Characterization of process air emissions in automotive production plants

J.B. D’Arcya, J.M. Daschb, A.B. Gundrump, J.L. Riverab,∗, J.H. Johnsonc, D.H. Carlsc, and J.W. Sutherlandd,∗

aGM Research and Development Center, General Motors Corporation, Warren, Michigan; bUniversity of Technology of Troyes, CNRS, CREIDDD, Troyes, France; cDepartment of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, Houghton, Michigan; dEnvironmental and Ecological Engineering, Purdue University, West Lafayette, Indiana

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ABSTRACT
During manufacturing, particles produced from industrial processes become airborne. These airborne emissions represent a challenge from an industrial hygiene and environmental standpoint. A study was undertaken to characterize the particles associated with a variety of manufacturing processes found in the auto industry. Air particulates were collected in five automotive plants covering ten manufacturing processes in the areas of casting, machining, heat treatment and assembly. Collection procedures provided information on air concentration, size distribution, and chemical composition of the airborne particulate matter for each process and insight into the physical and chemical processes that created those particles.

Introduction

A by-product of many manufacturing processes is the release of particles (also referred to as particulate matter) to the workplace air. Airborne liquid or solid particulate matter, or PM, can be produced by mechanisms such as mechanical abrasion, atomization, condensation, and combustion. PM from a particular source may have a distinctive aerodynamic particle size distribution that determines its removal efficiency by various control devices, its residence time in the worker breathing zone, and eventually its fate in the human respiratory system. [1]

Also of importance are the chemical and physical properties of the airborne particles (or aerosols). Size distributions can be based on particle number or count, particle surface area, and particle mass or volume. Generally, number distributions are dominated by fine particles and mass distributions are dominated by coarse particles. The mode, mean, and median increase as one moves from number to surface area to mass (or volume) distributions for the same set of particles. [2]

In the literature, there is a lack of consistency on the classification of particles based on their aerodynamic size. According to the U.S. Environmental Protection Agency National Ambient Air Quality Standards (NAAQS), [3] fine particles have a diameter less than 2.5 µm (PM2.5) and coarse particles have a diameter between 2.5 and 10 µm. In recent years, there has been increased attention to fine particles, since these particles are respirable. [2,4] Recent laboratory research has expanded our knowledge of fine particle health effects and has provided some theories to explain observations from epidemiological studies. [5–7] Some suggest that the number of particles or the surface area of the particles is important as well as the chemistry of the particles. [7–9] Particle number concentration is largely independent of aerosol mass concentration since fine particles dominate the number distribution, but have very little mass. [7]

While theories have been proposed that link health effects associated with fine particulate matter to particle number or surface area concentrations, most of the current standards relating to PM are based on mass concentration. The environmental standards currently in existence consider both coarse (PM10) and fine (PM2.5) particle mass concentrations. [3] However, owing to the increased attention to fine particles, there is considerable discussion on the need to amend these standards to consider even smaller particle sizes, e.g., particles smaller than 1.0 µm (PM1.0) or ultra-fine particles smaller than 0.1 µm (PM0.1). In spite of the growing interest in fine
particles relative to coarse particles, there exists little data on fine particles from manufacturing processes.

This study was performed to characterize particles associated with manufacturing processes commonly employed within the automotive industry. Ten manufacturing processes were studied from the general categories of casting, machining, heat treat and assembly. Sampling was performed at five different automotive plants to secure the data for the ten processes. Aerosol data were collected in the vicinity of each process using a procedure that was specifically developed for this study.

**Procedure and methods**

Prior to sampling, permission had to be gained from each plant to proceed. This alone could require weeks or even months of effort working through the various channels of the plant and the corporate entity. Typically, a presentation was made to the Plant Safety Review Board and often later to plant leadership. A printed overview was then distributed to other plant personnel and the union leadership. When access to the plant was approved, the procedure followed in this study consisted of the following four steps: process selection, distributed sampling, intensive sampling, and chemical analysis, as described below. Additional sampling details can be found in Dasch et al. [10]

**Process selection**

The first step was to select the processes to be studied and identify facilities involving the same. Several criteria were used to select the processes including previous knowledge of emissions and the potential for worker exposure. Decisions about selected processes were facilitated by plant managers. Five facilities (plants) were selected in three states that included the ten selected processes, which are listed in Table 1. For a full description of the processes, the reader is referred to the Supplemental Files.

