the following table is a summary of the cost effectiveness of the various options for particulate control on process heaters.

Table 16.

Control Methods and Cost Effectiveness for Process Heaters

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Process Heater Research	100%	$1,000,000
Annual Tune-up	34%	$5,153
Biennial Tune-up	22%	$3,983
Energy Audit	15%	$8,125
Oil to Gas Conversion	90%	Not estimated

The Oil to Gas Conversion was not estimated because a small percentage of process heaters fall into this category and the costs are variable and large.

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

According to the most recent inventory[11] the process heater $PM_{2.5}$ emissions are 1084 tons per year. This means that a 10% reduction requires 108 tons be eliminated and a 25% reduction requires that a 271 tons be eliminated.

If we assume that each of these measures can be applied enough to achieve these results, we obtain the following:

Table 17.

Cost to Reduce Process Heater $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Process Heater Research	100%	$108,400,000	$271,000,000
Annual Tune-up	34%	$558,585	$1,396,463
Biennial Tune-up	22%	$431,757	$1,079,393
Energy Audit	15%	$880,750	$2,201,875
Oil to Gas Conversion	90%	Not Possible	Not Possible

However, if assume that the annual tune-up, the biennial tune-up and the energy audit can each apply to no more than 25% of the boilers. In that case, with efficiencies of 34%, 22% and 15% respectively the most reductions each can obtain is

Annual Tune-up - 0.25 * 1084 *0.34 = 92 tons
Biennial Tune-up - 0.25 * 1084 *0.22 = 60 tons
Energy Assessment - 0.25 * 1084 *0.15 = 41 tons

Then none of these approaches can achieve a 108 ton or 10% reduction, much less a 25% reduction. For the purposes of this project we have assumed that each of these three approaches can achieve 1% or 10.8 tons worth of reductions and the remainder will have to be achieved through “research”.

The Oil to Gas Conversion is not possible because although it is 90% efficient, it can only be less than 10% of the process heaters.

XVI. Gas Turbines

A. Source Definition

Power plants use several methods to convert gas to electricity. One method is to burn natural gas or fuel gas in a combustion turbine to generate electricity. For these units, air is pulled in from outside and compressed; the compressed air is ignited by burning gas and expands. The expanding air pushes the turbine generators much like steam does in a steam-electric station. The turbines then turn the electric generators.

Another technology is called a "combined cycle" gas turbine. A combined-cycle primarily uses combustion turbines, heat-recovery steam generators (or boilers), and steam turbines to convert gas fuel to electricity. The gas is burned in the combustion turbines to produce mechanical power that is converted to electric power by the generators. For increased efficiency, the hot exhaust gases resulting from this combustion process are routed through the boiler, which produces steam and additional electricity.[64, 65]

B. Description of how the source emits $PM_{2.5}$

$PM_{2.5}$ emissions, as defined by US EPA, include filterable and condensable emissions, although in the EU and other places, PM requirements typically only include filterable emissions. Filterable emissions are emissions that exit the stack in either solid or liquid state. Condensable PM is the portion of PM emissions that exit the stack in gaseous form and condense upon mixing with cooler ambient air to form particulate matter. These emissions are most likely from liquid hydrocarbons and sulfates in the fuel.[66]

In general, gas turbines produce significantly fewer emissions than electricity formed by coal-burning or oil fired turbines, and are frequently noted as a solution to high emissions from these other sources. The reported emissions from gas turbines are dependent on the measurement techniques used, and may come from a variety of sources that are independent of the combustion process. A study by GE noted that filterable PM from combustion turbines may actually in part be from airborne PM that passes through the gas turbine inlet air filters or impurities in the water used for water injection. Condensable PM may consist of sulfates, especially if there is a selective catalytic reduction (SCR) system, and unburned fuel hydrocarbons. Formation of ammonium sulfates from the SCR system in a combined cycle application will also accelerate the corrosion of the heat recovery steam generator tubes downstream from the catalyst, potentially contributing to the PM loading."[67, 68]

$PM_{2.5}$ sampling methodologies were designed for relatively high concentration sources, making accurate measurement difficult for the dilute emissions from natural gas turbines. (See below)

How Much $PM_{2.5}$ is from Gas Turbines?

"PM emissions from turbines primarily result from carryover of noncombustible trace constituents in the fuel. PM emissions are negligible with natural gas firing"[69] Switching to natural gas from coal burning or diesel burning turbines is often recommended as a control measure because natural gas combustion is a much lower source of air emissions. However, while gas combustion is typically thought of as a "clean" process, the enormous quantities of gas burned in boilers, process heaters, and engines can make small emissions a notable source of $PM_{2.5}$. Tests of industrial gas-fired boilers and gas turbines in which particulate emissions measurements included both the filterable and condensable particles show that the condensable fraction is significant, sometimes exceeding the filterable fraction. Testing methods may overestimate particulate emissions, especially the ultrafine condensable particle fraction. This may be due to analytical method artifacts associated with application of methods designed for much higher particle concentrations.

