The body of literature relevant to tire based particulate matter is largely based on particulate matter (PM) pollution [2-10] associated with vehicular traffic on roads. Many studies look at the wear characteristics of tires and the health problems associated with particulate matter from tire wear. The concentration and chemical makeup of such particulate matter must be determined directly from artificial turf fields to make an accurate assessment of its impact on health.

Described below are the three primary sizes of particulate matter and their general, well documented impacts on health. The chemical contribution to health impact are discussed followed by the health impacts of tire based particulate matter. The indoor study on artificial turf with a focus on particulate matter is discussed next. Finally, future directions are suggested.

Particulate Matter as a pollutant – tutorial

Associations have been found between day-to-day inhalable particulate air pollution and increased risk of various adverse health outcomes, including cardiopulmonary mortality and respiratory health problems [2-4, 11]. While large particles are filtered through the nose and throat and do not cause problems, particles less than 10 microns (1/10th the diameter of coarse hair) in aerodynamic diameter (PM10 and PM2.5) have strong relationships to health effects [5-7, 11]. In the US, PM10 and PM2.5 are adopted for regulatory purposes.

PM10

Thoracic particles, (PM10, aerodynamic diameter <10 μm) and coarse particles (PM10-2.5, between 10 μm and 2.5 μm) tend to be related to acute airway symptoms because the settle in the bronchi and lungs and cause health problems. A relevant example is the study showing [12] fluctuations in PM10 levels related to acute respiratory hospital admissions in children, to school and kindergarten absences, to decrements in peak flow rates in normal children, and to increased medication use in children and adults with asthma [12].

Dockery and Pope reviewed the epidemiologic literature for similar adverse effects. They estimated increased mortality and morbidity associated with each 10-$\mu g/m^3$ increase in daily mean PM10 exposure. The total mortality was observed to increase by 1% for each 10-$\mu g/m^3$ increase in PM10. Perhaps more relevant, they demonstrated respiratory mortality increased by 3.4% and cardiovascular mortality increased by 1.4% for each 10-μg/m3 increase in PM10. Furthermore, hospital admissions and emergency department visits increased approximately 1% for all respiratory complaints, and 2% to 3% for asthma. Exacerbation of asthma increased by about 3%, as did lower respiratory symptoms. Small decreases in lung function, approximately 0.1%, have also been observed. This review suggests that the epidemiologic studies of adverse morbidity measures are coherent with the mortality studies showing quantitatively similar adverse effects of acute exposures to particulate pollution [12].

PM2.5
Fine particles (PM2.5, aerodynamic diameter <2.5 μm) tend to be associated with cardiovascular disease [6] and asthema [13] because they penetrate ino the gas-exchange regions of the lungs. This is because the PM is deposited in the alveolar region of the lung where the adsorption efficiency for trace elements is 60-80% [13]. PM2.5 can thus affect lung physiology, especially if the particles contain biologically available toxic metal [13].

Two studies below give a basis on which to assess the safety for particulate matter (PM2.5) generated by artificial turf fields, albeit not in the context of it chemical composition:

For example, Pope, et al. assessed the relationship between long-term exposure to fine particulate air pollution and all-cause, lung cancer, and cardiopulmonary mortality [11]. Based on an ongoing prospective mortality study, which enrolled approximately 1.2 million adults in 1982 the study showed a significant association of health effects to PM2.5. **Each 10-μg/m^3 elevation in fine particulate air pollution was associated with approximately a 4%, 6%, and 8% increased risk of all-cause, cardiopulmonary, and lung cancer mortality, respectively.** Dominici, et al. [14] estimated risks of cardiovascular and respiratory hospital admissions associated with short-term exposure to PM2.5 in 11.5 million Medicare enrollees (>65 years). They investigated hospital admissions for cerebrovascular, peripheral, and ischemic heart diseases, heart rhythm, heart failure, chronic obstructive pulmonary disease, and respiratory infection, and injuries as a control outcome. There was a short-term increase in hospital admission rates associated with PM2.5 for all of the health outcomes except injuries. The largest association was for heart failure, which had a 1.3% increase in risk per 10-µg/m3 increase of PM2.5 in the same-day.