**Distributed sampling**

The next step was to perform distributed sampling, or mapping, of the process area under study to provide an understanding of overall concentrations and to identify a location for intensive sampling. The mapping technique was developed to evaluate aerosols associated with metal removal operations [11] and has proven effective for focusing engineering efforts. Mapping was performed during a normal work shift, typically the day prior to intensive sampling.

Two real-time aerosol monitors (TSI DustTrak), fitted with PM\(_{10}\) and PM\(_{1.0}\) inlets respectively, were used to map the spatial distribution of coarse and fine particulate matter concentrations within the process area. DustTraks are battery-operated, data loggers that detect particles with a light-scattering laser photometer. The monitors were hand-carried at waist level from location to location and a single reading was taken at each location using a 20-s averaging time. Readings were often taken at pillars or between pillars, but actual locations were dependent on the layout of the plant. Typically, very large process areas were mapped (total areas listed in Table 1) and the number of sample points depended on the total area and the location of obstructions. The average area represented by each sampling point was approximately 1000 ft\(^2\), equivalent to a sampling point approximately every 33 ft. Over the course of the day, the entire area was mapped three times and average values from each location were used to construct the particle map.

A site within the process area was chosen for intensive sampling based on the following:

- visual analysis of the process area, input from workers in the area and plant engineering;
- minimal inconvenience for production workers;
- lack of conflict with material handling needs;
- access to 120 VAC electrical power;
- safety of the researchers; and
- a relatively high particle concentration as indicated by the mapping.

**Intensive sampling**

Once a specific intensive site was selected, intensive aerosol sampling was performed throughout the first working shift (7 hr approximately). The samplers used are listed in the Supplemental Files. The DustTraks that were used for mapping were also used to obtain temporal concentrations through the sampling time, using the 1.0 and 10.0 µm inlets, respectively. Readings were taken once a minute.

A Scanning Mobility Particle Sizer (SMPS) with a 16-min averaging time was used to obtain near real-time particle size distributions in the size range of 0.015–0.7 µm. It uses a differential Mobility Analyzer to differentiate particle sizes by measuring the electrical mobility of the particle. After separation by electrical mobility into 100 bins of particle sizes, they are counted with a Condensation Particle Counter. The data was used to provide the particle number and surface area of the particles.

A Micro-Orifice Uniform Deposit Impactor or MOUDI was the principal instrument for collecting aerosol mass distribution data. It was operated at 30 L/min for the 7-hr period and provided size segregation from >20 µm down to 0.06 µm. The MOUDI is a widely accepted device for particle size segregation and is often used to validate data obtained from other devices. [12] The unique micro-orifice design accomplishes this size segregation with low pressure drops across stages, allowing
Table 1. Processes studied.

| Plant | Facility Type | Process                  | Typical Products                        | Area Mapped (ft²) |
|-------|---------------|--------------------------|-----------------------------------------|-------------------|
| 1     | Casting       | Iron foundry melt/pour    | Blocks, heads, cranks, differentials    | 36,200            |
| 1     | Casting       | Iron foundry shakeout     | Blocks, heads, cranks, differentials    | 82,800            |
| 2     | Casting       | Aluminum (Al) lost foam   | Blocks, heads                          | 54,000            |
| 3     | Casting       | Al diecasting            | Transmissions, cases                   | 112,500           |
| 4     | Machining     | Wet machining aluminum   | Engines                                 | 74,500            |
| 4     | Machining     | Grinding steel with oil  | Engines                                 | 4,800             |
| 5     | Machining     | Dry machining cast iron   | Engines                                 | 93,600            |
| 3     | Heat Treat    | Carburizing furnace      | Gears                                  | 29,100            |
| 6     | Assembly      | Body shop welding        | Finished vehicles                       | 194,400           |
| 6     | Assembly      | Paint ovens               | Finished vehicles                       | 170,100           |

the collection of size-segregated samples of semivolatile compounds down to a very small size range. Traditional polyvinylchloride (PVC) filters were used for the MOUDI impaction substrates and backup filter. The upper cut-point on particles that could enter the impactor was arbitrarily taken as 40 µm.