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

According to the records, Harris County has 83 gas turbines that account for 637.8 tons of $PM_{2.5}$ emissions. Almost 60% of these emissions are related to electricity production that serves the electrical grid. The remaining emissions are related to co-generation plants that are used for industrial purposes such as petroleum refining and chemical production.

Measurement Issues

PM emissions from turbines primarily result from carryover of noncombustible trace constituents in the fuel. PM emissions are negligible with natural gas firing. Filterable PM is that portion of the total PM that exists in the stack in either the solid or liquid state. Stationary Internal Combustion Sources can be measured on a EPA Method 5 filter. Condensable PM is that portion of the total PM that exists as a gas in the stack but condenses in the cooler ambient air to form particulate matter. Condensable PM exists as a gas in the stack, so it passes through the Method 5 filter and is typically measured by analyzing the impingers, or "back half" of the sampling train. The collection, recovery, and analysis of the impingers is described in EPA Method 202 of Appendix M, Part 51 of the Code of Federal Regulations.[69]

According to EPRI, "Monitoring of PM from natural gas facilities is very challenging due to low PM emission rates. Both filterable and condensable PM emissions remain very difficult to measure at natural gas power plant stacks. The methods with highest potential for accuracy involve dilution tunnel sampling. However, even these methods have background $PM_{2.5}$ concentrations from the dilution air used (despite the use of High Efficiency Particulate Arresting [HEPA] filtration), such that this dilution air was the source of most of the overall measurement uncertainty. The dilution air itself must be measured carefully to understand the background PM values for each testing situation. It is important to note that the composition of

PM determined from testing with dilution methods as opposed to more traditional impinger methods results in a shift in dominance from sulfurous compounds to carbonaceous compounds. Regardless of the method used, and even with extreme care taken in method application, the blank PM values can in many cases approach the measurement values, and be highly variable. Thus, although the emissions of PM may be small, even small changes in method application, or changing of compliance samplers, may affect the emissions compliance status of a power plant."[70]

3. How is the $PM_{2.5}$ emission factor determined?

Argon National Lab[71]
Natural Gas Internal Combustion Turbines = 49.3 lb/million scf
Natural Gas Combined Cycle turbines = 0.0066 lb/million scf

Emission factors used in the RAINS model for stationary combustion of natural gas [kt/PJ]

Sector	**$PM_{2.5}$**
Power plants	0.0001
Conversion	0.0001
Industry	0.0001[72]

EMISSION FACTORS FOR CRITERIA POLLUTANTS AND GREENHOUSE GASES FROM STATIONARY GAS TURBINES[69]

Natural Gas-Fired Turbines (lb/MMBtu)
PM (condensable) 4.7 (filterable) 1.9 (total) 6.6
Emission factors are based on combustion turbines using water-steam injection
Natural Gas emits far fewer pollutants that oil or coal as indicated in this table taken– Natural Gas Issues and Trends 1998.[73]

Fossil Fuel Emission Levels
- Pounds per Billion Btu of Energy Input

Pollutant	**Natural Gas**	**Oil**	**Coal**
Particulates	7	84	2,744

D. Control Methods, Efficiencies and Costs

The RACT/BACT/LAER Clearinghouse (RBLC) data base[74] contains case-specific information on the "Best Available" air pollution technologies that have been required to reduce the emission

of air pollutants from stationary sources (e.g., power plants, steel mills, chemical plants, etc.).The RBLC documents do not list any post-combustion particulate control technologies being used on combustion turbines (either simple or combined cycle). Rather, the good combustion controls and clean burning natural gas (low sulfur fuel) is considered the best available control for PM/PM_{10}/ $PM_{2.5}$.[75]

Because the PM emissions are often based on the non-combustibles in the fuel itself, there is little that can be done, although there is some research being conducted on filters for the fuel source to remove contaminants such as the odorant that is added to natural gas, and which may contribute to $PM_{2.5}$. CA BACT for gas turbines plants 50MW or greater for PM is using natural gas with fuel sulfur content less than or equal to 1 grams/100 standard cubic feet

In addition, SCRs systems are used in natural gas turbines used to control NOx. These systems use ammonia, precursor to $PM_{2.5}$ as a reagent. Therefore, slip from these emission control units could constitute a source of $PM_{2.5.}$ However, modeling done in California showed that ammonia slip from power plant NOx emission controls are a relatively minor source of ammonia.

Energy efficiency measures can be undertaken to reduce the electrical demand, both industrial energy efficiency to improve industrial operations, and wider-spread programs such as those that CenterPoint undertakes to reduce demand on the grid. However it is likely that even these measures will only be able to reduce the emissions by a small factor.[76]

Finally, the locations could switch to renewable sources of energy that do not create particulate matter, although their ability to generate sufficient power may be limited by the physical location of some of the facilities. Typically, commercial wind turbines are sized at about 2 MW of installed capacity (2000 kW) and cost about $3 million to 4 million to be installed. (http://www.renewablegreenenergypower.com/how-much-wind-turbines-cost/). Prices for a similar sized solar facility could be similar, although would likely be slightly higher, depending on the location and installation (http://www.bizjournals.com/austin/blog/techflash/2014/05/austin-energy-buys-sun-power-texas-sized-array-on.html?page=all).