Ultrafine particles
Ultrafine particles (<100 nm or 1/1000th the diameter of hair) may pass through the lungs and affect other organs. One notable exception to chemical composition being the modulator for PM toxicity (discussed below) may be for ultrafine particulate matter where the actual physical size may be the specific particulate property responsible for toxicity. Particles 10nm in size, for example produce more significant pulmonary inflammatory response than the when exposed to the same chemical composition or same mass as larger (e.g. fine) particles [15].

In summary, smaller particles are generally considered more toxic than larger particles, motivating the recent change to use PM2.5 and PM10 instead of exclusively PM10 for regulator purposes [14, 16, 17].

Chemical composition as a modulator for PM toxicity:
While the number of particles is important as it realtes to health effects, so to is the size, shape, **chemical composition** [2, 6] and material properties. Chemicals absorbed or adsorbed to the particles may also have different toxicological effects. It is important thus to determine both the particle concentration and size distribution as well as determine the chemical properties of the parent material to asses the effect of inhalable particles. There is ample evidence [2, 5] suggesting that specific chemical properties of PM link with biological response. For example, it has been observed that coarse and fine particles of PM were greater in generating inflammatory mediators compared to carbon black, suggesting chemicals adsorbed onto the particle surface, rather than just the mere presence of the particle can be responsible for toxicity [17]. Obot, *et al.* [18] studied human alveolar

macrophages incubated with fine PM subjected to various procedures and concluded PM toxicity was dependent on the surface characteristics of the particles.

Of significant interest to this task force is evidence for toxicity of chemical constituents found in tire particulate matter. A class of carcinogens, namely, polycyclic aromatic hydrocarbons (PAH) are benzene-soluble organics which are of particular interest because of their toxicity. Li et al. used in vitro assays to show concentrated PM10 and PM2.5 induced oxidative stress in alveolar macrophages for PM which was highest in PAH [19].

Exposure limit difficulties
It has also been shown that the respiratory tract is actually more sensitive to particle number, not mass [20]. Determining the best way to express exposure limits is complex as further illustrated by Diociaiuti, *et al.* They demonstrated the effects on one studied endpoint to be greater for fine particles than for coarse particles delivered *at equal mass concentrations*. But no differences in response when exposure data were expressed in terms of *PM surface area per volume unit [16]*.

Tire Particulate Matter

The studies below discuss the chemical properties and size distribution of tire PM to enable a comparative, quantitative understanding of tire based pollution.

It has been shown that wear from tires largely impacts the particle concentration and contribute to poor environmental air quality [21]. The standard for PM10 stipulates that the daily mean concentration must not exceed 50 μg/m3 more than 35 days per year and the yearly mean can not exceed 40-$\mu g/m^3$ [7].

Chemical content of tire based PM
Analysis of tire dust or particulate matter from tires shows that it consists not only of debris from the tire but also assimilated heavy metal particles emitted from road traffic materials such as break lining and road paint [21]. For example, Fe, Cr/Pb clusters, Ti, Cr, Cu, Zn, Sr, Y, Zr, Sn, Sb, Ba, La, Ce and Pb [21].

It has been shown that zinc can be an excellent indicator of particulate matter generated by tire wear [8]. Zinc oxide is added as an activator to the vulcanizing process and give zinc concentrations of about 1% of the final rubber product. Further more, to speed vulcanization sulphur containing zinc organic accelerators are added at between 0.5 and 2 wt %. The major part of the zinc in tires is presnt as excess ZnO and ZnS. While not all the zinc can be assigned to tire wear, they showed the only significant contributor to extractable zinc in airborne particles is from tires, with the exception of engine oil. They were able to show 1290 ug of organic zinc is present per gram of tire. This number can thus be used to help determine the souce of particulate matter, especially as assigned to tire wear.

Road PM from tire particles
These studies below are helpful in yielding a comparative exposure to road tire particulate matter. Gustafsson et al. [2] used a road simulator with tires on a track to investigate PM generation from cars and truck on roads. The also investigated the inflammatory potential of the generated particles in human macrophages and epithelial cells. Chemical analysis was used to determine source (road,

tires, etc.). While the majority of wear particles were shown to be from pavement, the concentration of tire wear particles goes up for smaller particles (especially for ultra fine) as illustrated by the elevated Zn and S content which are specific to tires in the experiments. Measurements were made at **2 meters** from the simulated road when cars were driven 20km/hr in a closed room and reaching steady state concentrations. They measured 1 mg/m3 PM10 (all particles) which contained 400 ppm (0.04%) zinc, or 2-μg/m^3 of zinc. Using the above technique yields **520-μg/m^3 <u>tire</u> PM 10**. This estimates the concentration of PM due to tires is about 52% PM when compared to the road material (road stone, pavement, etc.). Gupta [13] showed that tire wear accounted for about 7% of all PM in roadside measurements when including the entire environment in a highly polluted region (Kolkata, India) at industrial sites. When looking at the number of particles directly behind a car, 100-250-μg/m^3 of 3-5 micron particles were measured and is consistent with the numbers above [4].