Filter samples were also collected for chemical analysis using two samplers equipped with a cyclone with a 2.5 µm aerodynamic cutpoint to obtain PM$_{2.5}$ samples. Both samplers operated at 10 L/min for the 7-hour period. Polycarbonate filters (47-mm with 0.4 µm pore size), which have a low trace-metal content, were used in one sampler for mass determination and elemental analysis. Prefired 47-mm quartz filters were used in the second sampler for carbon analysis.

An effort was also made to obtain background samples, that is, samples collected outside and upwind of the plant. Two PM$_{2.5}$ samplers were running outdoors for the entire intensive sampling period for mass and chemical analysis. In addition, the two DustTrak monitors were taken outdoors at the end of the intensive sampling period to measure outdoor air for a 30-min period.

Finally, a traditional industrial hygiene personal sampler was also set up at the intensive site to give an idea of the “total particulate matter” measured by traditional means. The 37-mm closed face filter cassette with a 5.0 µm pore size, PVC filter was operated at 2.0 L/min to provide reference data for comparison to historical exposure data. In general, this sampler does not collect particles efficiently above 20 µm.

Chemical analysis

The final step was to perform a chemical analysis on the PM$_{2.5}$ filters collected during intensive sampling to determine the composition of the particles. Chemical analyses included the analysis of carbon (carbonate, organic carbon and elemental carbon) on the quartz filter and elemental analysis on the polycarbonate filters.

Carbonate, organic, and elemental carbon were determined by combusting the particles collected on the quartz filter.$^{[13,14]}$ In the first stage, combustion is carried out in a nitrogen atmosphere such that only organics are combusted. The combusted material is converted to carbon dioxide and measured. In the second stage, oxygen is added and elemental carbon is combusted to carbon dioxide. The organic carbon is expected to be a large fraction of the particle mass in any process involving organic materials. Elemental carbon (soot) could be important from high-temperature processes involving organics such as foundries, diecasting, heat-treating, and welding. Elemental analysis (primarily metals) was performed using Proton Induced X-Ray Emission (PIXE), in which filters are irradiated with a beam of protons resulting in the emission of characteristic X-Rays from the individual elements that are detected by an energy-dispersive detector.

Air quality results

A wealth of data was collected from each of the 10 processes that were studied, including:

1. mass concentration: concentration maps, temporal behavior, and daily average concentration;
2. particle size distribution and median diameter; and
3. Particle chemical composition.

Reproducibility

Seven-hour samples were taken at a single location on three consecutive days to evaluate reproducibility. The highest relative standard deviation between samples was from the MOUDI samplers. Processing a MOUDI sample
requires making 20 weight measurements in the microgram range with greater opportunity for experimental errors, leading to greater variance between samplers. Yet it is considered the most accurate of the methods since it relies on gravimetric methods rather than indirect methods such as light scattering.

The particle mass as collected with the MOUDI sampler on those three consecutive days were 0.48, 0.56, and 0.62 mg/m$^3$ for a relative standard deviation of 15%. The mass median diameters measured on the three days were 2.8 (4.4), 3.3 (2.5), and 3.2 (2.7) µm. The numbers in parentheses are the geometric standard deviation. This is considered good reproducibility and indicates that particulate concentrations and sizes will be stable if the process is stable.

**Distributed sampling**

A Sample Distributed Sampling Map of PM$_{10}$ for the Iron Foundry Melt/Pour is shown in Figure 1 showing the variation in PM$_{10}$ concentrations throughout the process area. The remaining PM$_{10}$ and PM$_{1.0}$ maps for the 10 processes are shown in the Supplemental Files in addition to the color palette used. The location eventually chosen for intensive sampling is indicated by the arrow on each map.

Two of the maps are identical, Wet Machining of Aluminum and Grinding with Oil. The oil grinding was done in a small area indicated by the box in a larger wet machining area. The intensive sampling areas were chosen to be in the vicinity of the one process or the other. Also the area of the lost foam casting is represented by the box on that map.