E. Cost Effectiveness

As indicated by the previous discussions there are no controls currently available to address the particulate emissions from natural gas/process gas combustion. Even if those controls did exist the current measurement practices are not able to measure the reduction in emissions because the reductions would be within the noise of the readings. As a result we have place a very high default value of $1,000,000/ton of $PM_{2.5}$ and 100% efficiency to represent a placeholder for this category. As is true with all categories the user is able to enter their own controls, control efficiency and cost effectiveness if another option becomes available.

Table 18.

Control Methods and Cost Effectiveness for Gas Turbines

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Gas Turbine Research	100%	$1,000,000

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

Using the $1,000,000/ton PM2.5 cost effectiveness described in the last section and 736 tons identified from the most recent inventory[11] the cost of a 10% reduction will be:

0.10 * 736 tons * $1,000,000/ton PM2.5 = $73.6 million

A 25% reduction would cost:

0.25 * 736 tons * $1,000,000/ton PM2.5 = $184 million

Table 19.

Cost to Reduce Gas Turbine $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Gas Turbine Research	100%	$73,600,000	$184,000,000

XVII. Other Point Sources

A. Source Definition

Owners of point sources are required to submit their emission inventories each year to state regulatory environmental agencies. In 2011 the total of all $PM_{2.5}$ emissions from point sources in Harris County was 4,860 tons. Cooling water towers contributed 1741 tons or 35.8% of the total. Process Heaters contributed 1084 or 22.3% of the total. Boilers made up 638 tons or 13.1% of the total. Gas Turbines contributed 736 tons or 15.1% of the total. The remaining 661 tons or 13.6% were contributed by a variety of different "other point sources". There are over 24 different subcategories of other point sources and each category emits anywhere from 2.2 tons $PM_{2.5}$ per year to over 90 tons per year. Examples of the higher emitters in the other point source category include emissions related to plastics and synthetic resins, incinerators, iron and steel work, inorganic chemical production and abrasive blasting. However many of the emission sources in these categories are designated as "unclassified" and as such they cannot be evaluated for PM reduction control technologies without approaching the owners and asking for more details.

The table below shows the Harris County point source emissions broken down into five categories:

Table 20.

Harris County Point Source $PM_{2.5}$ Emissions Summary

Emission Source	Records	$PM_{2.5}$ Emissions (tons)
Cooling Water Towers	170	1639
Boilers	548	637.8
Process Heaters	660	1083.5
Gas Turbines	83	736.3
Other Point Sources	1694	724
Total	3155	4820.6

Just over half of the entries or emission sources did not fall into the categories that include cooling water towers, boilers, process heaters and gas turbines. These other point sources emitted 724 tons of $PM_{2.5}$, or 15% of the total. The average emission per entry was for other point sources were 0.43 tons/year. Compare that to cooling water towers which emitted on average more than 10 tons/year per cooling water tower. Gas turbines emitted an average of 8.9 tons/year/turbine. Boilers and process heaters emitted an average of 1.4 tons/year.

The low emission rates of the individual other point sources have significant implications for identifying emission controls in several ways. First, because these emission sources are so diverse, we cannot identify any single control option that will mitigate all or any significant section of these sources. In order to find out the appropriate control strategies substantial research must be done to identify the right strategies, locate the equipment that is applicable and implement the controls. Additionally, since the emissions per entry is very low the total emissions reduced will also be low, which will mean a higher price per ton or higher cost efficiency. A summary of the main subcategories of other point sources taken from the TCEQ emissions inventory is provided in the following table.

Table 21.

Subcategories of Other Point Sources in Harris County

Other Point Sources	Records	$PM_{2.5}$ Emissions (tons)	Average Emission/Record
Abrasive Blasting	61	48.2	0.79
Asphalts	10	7.4	0.74
Cat Cracker	2	16.8	8.40
Coating and Printing	124	16.5	0.13
Dryers	74	22.2	0.30
Fiberglass	11	8.2	0.75
Flares	39	18.7	0.48
Food/Agriculture	46	6.6	0.14
Fugitive/Unclassified	47	92.3	1.96
Glass	27	5.2	0.19
Gypsum	24	4.5	0.19
I.C. Engines	434	24.2	0.06
Incinerators	86	73.4	0.85
Inorganic Chemicals	26	50.2	1.93
Iron and Steel	65	51.4	0.79
Not Classified	151	39.5	0.26
Oxidizers	45	12.4	0.28
Petroleum or Coke	13	3.6	0.28
Plastics Materials and Synthetic Resins	165	85.7	0.52
Plastics Production	24	40.2	1.68
Surface Coating	50	2.7	0.05
Vertical Fixed Roof Tanks	39	2.2	0.06
Miscellaneous	131	29.1	0.22

In order to identify the appropriate control options, efficiencies and costs each of these point source subcategories must be investigated further. Because there are a large number of variables to contend with and the application of any specific control strategy would have limited impact for reducing overall $PM_{2.5}$ emissions, the database includes generic control options for this category. The first option is to "Investigate and Control Emissions" assuming a generic control strategy is applied. The second option is to "Investigate, Repair and Maintain", assuming that the only new "control" added is a documented repair and maintenance program. As always the user can add additional controls along with their control costs and efficiencies that are specific to the problem that is of concern.

