A Comparative Assessment of PM2.5 Exposures in Light-rail, Subway, Freeway, and Surface Street Environments in Los Angeles and Estimated Lung Cancer Risk

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1. Introduction

As a major metropolitan area characterized by urban sprawl, over 570,000 commuters in Los Angeles travel for over 60 minutes to work, yielding a daily commute of over two hours (American Community Survey, U.S. Census Bureau). Studies have shown that a substantial portion of particulate matter (PM) exposure can occur during commute depending on type and route of travel (Chan et al. 2002). The link between elevated levels of PM, particularly $PM_{2.5}$ (aerodynamic diameter d_p<2.5 µm), and adverse health effects has been well established (Pope and Dockery 2006). Numerous health studies have also indicated that long-term ambient PM exposure can be related to risk of lung cancer (Turner et al. 2011), cardiovascular disease (Brook et al. 2010), and neurodegenerative disorders (Morgan et al. 2011).

The focus of this study is to assess and compare $PM_{2.5}$ exposures between five different transport environments in the Los Angeles area (subway, light-rail, surface street, two major freeways with a low and high truck fraction). Key species for comparison are EC, OC, metals and trace elements, and PAHs. They are presented as mass per m^3 of air. Sources of PM components and species will be discussed in detail as well as its contribution from the commute environment. Lastly, estimates of lung cancer risk based on concentrations of PAHs are calculated to determine risk associated with each commute environment. Results from this study are of primary interest not only for commuters of these specific commute environments, but also for residents and pedestrians who are in the vicinity of major roadways that are sources of these pollutants.

2. Experimental methodology

This study represents the integration of two major campaigns that were conducted independently but with common measurement methods. The two campaigns will be referred to as the METRO study and the on-road study. Table 1 shows a summary of the sampling dates and times, routes, and meteorological parameters. Meteorological data is based on South Coast Air Quality Management District (SCAQMD) monitoring sites that are closest in proximity to the sampling route. Average temperatures varied from 17 – 24 °C for the two campaigns and variation of relative humidity were due to the longer sampling time period for the on-road campaign (6AM-5PM) as compared to the METRO campaign (9:30AM-1:00PM). The USC site, which is centrally located near downtown Los Angeles, was sampled concurrently during both campaigns as a reference site.

Route	Dates of sampling	Sampling times	Temperature (°C)	RH (%)	Prevailing wind direction	Wind speed (m/s)
METRO study						
METRO lines	5/3-8/13/10	9:30am - 1:00pm	24.0 ± 3.5	55 ± 9.7	SW	3.2 ± 0.9
on-road study						
110	3/1-3/8/11, 4/11-4/18/11	6:00am - 5:00pm	18.3 ± 4.5	57.2 ± 21.5	W	3.2 ± 1.2
710	3/17-3/25/11, 4/19-4/25/11	6:00am - 5:00pm	17.3 ± 3.6	59.9 ± 18.2	W	3.5 ± 1.3
Wilshire/Sunset	3/9-3/16/11, 4/26-5/2/11	6:00am - 5:00pm	23.8 ± 5.7	42.0 ± 20.9	SW	3.3 ± 1.6

Table 1. Summary of sampling dates and times and meteorological parameters for the METRO and on-road studies. Meteorological parameters are based on South Coast Air Quality Management District (SCAQMD) sites closest in proximity to designated route.

2.1 Description of campaigns

In the METRO study, two lines (the red line and gold line) were sampled concurrently using identical instruments. PM was collected by simulating the commute of a typical passenger who spends 75% of time inside the train and 25% of time waiting at a station. The red line is a subway line powered by electric third-rail that connects Downtown Los Angeles to North Hollywood and has the highest ridership of the METRO system; the gold line is a ground-level light rail line that connects Downtown Los Angeles to Pasadena. $PM_{2.5}$ was collected using the Personal Cascade Impactor Sampler (PCIS). Two sets of samples (N=2) were collected.