The maps provide a quick way to view a large amount of data. The highest concentrations measured during mapping were from the Iron Foundry Melt/Pour process with peak values of 7.6 mg/m$^3$ PM$_{10}$ and 0.97 mg/m$^3$ for PM$_{1.0}$. Aluminum Diecast had the next highest concentrations during mapping with maximum values measured of 1.1 mg/m$^3$ PM$_{10}$ and 0.56 mg/m$^3$ PM$_{1.0}$. In contrast, the Paint Oven map is uniformly dark indicating very low concentrations. Here the peak concentrations were 0.16 mg/m$^3$ PM$_{10}$ and 0.11 mg/m$^3$ PM$_{1.0}$.

**Temporal variations**

The temporal variation of the particles from the Iron Foundry Melt/Pour as measured with the two DustTraks with the PM$_{10}$ and PM$_{1.0}$ inlets is shown in Figure 2. Background samples were also measured at the end of most days (dependent on weather conditions) upwind of the plant. The temporal plots for the other processes are shown in the Supplemental Files. Some processes were halted as the plant shut down for lunch or breaks and particle concentrations dropped during those periods. Welding is a good example. Other processes ran continuously throughout the shift and showed no obvious downturns in concentration. The Carburizing Furnace is an example. Two processes, Al Lost Foam and Wet Machining Al, showed decreasing values over the course of the shift, most likely due to processes being shut down.

In areas where the two traces are far apart, large particles predominate. The Carburizing Furnace is probably the best example of this. In contrast, the Paint Ovens have fairly small differences between the plots indicating a larger fraction of small particles. Similarly, in some processes there is a strong correlation between the PM$_{10}$ and PM$_{1.0}$ concentration over the course of the work shift. Aluminum Diecast, Wet Machining Aluminum, Carburizing Furnace, and Paint Ovens all had correlation coefficients greater than 0.9. The lowest correlation coefficient was from the Iron Foundry with 0.44 for Shakeout and 0.66 for Melt/Pour.
Table 2. Mass concentration of particles in four particle fractions as measured with a MOUDI impactor (mg/m$^3$).

| Process                          | PM$_{1.0}$ | PM$_{2.5}$ | PM$_{10}$ | Total PM |
|----------------------------------|------------|------------|-----------|----------|
| Iron Foundry – Melt-Pour         | 0.074      | 0.11       | 0.13      | 0.14     |
| Iron Foundry – Shakeout          | 0.045      | 0.074      | 0.12      | 0.20     |
| Al Lost Foam Casting             | 0.035      | 0.076      | 0.10      | 0.11     |
| Al Diecast                       | 0.25       | 0.44       | 0.59      | 0.69     |
| Wet Machining Al                 | 0.029      | 0.057      | 0.075     | 0.081    |
| Grinding steel with oil          | 0.024      | 0.089      | 0.16      | 0.18     |
| Dry Machining Cast Iron          | 0.048      | 0.13       | 0.28      | 0.56     |
| Carburizing Furnace              | 0.055      | 0.21       | 0.34      | 0.38     |
| Body Shop Welding                | 0.19       | 0.29       | 0.32      | 0.37     |
| Paint Ovens                      | 0.044      | 0.052      | 0.055     | 0.058    |

**Mass concentrations**

Table 2 shows the particle mass as measured with the MOUDI for four particle size fractions, PM$_{1.0}$, PM$_{2.5}$, PM$_{10}$, and Total PM for each process. The highest total PM mass concentrations are from Al Diecast, Dry Machining Cast Iron, Carburizing Furnace, and Welding. The highest PM$_{1.0}$ mass concentrations are from Al diecast, Welding, and Iron Foundry Melt/Pour.

Table 3 shows the particle concentration for each process in terms of particle number, surface area, and total mass arranged in order of particle number. Particle number and surface area are in terms of cubic centimeters of air volume and mass is in cubic meters of air volume. The mass numbers were taken from the MOUDI sampler and the number and surface area were from the SMPS, which accurately measures the small particles that dominate particle number and surface areas. The number, surface area, and mass values are not expected to be correlated across processes as small particles have higher surface areas, but lower mass, than large particles. Particle number concentration was lowest for Welding and highest for Aluminum Diecast. Surface area concentration was lowest for Iron Foundry Shakeout and highest for Diecast. Mass concentration was lowest for Paint Ovens and Wet Machining and highest for Dry Machining and Diecast.

SMPS measurements were made from the air outside of the plant on six occasions. They show considerable variability and are not necessarily related to the values inside the plant since they would be highly influenced by photochemical production of fine particles. However, the median values for particle number and surface areas as measured by the SMPS are included in Table 3.