Some of the other point sources that would fit in this category but are not included because they are not found in Harris County include cement plants, paper and pulp mills and coal fired electric generating units. There are several documents developed that describe the emission reduction techniques for a broad range of sources including the "other point sources" identified here.[14, 19, 31, 77]

B. Description of how the source emits $PM_{2.5}$

Because the other point sources are different they have various means of forming $PM_{2.5}$. Some (e.g. flares and incinerators) form $PM_{2.5}$ from combustion processes, while others (e.g. abrasive blasting) are emitted from physical processes. Each source must be evaluated on a case by case basis to identify how $PM_{2.5}$ is created and how to select proper $PM_{2.5}$ reduction control strategies.

C. Impacts on Emission Estimates/Sources of Error

Emissions from point sources are self-reported. Because this category has a variety of different sources the estimates will be very different depending on the source. In some cases point source operators have opted to estimate that all of their PM_{10} emissions are $PM_{2.5}$ for expediency. This practice may over-represent some of the $PM_{2.5}$ emissions. Almost all particulate emissions from combustion processes are $PM_{2.5}$, however only a small fraction of the particulate from physical processes are typically in the $PM_{2.5}$ range.

D. Control Methods, Efficiencies and Costs

Control methods will vary depending on the emission source.

E. Cost Effectiveness

The average source in this category emits 0.4 tons of $PM_{2.5}$ per year. This value is very low when compared with the other Harris County point sources that have an average of 2.9 tons of $PM_{2.5}$/year. Because the sources are so varied and the solutions will be unique and cannot be widely applied, we have set a default cost effectiveness of $1,000,000 per ton of $PM_{2.5}$ for control strategies. This includes the cost to identify and locate specific sources as well as the means to control the emissions. This high end default value has been listed to account for all of the uncertainties. These values can be changed in the database or alternatively, new controls can be entered in along with their control efficiency.

Table 22.

Control Methods and Cost Effectiveness for Other Point Sources

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Other Point Source Research	100%	$1,000,000

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

There are 724 tons of $PM_{2.5}$ emitted each year in Harris County from Other Point Sources. Based on the $1,000,000/ton $PM_{2.5}$ default it will cost $66,100,000 to reduce emissions from this category by 10% and $1,653,000,000 to reduce emissions from this category by 25%.

Table 23.

Cost to Reduce Other Point Source $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Other Point Source Research	100%	$72,400,000	$181,000,000

XVIII. Mobile Sources



Photographed by Alex Cuclis

A. Source Definition

Mobile source emissions are generated by on-road and off-road vehicles and equipment. On-road sources consist of passenger cars, trucks, buses, motorcycles, etc., or other motorized vehicles that travel on public roads. Off-road vehicle and equipment consists of locomotives, commercial marine vessels, cargo loading equipment, construction equipment, lawn and garden equipment, recreational vehicles and aircraft, though aircraft are sometimes placed in their own category.

B. Description of how the source emits $PM_{2.5}$

Particulate emissions from mobile sources arise from the combustion of fuels. Diesel, marine and jet fuels create most of the particulate matter, especially if not controlled. Typically gasoline and gasoline engines generate only very small amounts of $PM_{2.5}$. Most of the particulate matter generated from combustion of these fuels is $PM_{2.5}$.

C. Impacts on Emission Estimates/Sources of Error

1. Number of Sources

For mobile sources of $PM_{2.5}$ the focus is typically on the number of diesel powered trucks on the road, as well as locomotives and commercial marine vessels if there is a port nearby. In the Los Angeles area the two major ports, Los Angeles and Long Beach, are responsible for about 25% of the total PM. Most port emissions come from ocean going ships, auxiliary engines on those ships and harbor craft. A 2007 study found that between 60-66% of particulates at the Port of Houston come from ocean going vessels.[78] Cargo handling equipment is also a significant contributor.[19] Other considerations include the diesel emissions related to the on-road and off-road equipment associated with construction activity and lawn and garden services in the area. In rural areas (outside Harris County) agricultural equipment can play a significant role.

2. Capacity/Usage Rate/Duty Cycle

For on-road sources of emissions the vehicle miles travelled (VMT) governs a large portion of the emissions. However there are also emissions associated with idling that must be addressed. For locomotives, the emissions that are often of greatest concern is from switcher yard trains which spend all their time in a relatively small area moving various compartment cars. For commercial marine vessels, there are certainly emissions during travel, but there are also emissions while docked at port since the engines usually continue to run to provide power, cooling, etc. for the vessel.

3. Condition

The condition of diesel engines has been addressed by EPA in the past 10 - 15 years by providing increasingly strict regulations on new engines being built known as the Tier 1, 2, 3 and 4 regulations. These regulations have substantially reduced emissions in recent years. However many diesel engines last for decades, so getting them replaced with new engines often requires substantial financial incentives.