On-road sampling was conducted for three roadways during different time periods (Table 1), each representing differential private commute environments. The 110 is a high-traffic freeway that runs from the Port of Los Angeles through Downtown Los Angeles to Pasadena, and is composed mostly of light-duty vehicles (LDVs); the 710 is less trafficked but serves as the main corridor for heavy-duty vehicles (HDVs) traveling to and from the Port of Los Angeles; Wilshire/Sunset Boulevards are major surface street routes that are composed primarily of LDVs and negligible HDVs and characterized by “stop-and-go” (frequent acceleration and deceleration) driving conditions. In the Los Angeles Basin, the 110 and 710 represent the lowest HDV (3.9%) and highest HDV (11.3%) traffic composition of the freeways in the area, respectively. The sampling vehicle was a Honda Insight Hybrid 2011 equipped with a curved inlet for roadway air entry to the sampling instruments. PCIS were also used to provide robust results for comparison to the METRO campaign. Since anisokinetic effects, which may result in the overestimation or underestimation of relatively larger particles (i.e. $PM_{10-2.5}$) need be considered for on-road PM measurements, it was determined that $PM_{2.5}$, the PM fraction of interest in this study, is largely unaffected by anisokinetic sampling (Kam et al. 2012).

2.2 Sample analysis

Both campaigns were analyzed using the same analytical methodology. The Teflon filters were gravimetrically analyzed to determine mass concentration using a MT5 Microbalance. For chemical analysis, Teflon filters were extracted by acid and subsequently analyzed by magnetic-sector Inductively Coupled Plasma Mass Spectroscopy (SF-ICPMS) to determine metals and trace elements. The quartz filters were analyzed using the Thermal Evolution/Optical Transmittance analysis to measure elemental and organic carbon (EC/OC). Water extracts of the samples determined WSOC and water soluble metals and trace elements. Organic speciation was measured with gas chromatography mass spectroscopy (GC/MS).

3. Results and discussion

3.1 Major PM components

Figure 1 shows the concentrations of major PM components (OC, WSOC, TC, and EC) for the five microenvironments. The bars represent the upper and lower data points. Overall, the 710 exhibits the highest concentrations of OC and EC, and thus TC, while the two METRO lines have the lowest concentrations of OC and TC. The relatively higher levels observed on the 710 can be attributed to its higher volume of heavy-duty vehicles (HDVs), which are the greatest emitters of EC (Schauer 2003) and OC (Geller et al. 2005) in a traffic environment. For OC, the concentrations of the 110 and Wilshire/Sunset are comparable and are approximately 20% higher than the METRO lines even though reference OC levels at USC were 11% higher during the METRO campaign. The source of OC in the METRO red line is primarily from the entrance of ambient air through the ventilation system. For WSOC, the concentrations of the microenvironments range from 1.2-2.0 $\mu g/m^3$, with the METRO red line exhibiting the lowest concentration and Wilshire/Sunset exhibiting the highest. For EC, the 710 concentrations are 2.0-3.3 times higher than the other commute microenvironments. Similar to OC, the main source of EC for the METRO lines is the influence of ambient air. Although Wilshire/Sunset is a highly-trafficked roadway environment, its low levels of EC can be explained by its negligible HDV volumes, designating it as a primarily LDV roadway. Moreover, Geller et al. (2005) showed that the fuel-based emission factors (mg of pollutant emitted per kg of fuel burned) for HDVs and LDVs for $PM_{2.5}$ is 710 and 29 mg/kg of fuel, respectively, which means HDVs emit almost 25 times more EC than LDVs per kg of fuel burned.