**Size distribution**

The MOUDI provided the best indicator of the particle size distribution. The size distribution histogram for the Iron Foundry Melt/Pour as measured with the MOUDI is shown in Figure 3. The y axis indicates the mass on each stage normalized to the size interval covered by that stage (dLog(Dar)) where Dar is the aerodynamic diameter of particles. The remaining histograms for the other processes are shown in Supplemental Files.

The histograms present a very different picture of size distributions depending on the process. The two processes with high large particle concentrations are Dry Machining of Cast Iron and the Iron Foundry Shakeout. Both processes produce particles through physical processes. The pattern is very different from Paint Ovens and Welding that have a stronger fine particle component. Most histograms indicate a unimodal distribution, but a few are bimodal, such as Iron Shakeout and Diecast.

Table 4 shows aerodynamic size distribution information for each of the 10 processes, arranged in order of mass median diameter. Again, the mass numbers were...
Table 4. Median diameter based on particle number, surface area, and mass for each process. The data is sorted by mass median diameter.

| Process                        | Number µm | Surface area µm | Mass µm |
|--------------------------------|-----------|-----------------|---------|
| Paint ovens                    | 0.068     | 0.13            | 0.44    |
| Body shop welding              | 0.16      | 0.47            | 0.93    |
| Iron foundry melt/pour         | 0.054     | 0.24            | 0.95    |
| Wet machining Al               | 0.042     | 0.22            | 1.3     |
| Al lost foam casting           | 0.047     | 0.13            | 1.6     |
| Al diecasting                  | 0.059     | 0.17            | 1.6     |
| Carburizing furnace            | 0.044     | 0.24            | 2.0     |
| Grinding steel with oil       | 0.053     | 0.38            | 2.5     |
| Iron foundry shakeout          | 0.045     | 0.25            | 5.1     |
| Dry machining cast iron        | 0.042     | 0.49            | 10.0    |

Note: Particle number and surface area from SMPS; Total particle mass from MOUDI.

taken from the MOUDI sampler and the number and surface area were from the SMPS. As mentioned previously, the number median diameter is smaller than the surface area median diameter, which is smaller than the mass median diameter in all cases. For example, in the case of Wet Machining of Aluminum, the number median diameter (diameter where half of the particles have a larger diameter and half have a smaller diameter) is 0.04 µm, the surface area median diameter is 0.22 µm and the mass median diameter is 1.3 µm. The table shows that Paint Ovens, Welding, and Iron Casting Melt/Pour produced particles with the smallest mass median diameter (MMD). A small MMD suggests that particles are formed from high-temperature processes, e.g., condensation of metal oxides or pyrolysis of phenolic resin cores. Particles from low temperature processes that produced emissions based on mechanical abrasion (e.g., Dry Machining or Iron Foundry Shakeout) produced the highest mass median diameters.

Figure 4 is a plot of the ratio of PM$_{1.0}$ mass concentration to the total particle concentration for each process, as measured with the MOUDI. For some of the processes the PM$_{1.0}$ particles are less than 15% of total particles (e.g., Dry Machining, Grinding with Oil, and Carburizing Furnace); for these processes, the larger particles dominate. For other processes (e.g., Paint Ovens, Iron Foundry Melt/Pour, and Welding) more than half of the particle mass is in the PM$_{1.0}$ fraction. In particular, PM$_{1.0}$ dominates for the Paint Ovens where 76% of the particles are less than 1 µm.

Aerosol chemical analysis

Chemical analysis was performed on the particulate matter collected from each process to measure carbon in various forms and other elemental content of the aerosol (twenty species in all). The background concentrations measured upwind of the plant were subtracted from the plant concentrations. Table 5 summarizes the principal chemical constituents for each of the ten processes. Values below the detection limit are not listed. The rows of numbers at the bottom of Table 5 show the sum of the measured chemicals compared to the total mass detected on the PM$_{2.5}$ filter. The sum is expected to be less than the total since species such as hydrogen, nitrogen, and oxygen were not measured. The chemical composition breakdown (or fingerprint) varied widely across the processes. Organic carbon was the primary constituent found for many of the processes. Possible sources of the chemicals in the airborne particulate are provided below.