4. Fluctuations due to time of day, day of week and time of year

On-road emissions are subject to typical traffic cycles and thus are highest during rush hours. Others are related to the time they are used. Construction equipment is used most often between business hours from Monday to Friday, so that is when they have their greatest contribution.

5. How is the $PM_{2.5}$ emission factor determined?

Emission factors are developed by measuring the exhaust from engines placed under different loads to simulate a typical duty cycle in laboratories. The on-road emissions are developed by identifying the vehicle miles traveled of each of several different classes of diesel engines and entering it into a model such as Mobile6 or MOVES. These models generate the total pollutants from diesel engines.

For other sources such as locomotives, commercial marine vessels and airports, a similar approach is taken; however, generally determining the total emissions involves an extensive task not only of the types of locomotive, marine vessel or aircraft equipment, but also the emissions from the cargo handling and other support equipment.

D. Control Methods, Efficiencies and Costs

Most of the specifications for controls on mobile sources are generally governed by national and sometimes international laws and agreements and plans for reducing $PM_{2.5}$ from sources in this category is outside the scope of this project. Federal regulations dominate the required pollution controls for mobile sources including reduction of PM in the exhaust and the sulfur content of diesel fuels. Cost effective reduction of $PM_{2.5}$ emissions by local authorities from these sources often rely on incentive programs that are not under the jurisdiction of the local government. The incentive programs impact both on-road and off-road vehicles and equipment.[17] Incentive programs exist in California's Carl Moyer Memorial Air Quality Standards Program, the Texas Emissions Reduction Program, and programs in New York, New Jersey and the Puget Sound area.[19]

Gasoline engines produce very little particulate matter, so the majority of reductions come by addressing problems with diesel engines. Many diesel engines, both on-road and off, last for many years, so turnover can be very slow. The reductions which are set in place typically come from one of the following approaches:

1. Reduction in Usage

By encouraging low emission driving techniques, controlling traffic flow, cargo handling policies, implementing no idling rules, etc. pollutants of all kinds are reduced.

2. Incentive Funding

Incentives may be applied in a variety of ways to reduce emissions. Funding may be provided to off-set the purchase of a new vehicle or equipment that meets current standards, but in

some cases the funding is limited to an upgrade using technologies that have been verified to reduce emissions.[79, 80] The categories of items that incentives are given to are as follows:

a. Replace/accelerate retirement – provides funding to purchase a new, cleaner vehicle or equipment as long as the old polluting device is retired.

b. Repower – keep the vehicle/equipment, but replace the engine with a cleaner one.

c. Convert to electric/hybrid electric

d. Alternative fuels. A variety of different fuels is available; however converting from diesel to natural gas is the most effective, reducing particulate matter by more than 90%.[81] One technique is to use biofuels which can reduce particulate matter, however they can also create an increase in nitrogen oxides.[82]

e. Retrofits - Most are after-treatment installed on the exhaust systems. The two most common retrofit technologies are diesel oxidation catalyst and diesel particulate filters. The cost effectiveness of these controls ranges from $11,000 to $70,000 per ton of PM/ $PM_{2.5}$.[77] Other options are flow-through filters (FTFs), selective catalytic reduction (SCR) and exhaust gas recirculation (EGR).[84, 85]

f. Repair or rebuild – Even if there are no technological changes, simply putting the engine in good running condition by fixing problems or doing a complete engine overhaul will help to reduce pollutants of all kinds.[19]

Many of these techniques have been applied to school buses due to the impact that high emissions of $PM_{2.5}$ can have on school children.[86]

The techniques described above for reduction of particulate matter for on-road engines also applies to off-road vehicles and equipment. Some off-road equipment like commercial marine vessels, locomotives and aircraft has unique challenges and opportunities for reducing $PM_{2.5}$. Locomotives include long haul, regional and local switch cars. It is difficult to address pollutants from locomotives that pass through from one state to the next; however, some measures, like reducing idle times, may be employed. More effective techniques are generally associated with upgrading or replacing switcher engines.[17] Diesel engines have undergone dramatic improvements due to regulations that have been introduced since the late 1990's. The amount of reduction required depends on the year of the vehicle or equipment and the Tier level.[87]

3. Commercial Marine Vessels

Commercial marine vessels fall into a special category because they involve International Ocean going ships and thus cannot be regulated by the U.S. alone. However there are some options available to reduce particulate emissions. Note that for burning marine fuel oil it is estimated that 80% of the PM_{10} is $PM_{2.5}$. For diesel 97% of PM_{10} is considered to be $PM_{2.5}$ and 100% of propane/natural gas PM_{10} is $PM_{2.5}$.[78]

a. Cold Ironing – This term is used to describe the use of on-shore based electricity to power lights, cooling systems, cranes and other equipment on vessels when they are docked. This reduces the particulates associated with the burning fuel, typically diesel. The objection to

this process is that many ships have different electrical power needs in terms of watts, amperage, connectors, etc. The California Air Resources Board has identified a number of cases where cold ironing is used and concludes that it is technically feasible. However, they also indicate that the costs for creating the on-shore infrastructure are high and obtaining the property to build it on will be costly as well. In addition, the costs to retrofit commercial marine vessels will also be high. Since many of these vessels fly under international flags, the ability to encourage these retrofits is limited.[88]

b. Repower Category 1 marine engines (e.g. tugboats). Engine replacement costs can exceed $100,000.[19, 88] Because harbor vessels can outlast their engines, this may be an alternative. Identifying the efficiency of this control is difficult since engines vary widely in emissions depending on age and condition.