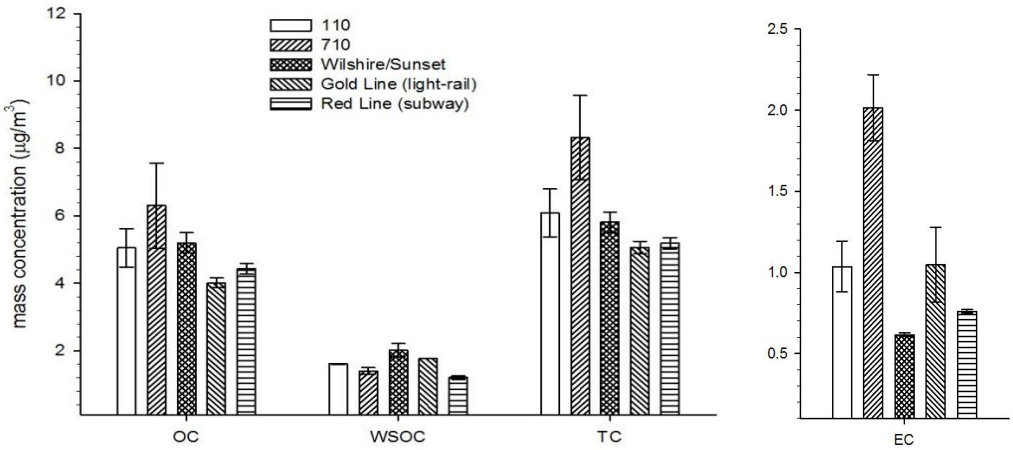

Figure 1. Comparison of major PM components (OC, WSOC, EC, and TC) for the five commute microenvironments. EC appears on a separate axis to highlight differences.

3.2 Metals and trace elements

A number of metals and trace elements that have been quantified in this study are identified as hazardous air pollutants under the U.S. EPA Clean Air Act Amendments of 1990, which includes Sb, Cd, Cr, Co, Pb, Mn, and Ni compounds. The U.S. EPA states that these airborne pollutants are known to cause or possibly cause cancer or other serious health effects, including birth defects, further emphasizing the importance of understanding the exposure of metals and trace elements for public and private commuters as well as residents who are in the vicinity of major roadways. Figure 2 shows the concentrations (ng/m^3) of total metals and trace elements for the commute microenvironments, and are presented based on concentration levels. Overall, the METRO red line (subway) exhibits the highest concentrations for Fe, Mn, Mo, Ba, Cr, Co, Ni, and Cd. For Fe, the red line is approximately 10 times higher than the 110 and 710, 15 times higher than Wilshire/Sunset, and 20 times higher than the gold line (light-rail). In the enclosed underground environment, subway dust is generated mainly from the abrasion processes between the rail, wheels, and brakes as well as by the mechanical wearing of the parts. The rail tracks and the main body of the train are composed of stainless steel, an Fe-based alloy mixed with other metallic elements to enhance its properties. The same study also demonstrated that