It is interesting to note at that the concentration of zinc goes up to 2000 ppm (0.2%) Zn for 100nm PM, indicating an increase in tire PM at the ultra fine size [2]. While the study concludes that studded tire wear pavements induced inflammation in airways and the tire and pavement type are important in determining the level of response, they did not break out the biological responses due to tire vs. pavement.

Settling time of PM

The time particles are in the air is an important parameter, Table 1. One meter height is consistent with how high the rubber infill may rebound or be kicked up during use. When the large tire granules are carried into the air, they will re-suspend particulate matter (PM10, PM2.5, etc) into the air. Their persistence in the air impacts the time they are available for inhalation.

Table 1: Terminal gravitational settling velocities and settling times for particles [1].

	PM10	PM2.5	PM 100nm
Settling Velocity (cm/sec)	0.5	0.02	0.0001
Time to settle 1 meter	3.3 min	83 min.	11.5 days

Indoor NILU study

Table 2 presents the particulate matter results from the NILU study [22] and select carcinogenic gas phase results. Of particular interest is the fact that the known carcinogen BaP is present in the PM at quantities near the maximum goal levels directed by various agencies. Both the concentration of PM together with the chemical composition indicates a concern. Results of chemical characterization of the airborne dust showed the presence of PAHs, phthalates, other SVOCs, benzothiazoles, and aromatic amines, also referenced in the NYC study [23]. Higher levels were seen in the SBR rubber air measurements than in the thermoplastic elastomer air measurements.

On average, 28% of the dust was natural latex rubber for PM10 and 45% of the dust was rubber for PM2.5. Because the average European car tire consists of 42% rubber [Section 4.3.4 of 22], the dust it was concluded the dust is from recycled tires and NOT from ambient background.

Table 2: Select PM and vapor phase statistics near recommended limits from NILU study [22] for three indoor turf halls, Valhall (Val), Ostfordhallen (Ost), and Manglerudhallen (Mang).

Pollutant	**Val**	**Ost**	**Mang**	**Limits**
PM10 ($\mu g/m^3$)[a]	32	31	40	35[b]
PM2.5 ($\mu g/m^3$)	19	10	17	20[c]
Benzo(a)pyrene[d] (ng/m^3) in PM10	0.56	0.38	1.2	1.0[e]
Benzene ($\mu g/m^3$) gas phase[f]	2.4	2.0	2.3	2.0[g]
Total PAH[h] (ng/m^3) in gas phase	364	121	174	NA

High Risks in NILU

The review [24] of the NILU study concludes 1.2 ng/m3 BaP will give a lifetime cancer risk of $\mathbf{10^{-4}}$. The review [24] dismisses this and concludes the PAH values are from surrounding air with poor support or evidence. The BaP was dissolved out of the collected particulate matter during analysis and appears to be taken in good lab practices. The review also concludes a concentration of the gas phase carcinogenic benzene of 1.7 $\mu g/m^3$, linked to leukaemia in humans, has a lifetime cancer risk of $\mathbf{10^{-5}}$. These risks are higher than the *di minimis* risk level of 1 case per one million established by OEHHA [25].

NYC study

A very recent study by NYC [23] described the SBR crumb rubber as containing several chemicals of potential concern (COPC). They discussed extraction studies above and others as illustrating crumb rubber contains polycyclic aromatic hydrocarbons (PAHs), including carcinogenic PAHs (benzo[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene,

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[a] Both PM sizes contained measurable amounts of 28 various chemicals (not including PAHs)

[b] In the EU, the recommended norm for oudoor air is 35 $\mu g/m^{3.}$ The US standard for PM10 stipulates that the daily mean concentration must not exceed 50 $\mu g/m^3$ more than 35 days/year and the yearly mean can not exceed 40 $\mu g/m^3$[7] Johansson C, Norman M, Gidhagen L. Spatial & temporal variations of PM10 and particle number concentrations in urban air. Environmental Monitoring and Assessment 2007;127:477..