Photographed by Alex Cuclis

Costs and cost effectiveness varies depending on the subcategory within mobile emissions. Below are descriptions specific to the four main categories of on-road, off-road, commercial marine vessels and locomotives.



Photographed by Alex Cuclis



Caterpillar 3508 engine on a tugboat. Photographed by Alex Cuclis

E. Cost Effectiveness

Cost effectiveness for mobile emissions can vary significantly depending on the source and the selected control method. As mentioned previously, substantial emission reductions have occurred and will continue to occur simply due to fleet turnover and the requirements for newly purchased engines to meet more stringent pollution controls. The cost per ton will vary depending on the cost of the new vehicle or equipment purchased and the amount of pollution reduced by eliminating the old equipment. Retrofitting equipment can have a cost efficiency ranging between $11,000 and $70,000 per ton of PM/$PM_{2.5}$ (2006 dollars).[83] Because the cost of replacement or even retrofits can be high financial incentive programs like California's Carl Moyer program or Texas's Emission Reduction Plan (TERP) are generally required to make this happen.

The efficiency and cost-effectiveness for the most common methods to reduce $PM_{2.5}$ from on-road sources is provided below. It should be remembered that cost, emissions and potential emissions reductions vary significantly between different vehicles. The costs provided below are average values. More details about these calculations can be found in Appendix C.

Table 24.

Control Methods and Cost Effectiveness for On-Road Sources

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Diesel Oxidation Catalyst	20%	$46,215
Catalytic Diesel Particulate Filter	90%	$52,700
Other Retrofit, Repower or Replacement	95%	$100,000

According to the most recent inventory there are 1795 tons of $PM_{2.5}$ emitted each year from mobile on-road sources. In order to reduce the emissions by 10% and 25% the emissions must be reduced by 180 tons and 450 tons respectively. The most economical method to reduce emissions is using a DOC, however DOCs only have a 20% efficiency so they cannot achieve a 25% reduction. The next most economical choice is to use a CDPF. The results of calculations as shown in previous examples yield the following results:

Table 25.

Cost to Reduce On-Road $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Diesel Oxidation Catalyst	20%	$8,318,700	Not Possible
Catalytic Diesel Particulate Filter	90%	$9,486,000	23,715,000

For the purpose of this project it has been assumed that a 50/50 split in the use of diesel oxidation catalyst and catalytic diesel particulate filter is applied for estimating the cost of a 10% and 25% reduction in this category.

The efficiency and cost-effectiveness for the most common methods to reduce $PM_{2.5}$ from off-road sources is provided in the next table. It should be remembered that cost, emissions and

potential emissions reductions vary significantly between different off road sources. The costs provided below are average values. More details about these calculations can be found in Appendix C.

Table 26.

Control Methods and Cost Effectiveness for Off-Road Sources

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Diesel Oxidation Catalyst	20%	$45,942
Catalytic Diesel Particulate Filter	90%	$51,072
Other Retrofit, Repower or Replacement	95%	$100,000

According to the most recent inventory there are 1090 tons of $PM_{2.5}$ emitted each year from mobile off-road sources. In order to reduce the emissions by 10% and 25% the emissions must be reduced by 109 tons and 273 tons respectively. The most economical method to reduce emissions is using a DOC, however DOCs only have a 20% efficiency so they cannot achieve a 25% reduction. The next most economical choice is to use a CDPF. The results of calculations as shown in previous examples yield the following results:

Table 27.

Cost to Reduce Off-Road $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Diesel Oxidation Catalyst	20%	$5,007,700	Not Possible
Catalytic Diesel Particulate Filter	90%	$5,566,800	13,917,000

For the purpose of this project it has been assumed that a 50/50 split in the use of diesel oxidation catalyst and catalytic diesel particulate filter is applied for estimating the cost of a 10% and 25% reduction in this category.

The efficiency and cost-effectiveness for the most common methods to reduce $PM_{2.5}$ from commercial marine vessels is provided in the next table. Cold ironing or providing power from

on-shore to the ships that are docked and harbor craft repowering were identified as the most likely candidates for emission reductions. More details about these calculations can be found in Appendix C.

Table 28.

Control Methods and Cost Effectiveness for Commercial Marine Vessels

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Cold Ironing	Varies	$1,000,000
Harbor Craft Repower	60%	$192,571

According to the most recent inventory there are 661 tons of $PM_{2.5}$ emitted each year from commercial marine vessels. In order to reduce the emissions by 10% and 25% the emissions must be reduced by 66 tons and 165 tons respectively. Further research may identify a means to reduce the cost and installation of cold ironing. However it may be that harbor craft repowering is the most economical method to reduce emissions as indicated in the following table.

Table 29.