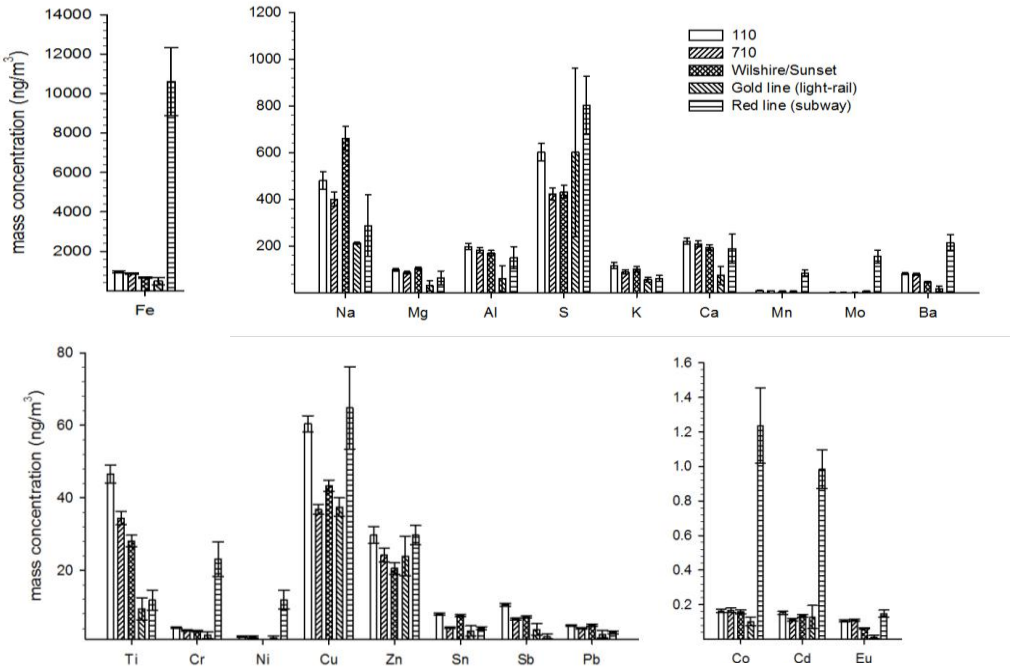

Figure 2. Comparison of concentrations of total metals and trace elements for the five commute environments.

Fe is strongly correlated with Cr, Mn, Co, Ni, Mo, Cd, and Eu ($R^2 > 0.9$, $p < 0.05$), indicating that these species may be components of stainless steel. In addition, PM may be resuspended due to train and passenger movement. Although the gold line (light-rail) exhibits relatively low concentrations of these steel-associated elements, the study determined that based on crustal enrichment factors, of which values close to 1 indicates crustal origins and greater values indicate anthropogenic sources, these elements have enrichment factors that are 2-3 times greater than the USC reference site. This suggests that these elements have indeed been influenced by additional sources (i.e. steel abrasion, wear of rail parts, etc.) that do not influence USC. Regardless of its additional source, the concentrations of metals and trace elements on the gold line (light-rail) are the lowest of the five commute environments, meaning commuters of this light-rail line are exposed to the lowest amounts of these airborne toxics.

The differential microenvironments play a major role in the contribution of various sources of metals and trace elements presented in this study. For example, Na may be part of soil dust, but because Los Angeles is largely affected by the southwesterly onshore breeze from the Pacific Ocean, sea salt is a substantial source of Na in the Basin. The higher Na concentrations observed on the three roadways relative to the METRO lines are expected in light of its major sea salt influence. Moreover, the higher levels of Na observed at Wilshire/Sunset relative to the 110 and 710 (average of 33% higher), can be explained by the proximity of the Wilshire/Sunset route to the coast, while the 110 and 710 routes are located more inland, and thus less influenced by sea salt. The average concentrations of Mg, Al, and K for the three roadways are 96.3±8.8, 183.3±13.6, 102.6±14.2 ng/m^3, respectively, and are all higher than average corresponding concentrations on both METRO lines (47.2±23.4, 106.2±63.0, and 59.9±3.2 ng/m^3). This is consistent with previous studies which determined that these species are primarily of crustal origin and derived from resuspension rather than from vehicular sources (Sternbeck et al. 2002).

Studies have shown that Fe, Al, Ca, Mg, K, Na are abundant in crustal materials, but road dust may be enriched with some of these elements, indicating anthropogenic sources (Lough et al. 2005). While the focus of this study is not to quantify the enrichment of these species relative to a reference site, our data is consistent with earlier roadside studies for elements which have a contribution from traffic sources (i.e. Cu, Ba, Pb, Fe, Ca, Sb, etc.). The most obvious observations are the elements that are associated with vehicular traffic but not rail abrasion or wear, which are Ca, Ti, Sn, Sb, and Pb. These elements are primarily derived from vehicular wear processes such as brake and tire wear (Ti, Sb, and Pb) and motor oil additives (Ca) (Lough et al. 2005). The average concentrations for the three roadways are 208.3±13.0 ng/m^3 for Ca, 36.3±9.4 ng/m^3 for Ti, 6.51±2.1 ng/m^3 for Sn, 8.0±2.2 ng/m^3 for Sb, and 4.6±0.5 ng/m^3 for Pb, while corresponding averages for the two METRO lines are 131.9±81.6, 10.6±1.7, 3.7±0.5, 2.7±1.4, and 2.6±0.4 ng/m^3. HDVs are known to be greater emitters of elements associated with brake wear due to the greater mechanical force required to decelerate relative to LDVs (Sternbeck et al. 2002). However, our results found no statistically significant difference for Ca, Ti, Sn, Sb, and Pb between the 110, which is composed of 3.9% HDVs, and 710, which is composed of 11.3% HDVs ($p=0.42$).