Iron foundry melt/pour

Elemental carbon, silicon, chromium, manganese, iron, and copper, which were measured in the particulate, are constituents of grey cast iron. Additional metals such as aluminum, zinc, and lead may be constituents of the scrap iron melted in the cupola. Calcium and carbonate may come from the limestone (CaCO$_3$) added to the cupola to remove impurities. Silicon and potassium both are crustal components and probably originate from the sand used in the molds. The source of chlorine is unknown.

Iron foundry shakeout

As with the melt/pour process, constituents of the grey cast iron include elemental carbon, silicon, chromium, manganese, iron, and copper. Aluminum and zinc may be constituents of the scrap iron melted in the cupola. Constituents of the limestone added to the cupula are calcium and carbonate. Aluminum, silicon, potassium, and titanium are crustal components and may originate from the sand.
Table 5. Chemical composition of air particles (PM$_{2.5}$) associated with manufacturing processes (µg/m$^3$).

|                | Iron | Iron | Aluminum | Aluminum | Wet | Grind. | Dry | Carburizing | Body | Paint |
|----------------|------|------|----------|----------|-----|--------|-----|-------------| shop | ovens |
|                | melt/pour | shake-out | lost foam | die-casting | machining steel with oil | Al | steel cast iron | furnace | welding | |
| Carbonate      | 0.53 | 0.50 | 1.40 | 1.40 | 0.42 | 1.47 | 5.10 | 1.40 | 37.0 | 80.0 | 43.0 |
| Elem. carbon   | 2.40 | 5.57 | 1.40 | 25.0 | 295.0 | 19.3 | 26.3 | 46.8 | 37.0 | 80.0 | 43.0 |
| Org. carbon    | 1.67 | 2.37 | 1.31 | 1.09 | 8.15 | 0.74 | 0.83 | 0.55 | 1.24 | 3.69 |
| Sodium         | 0.06 | 5.99 | 0.99 | 5.99 | 0.99 | 0.98 | 0.98 | 1.24 | 3.69 |
| Aluminum       | 0.67 | 2.37 | 1.31 | 1.09 | 8.15 | 0.74 | 0.83 | 0.55 | 1.24 | 3.69 |
| Silicon        | 8.15 | 8.25 | 4.47 | 6.82 | 0.74 | 0.74 | 0.74 | 0.55 | 1.24 | 3.69 |
| Phosphorus     | 2.09 | 1.93 | 1.33 | 0.72 | 0.72 | 0.72 | 0.72 | 0.72 | 0.72 | 0.72 |
| Sulfur         | 0.14 | 0.20 | 0.03 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Chlorine       | 0.13 | 0.10 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Potassium      | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 |
| Calcium        | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 |
| Titanium       | 0.10 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| Chromium       | 2.09 | 1.93 | 1.33 | 0.72 | 0.72 | 0.72 | 0.72 | 0.72 | 0.72 | 0.72 |
| Manganese      | 0.13 | 0.10 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Iron           | 0.14 | 0.20 | 0.03 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Nickel         | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 |
| Copper         | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 |
| Zinc           | 0.10 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| Bromine        | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| Lead           | 3.08 | 3.08 | 3.08 | 3.08 | 3.08 | 3.08 | 3.08 | 3.08 | 3.08 | 3.08 |
| Sum            | 96.0 | 90.0 | 57.0 | 375.0 | 18.0 | 64.0 | 76.6 | 61.9 | 295.0 | 43.1 |

Aluminum lost foam
Aluminum, silicon, manganese, iron, and zinc are present in the aluminum 319 alloy castings. Other possible constituents from the production furnace are calcium and titanium. Zinc is added to the polystyrene beads when the pattern is made. Elemental carbon and organic carbon are products of combustion formed during the burning of polystyrene. The sand could be a source of aluminum, silicon, potassium, and chlorine. The sources of the carbonate, sodium, and chloride are unknown. The source of the potassium is unknown as none of the fluids used in the vicinity of the grinder contained potassium.

Aluminum diecast
Aluminum, silicon, iron, copper, and zinc are components of the aluminum alloy delivered to the plant. Organic carbon, sodium, silicon, and sulfur were constituents of the die- and tip-lubes. The sources of the chloride, potassium, and calcium are unknown. Organic carbon was far higher here than from the other sources, accounting for 78% of the particle mass.