Cost to Reduce Commercial Marine Vessel $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Cold Ironing	Varies	$66,100,000	$165,000,000
Harbor Craft Repower	60%	$13,106,000	$32,764,000

Table 30.

The efficiency and cost-effectiveness for the most common methods to reduce $PM_{2.5}$ from locomotives is provided in the next table. More details about these calculations can be found in Appendix C.

Control Methods and Cost Effectiveness for Locomotives

Control Method	Efficiency	Cost Effectiveness in dollars/ton of $PM_{2.5}$
Diesel Oxidation Catalyst	25%	$13,529
Idle Reduction/Switch Yard	60%	$14,297
Repower with New Engine	60%	$409,314

According to the most recent inventory there are 97 tons of $PM_{2.5}$ emitted each year from locomotives. In order to reduce the emissions by 10% and 25% the emissions must be reduced by 9.7 tons and 24.3 tons respectively.

Table 31.

Cost to Reduce Locomotives $PM_{2.5}$ by 10% and 25%

Control Measure	Efficiency	10% Reduction	25% Reduction
Retrofit – Diesel Oxidation Catalyst	25%	$131,231	$328,078
Idle Reduction/Switch Yard	60%	$138,681	$346,702
Repower with New Engine	60%	$3,970,346	$9,925,864

F. What would the best way to reduce $PM_{2.5}$ in this category by 10% and by 25% and how much would it cost?

Based on the analysis above the best option for this application is to use a diesel oxidation catalyst at a cost of $131,231 for a 10% reduction and $328,078 for a 25% reduction. Note that according to the inventory 53 tons of $PM_{2.5}$ come from rail yard locomotives. The total $PM_{2.5}$ emission reductions that could be achieved from this category would be 0.6 * 53 = 32 tons of $PM_{2.5}$.

XIX. Achieving 10% and 25% Reductions of $PM_{2.5}$ in Harris County

One approach to achieve targeted reductions is to require reductions by 10% and 25% in each sector.

Table 32.

Cost to Reduce Overall $PM_{2.5}$ by 10% and 25% for Each Sector

Sector	Annual PM2.5 Emissions (tons)	Control Measure	Cost Effectiveness ($/ton)	10% Reduction (tons)	Cost of 10% Reduction	25% Reduction (tons)	Cost of 25% Reduction
Unpaved Roads	4815	Chemical Stabilizer	$ 29,545	481.5	$ 14,225,918	1203.8	$ 35,564,794
Construction	1843	Dust Control Plan	$ 356,245	184.3	$ 65,655,954	460.8	$ 164,139,884
Paved Roads	2317	Pave Existing Shoulders	$ 149,525	115.9	$ 17,322,471	289.6	$ 43,306,178
		Pave Interior Roads	$ 166,372	115.9	$ 19,274,196	289.6	$ 48,185,491
Commercial Cooking	2087	Catalytic oxidizer	$ 7,134	140.0	$ 998,760	140.0	$ 998,760
		Electrostatic Precipitator	$ 12,123	68.7	$ 832,850	381.8	$ 4,627,955
Residential Wood Combustion	735	Remove Old Wood Stoves for Money or "Bounty"	$ 5,495	73.5	$ 403,883	183.8	$ 1,009,706
Cooling Water Towers	1638.5	Cooling Water Tower Research	$ 1,000,000	114.7	$ 114,695,000	360.5	$ 360,470,000
		Install a Drift Eliminator	$ 4,170	16.4	$ 68,325	16.4	$ 68,325
		Replace Existing Drift Eliminator	$ 5,628	16.4	$ 92,215	16.4	$ 92,215
		Implement Maintenance Plan	$ 11,461	16.4	$ 187,788	16.4	$ 187,788
Boilers	637.8	Boiler Research	$ 1,000,000	44.6	$ 44,646,000	140.3	$ 140,316,000
		Annual Tune-up	$ 7,271	6.4	$ 46,374	6.4	$ 46,374
		Biennial Tune-up	$ 5,620	6.4	$ 35,844	6.4	$ 35,844
		Energy Audit	$ 11,465	6.4	$ 73,124	6.4	$ 73,124
Process Heaters	1083.5	Process Heater Research	$ 1,000,000	75.8	$ 75,845,000	238.4	$ 238,370,000
		Annual Tune-up	$ 5,153	10.8	$ 55,833	10.8	$ 55,833
		Biennial Tune-up	$ 3,983	10.8	$ 43,156	10.8	$ 43,156
		Energy Audit	$ 8,125	10.8	$ 88,034	10.8	$ 88,034
Gas Turbines	736.3	Gas Turbine Research	$ 1,000,000	73.6	$ 73,630,000	184.1	$ 184,075,000
Other Point Sources	724	Other Point Source Research	$ 1,000,000	72.4	$ 72,400,000	181.0	$ 181,000,000
On-Road	1795	Diesel Oxidation Catalyst	$ 46,215	89.8	$ 4,147,796	89.8	$ 4,147,796
		Catalytic Diesel Particulate Filter	$ 52,700	89.8	$ 4,729,825	359.0	$ 18,919,300
Off-Road	1090	Diesel Oxidation Catalyst	$ 45,942	54.5	$ 2,503,839	54.5	$ 2,503,839
		Catalytic Diesel Particulate Filter	$ 51,072	54.5	$ 2,783,424	218.0	$ 11,133,696
Commercial Marine Vessels	661	Harbor Craft Repower	$ 192,571	66.1	$ 12,728,943	165.3	$ 31,822,358
Locomotives	97	Diesel Oxidation Catalyst	$ 13,529	4.9	$ 65,616	4.9	$ 65,616
		Idle Reduction/Switch Yard	$ 14,297	4.9	$ 69,340	19.4	$ 277,362
Totals*	**20260.1**			**2026.0**	**$ 527,649,509**	**5065.0**	**$ 1,471,624,428**