[c] Indoor and outdoor national standard

[d] Known carcinogen and PAH; its chemical composition has been shown to be a modulator for PM toxicity

[e] 2004 EU directive for outdoor air

[f] Highest of two or three readings per hall. The lowest reading was 1.7 $\mu g/m^3$

[g] 2010 National Target

[h] The group of polycyclic aromatic hydrocarbons (PAH) measured included 40 plus chemicals

dibenz[a,h]anthracene and and indeno(1,2,3-cd)anthracene) [23, p2-7]. They also pointed out PAHs were identified in PM_{10} and $PM_{2.5}$ samples collected from indoor sports halls, i.e. the NILU study.

The NYC study concludes [23] new research is necessary to give more representative data on exposures related to urban field use. They suggested COPCs and PM should be measured at the breathing zone levels of users (specifically children due to their closer proximity to COPCs [23, p3-7]), on both newly installed and older synthetic turf fields containing crumb rubber should be. Air monitoring targets should include PAHs, VOCs, and particulate matter, and should occur during hot weather and calm wind conditions to approximate worst case exposure scenarios. In addition, background air sampling should be conducted at nearby off-field sites simultaneously, as well as natural and/or asphalt fields, in order to provide comparative data on exposures related to urban environments .

Phthalates, alkylphenols, and benzene have been found to off-gas during tire manufacturing (Cocheo et. al. 1983). In addition, studies have also shown that various chemicals such as phthalates, alkylphenols, and benzene may become bonded to tires during use (Willoughby 2006a, b). Since these chemicals are used during the tire manufacturing process, or are present in the environment while the tires are in use, their presence in the crumb rubber would be expected.

Risk levels
Risk level of 1 in 10,000 (10^{-4}) is considered the maximum acceptable risk while a risk of 1 in 1,000,000 (10^{-6}) is considered a virtual safe dose and constitutes a negligible risk. The debate [26] regarding the maximum acceptable risk should be discussed within the taskforce. While measuring risk is scientific, judging the acceptability of risk is a value judgment [27, 28] and it is unclear if 10^{-4} in San Francisco considers the identified and potential risks as acceptable. Risk levels less stringent than 10^{-6} are often due to economic or technological considerations. Regulatory agencies generally view these higher risk levels (10^{-4} ,10^{-5}) to be acceptable if there is no feasible way to reduce the risks further [25].

Future Steps
To accurately assess the potential for human health toxicity, accurate measurements of particulate matter, specifically PM10, PM2.5 and ultra fine particles are required. Currently, the literature does not address this, though it does for indoor PM from artificial turf. The indoor numbers demonstrate the source of dust is primarily from the recycled tire infill and the source strength for both the particle concentration and composition is comparable to EU and US standards for pollution, indicating the infill is a particulate matter pollution source.

Experiments suggested:
Determining if the recycled tire infill is a pollution source and health risk outdoors requires further research. It is suggested such experiments be performed at local San Francisco artificial turf installations such as Garfield Park. Such experiments should be done to mimic use by children as they are closest to the source (measured at child height, say 32 inches). Similarly, the sampling should be done both during used (running, etc.) and close to where the re-suspension will take place (e.g. close to the athlete's breathing zone). Measurements on hot and cold days should be perforemed. Hot days may increase out gassing and lead to more adsorption of chemicals on the PM;

cold days may increase PM generation due to stiffening of the rubber tire material enabling more mechanical formation of PM.

Risk assessment can then be undertaken armed with accurate concentrations and compositions of the PM. Short of outdoor data, the indoor PM data should be used to make an assessment – concluding the levels of PM and the composition therein are at or above to EU and US standards for pollution, not below. Factors such as radiant heating (sun) and low/no wind days may create scenarios where the indoor values are applicable.

Michael Vestel, Ph.D.
Staff Scientist

Applied Optics Laboratory
Physical Sciences Division

SRI International
333 Ravenswood Ave, Bldg 301-81
Menlo Park, CA 94025
Michael.Vestel@sri.com

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