Wet machining
Organic carbon originates from the machining fluid or washer fluid. Manganese, iron, and zinc are present in the aluminum 319 alloy, and may also originate from the cast iron being dry machined nearby. The sources of the carbonate and potassium are unclear.

Grinding with oil
Organic carbon originates from the straight oil metal removal fluid. Iron and manganese are constituents of grey iron. The source of the potassium is unknown as none of the fluids used in the vicinity of the grinder contained potassium.

Dry machining
The organic carbon and sodium could originate from the machining fluid used at nearby operations. Elemental carbon, silicon, and manganese are constituents of grey cast iron. Chromium is a constituent of high-speed steel tools. Copper and zinc may be trace constituents of cast iron or tooling. Calcium and carbonate may remain from the limestone used during the casting process. The source of the chloride is unclear.

Carburizing furnace
Organic and elemental carbon could result from volatilized and pyrolyzed quenchant and from the reaction gas and the combustion process that creates it. Potassium is a constituent of the washer fluid. Phosphorus, chromium, iron, manganese, and nickel are constituents of steel. The sources of the chlorine, copper, and bromine are not known.

Welding
Organic carbon may be from residual forming oils on the steel. The iron, nickel, and manganese are components of the steel. Copper electrodes are used with the welding equipment. Zinc is used to galvanize steel. The sources of the chlorine and calcium are unclear. Iron, copper, and...
zinc levels were higher from welding than any other process.

**Paint ovens**
The vast majority of the PM$_{2.5}$ mass was organic carbon originating from the semi-volatile material in the coatings that evaporated in the hot oven and then condensed. The source of the iron may be from abraded steel from the car bodies or transfer equipment. This one process had significantly less mass listed for particulate matter concentration as compared to the sum of the individual chemical constituents, attributed to the high organic level. The particulate matter concentration was based on mass measured on a polycarbonate filter, whereas the organic carbon was measured on a quartz filter. This difference in filter materials may explain the measurement anomaly, as the semi-volatile organics present in the paint area could pass through a filter or be collected by a filter, depending on the filter material.

**Comparison to recommended concentrations**
The purpose of this study was not to investigate potential health effects related to fine particles. However, it is known that biological cells can be damaged by Reactive Oxidative Species (ROS) and many of the transition metals measured in this study have been linked to the formation of ROS, through direct oxidation or catalysis. Kunzli et al. referred to the transition metals, Fe, Cu, Cr, Ti, Ni, Co, V, and Mn as oxidizers or sources of free radicals. Prahalad et al. found that insoluble Si, Fe, Mn, Ti, and Co were related to ROS activity, but no relationship was found with V, Cr, Ni, or Cu. Effects are far from straightforward, though, as variables such as particle size, the chemical environment, the solubility of the metal, and the acidity of the solution can all affect outcomes.

As a first step, it is useful to compare the maximum measured daily concentrations observed in this study with available health standards. Table 6 shows the highest daily values recorded from the 10 processes compared to two health-based standards, the ACGIH Threshold Limit Values and OSHA Permissible Exposure Limits. The health standards are often based on a specific chemical form of an element whereas the chemical forms of the elements measured in this study are unknown. Therefore, the most likely form was chosen for comparison. In all cases, the measured value was far below the health-based standard.

**Summary and discussion**
A study was undertaken to investigate the particulate matter generated by ten manufacturing processes common in the automotive industry. Processes included four casting processes (Iron Foundry Melt/Pour; Iron Foundry Shakeout; Aluminum Lost Foam; Aluminum Diecast), three machining processes (Wet Machining Aluminum; Grinding with Oil; Dry Machining Cast Iron), one heat treat process (Carburizing Furnace) and two assembly processes (Welding; Paint Ovens).

A variety of sampling instrumentation was employed to collect particles for analysis of mass, size distributions and chemistry. The particle concentrations in the process area were mapped (distributed sampling) with PM$_{10}$ and PM$_{1.0}$ real-time samplers to determine the range of concentrations in the process area. Based on the mapping and other considerations, a site was selected for intensive measurements. Temporal variations of PM$_{10}$ and PM$_{1.0}$ and particle size distributions were measured at the intensive sites over the course of one working shift. Particle size distributions were measured with a MOUDI impactor and SMPS. PM$_{2.5}$ filters were collected for mass and chemical analysis.