*Note: totals do not include 208 tons associated with miscellaneous area and mobile sources.

In Table 32 several sectors have more than one entry. This is because some of the controls only pertain to a small percentage of the emissions within that sector and/or their efficiencies may be low so that they cannot attain the 10%/25% total reductions for their sectors alone.

A more common approach is to take the most cost effective (lowest cost) controls across all sectors and identify the lowest cost to achieve overall reductions of 10% and 25%. This approach is illustrated in the following table:

Table 33.

Cost to Reduce Overall $PM_{2.5}$ by 10% and 25% Using Least Expensive Controls

Sector	Annual PM2.5 Emissions (tons)	Control Measure	Cost Effectiveness ($/ton)	10% Reduction (tons)	Cost of 10% Reduction	25% Reduction (tons)	Cost of 25% Reduction
Unpaved Roads	4815	Chemical Stabilizer	$ 29,545	0.0	$ -	1203.8	$ 35,564,794
		Additional Chemical Stabilizer	$ 29,545	0.0	$ -	1429.3	$ 42,228,669
Commercial Cooking	2087	Catalytic oxidizer	$ 7,134	140.0	$ 998,760	140.0	$ 998,760
		Electrostatic Precipitator	$ 12,123	68.7	$ 832,850	381.8	$ 4,627,955
		Additional Electrostatic Precipitator	$ 12,123	1136.5	$ 13,777,790	1205.3	$ 14,611,246
Residential Wood Combustion	735	Remove Old Wood Stoves for Money or "Bounty"	$ 5,495	73.5	$ 403,883	183.8	$ 1,009,706
		Additional Wood Stoves	$ 5,495	146.5	$ 805,018	36.2	$ 198,919
		Phase 2 Qualified Fireplaces	$ 9,775	360.0	$ 3,519,000	360.0	$ 3,519,000
Cooling Water Towers	1638.5	Install a Drift Eliminator	$ 4,170	16.4	$ 68,325	16.4	$ 68,325
		Replace Existing Drift Eliminator	$ 5,628	16.4	$ 92,215	16.4	$ 92,215
		Implement Maintenance Plan	$ 11,461	16.4	$ 187,788	16.4	$ 187,788
Boilers	637.8	Annual Tune-up	$ 7,271	6.4	$ 46,374	6.4	$ 46,374
		Biennial Tune-up	$ 5,620	6.4	$ 35,844	6.4	$ 35,844
		Energy Audit	$ 11,465	6.4	$ 73,124	6.4	$ 73,124
Process Heaters	1083.5	Annual Tune-up	$ 5,153	10.8	$ 55,833	10.8	$ 55,833
		Biennial Tune-up	$ 3,983	10.8	$ 43,156	10.8	$ 43,156
		Energy Audit	$ 8,125	10.8	$ 88,034	10.8	$ 88,034
Locomotives	97	Diesel Oxidation Catalyst	$ 13,529	0.0	$ -	4.9	$ 65,616
		Idle Reduction/Switch Yard	$ 14,297	0.0	$ -	19.4	$ 277,362
		Additional Idle Reduction/Switch Yard	$ 14,297	0.0	$ -	12.6	$ 180,142
Totals*				**2026.0**	**$ 21,027,994**	**5065.0**	**$ 103,792,720**

*Note: totals do not include 208 tons associated with miscellaneous area and mobile sources.

In Table 33 the light green cells were taken from the previous table because they had the lowest cost effectiveness values, and thus could be used to achieve reductions at the lowest cost. Additional emission reductions were needed from the commercial cooking and residential

wood combustion sectors to achieve the overall 10% reduction of 2026 tons of $PM_{2.5}$. These sectors were selected specifically because there were more emissions available to be reduced and there were also controls that had low cost effectiveness values. However, there were not enough emissions available in those control options to achieve the 25% reduction target. In order to get additional reductions emissions from locomotives and from unpaved roads were included with their associated controls and cost effectiveness. All of the "new" emissions that are reduced in Table 33 have been highlighted in yellow.

Note that in both Tables 32 and 33 the cost to reduce emissions by 25% is much more than 2.5 times the cost to reduce emissions by 10%. That is simply a result of removing the least expensive emissions first.

Also note that the total costs for 10% and 25% reductions in table 33 are more than an order of magnitude lower that the costs identified in Table 32. This again suggests that targeting certain sectors can provide a substantial savings when seeking options to reduce pollution.

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