Based on the methods and procedures employed to study the airborne particles associated with the manufacturing processes, the following conclusions may be drawn.

- The mass median diameter of the particles varied over a wide range, from 0.44 µm in the vicinity of Paint Ovens to 10 µm near a Dry Machining area.
- The number median diameter is much smaller, typically around 0.04 µm.
- High-temperature processes such as Paint Ovens, Welding, and Iron Foundry Melt/Pour produced particles with the smallest mass median diameters and mechanical processes such as Dry Machining and Foundry Shakeout produced particles with the largest mass median diameters.
- In these particular processes and locations, Aluminum Diecasting had the highest levels of total mass concentrations and small particles.
- The chemical mass was dominated by organic carbon in eight of the ten processes, which is attributable to the various organic chemicals used in processing.
- The airborne particle levels and individual chemical levels were below current recommended exposure limits for all processes.

The processes studied here cover the most important processes used in the auto industry (casting, machining, heat treatment, and assembly) as well as in many other industries. The concentrations measured at the intensive sites are, of course, particular to that plant and that site. Comparison to the mapping levels provides an idea of maximum concentrations in that plant. Concentrations of similar processes in other industries will vary based on the particular process, density of machines, the controls
Table 6. Highest daily concentrations measured in study compared to recommended standards.

| Elemental Carbon | ACGIH 2008 TLV µg/m³ | OSHA 2008 PEL µg/m³ | Max. Study Value µg/m³ | Associated Process |
|------------------|-----------------------|----------------------|------------------------|-------------------|
| Sodium           | 3,500                 | 3,500                | 5.6                    | Shakeout          |
| Aluminum         | 1,000                 | 5,000                | 2                      | Shakeout          |
| Silicon          | 25                    | 30                   | 8.3                    | Shakeout          |
| Phosphorus       | 1,000                 | 1,000                | 0.6                    | Carburiz. Furnace |
| Sulfur           |                       |                      | 2.1                    | Diecast           |
| Chlorine         |                       |                      | 19                     | Diecast           |
| Potassium        |                       |                      | 6                      | Diecast           |
| Calcium          | 2,000                 | 5,000                | 1.2                    | Shakeout          |
| Titanium         | 10,000                | 15,000               | 0.16                   | Lost Foam         |
| Chromium         | 500                   | 100                  | 0.2                    | Carburiz. Furnace |
| Manganese        | 200                   | 5,000                | 3.2                    | Melt/Pour         |
| Iron             | 5,000                 | 10,000               | 143                    | Weld              |
| Nickel           | 200                   | 1,000                | 0.08                   | Weld              |
| Copper           | 200                   | 100                  | 2.4                    | Weld              |
| Zinc             | 2,000                 | 5,000                | 64                     | Weld              |
| Lead             | 50                    | 50                   | 3.1                    | Carburiz. Furnace |
| Particles        | 3,000                 | 5,000                | 400                    | Iron Melt         |

Notes: aCarbon Black; bAs oxide; cAs fume; dRespirable; eAl metal; fCrystalline silica; gSource: OSHA [22]; hAs phosphoric acid; iCr metal + Cr III; jCr metal and insoluble salts; kInsoluble Ni compounds

in place, ventilation levels, etc. The size distributions and chemistry of the particles are more generally applicable to other situations, in that they are more representative of the process rather than the location of samplers.

The particle mass concentration has been the norm for the establishment of exposure limits in occupational environments. As mentioned in the Introduction, particle number, surface area, and chemistry may play a more important role in producing toxic effects resulting from exposure than particle mass concentration. For smaller particles, the mass becomes negligible and number, surface area and chemistry play a larger role. High-temperature processes, such as diecasting and welding, generate larger numbers of ultrafine particles compared to abrasion processes such as shakeout. The information provided here will prove useful if future standards are to be developed on factors that go beyond mass concentration.

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[21] **US Occupational Safety and Health Administration (OSHA):** Table Z-1 Limits for Air Contaminants. [Standard] Standard number: 1910.1000 Table Z-1, 2008.

[22] **US Occupational Safety and Health Administration (OSHA):** Table Z-3 Mineral Dusts. [Standard] Standard number: 1910.1000 Table Z-3, 2008.