Elements associated with both steel and vehicular sources include Fe, Ba, Cu, and Zn. Traffic sources for these elements include engine wear (Fe), brake wear (Ba and Cu), and tire wear (Zn) (Sternbeck et al. 2002). The overall trend for these four elements is substantially higher than concentrations in the red line (subway) relative to the other environments except for Zn, which exhibit comparable levels for the five environments. For Fe, Ba, and Cu, concentrations on the three roadways vary within 50% of each other (with averages of 829.4±147.8 ng/m^3 for Fe, 69.6±20.0 ng/m^3 for Ba, and 46.8±12.2 ng/m^3 for Cu), and are generally higher than the gold line (490.5 ng/m^3 for Fe, 18.4 ng/m^3 for Ba, and 37.5 ng/m^3 for Cu).

Sulfur, which is the predominant element in all environments, shows unexpectedly high concentrations for the METRO lines relative to the three roadways. Since S is most likely in the form of ammonium sulfate in the Los Angeles Basin (Hughes et al. 2000), this is most likely explained by the warmer temperatures observed during the METRO campaign, leading to greater formation of sulfate from increases in photochemical reactions.

3.3 Polycyclic aromatic hydrocarbons (PAHs)

The U.S. EPA classifies 16 PAHs as priority pollutants based on their carcinogenicity and mutagenicity. Many PAHs and their derivatives are identified as probable (Group 2A) or

possible (Group 2B) carcinogens as defined by the International Agency for Research on Cancer (IARC). Therefore, it is essential to identify and quantify the concentrations of PAHs of which public and private commuters are exposed to on a daily basis. Figure 3a and 3b shows the average and range of concentrations of 11 PAHs (ng/m^3) and total PAH concentrations for the five commute environments. Total PAH concentrations are substantially higher on the roadway environments than on the two METRO lines. Specifically, the 710, 110, and Wilshire/Sunset roadways are 4.2, 2.8, and 2.2 times higher than the average of the two METRO lines, respectively. For most of the individual PAH species, the 710 levels are generally 2-3 times higher than the other two roadway environments, except for pyrene, where levels are 4-8 times higher. Although the 710 has the highest total PAH concentrations, statistical analysis using a t-test showed that the concentrations of all the PAHs (N=11) on the 710 were not significantly different with the 110 ($p=0.37$) or Wilshire/Sunset ($p=0.18$). PAH concentrations for the two METRO lines are consistently lower than the roadways, which is expected considering the main source of PAHs in the subway and light-rail environment is most likely entrainment from ambient air. Pairwise multiple comparison tests (Tukey test) was performed to further investigate statistical significance, which determined that only two pairs (710 and red line, 710 and gold line) were significantly different ($p<0.05$).

In urban environments, the main source of PAHs is from fuel and combustion processes. Both LDVs and HDVs emit PAHs, but HDVs emit PAHs at substantially higher amounts than LDVs (Phuleria et al. 2006). Numerous studies which have apportioned PAH emission factors (µg of pollutant/kg of fuel burned) for HDVs and LDVs through tunnel studies (Phuleria et al. 2006) and dynamometer studies (Schauer et al. 2002) have found that HDVs can emit up to 50 times more PAH levels than LDVs. The same studies also found that low molecular weight (MW) (MW ≤ 228) PAHs (i.e. pyrene) are primarily emitted by HDVs and high MW (MW ≥ 276) PAHs (i.e. benzo(*ghi*)perylene, indeno(*1,2,3-cd*)pyrene) are emitted by both HDVs and LDVs, which is consistent with the results of our current study. Although the 110 has high total traffic flows but low HDV flows (6378 veh/hr and 243 trucks/hr) and the 710 has a lower total traffic flow but higher truck flow (4247 veh/hr and 470 trucks/hr), the near 2-fold difference in truck volumes present on the 710 is most likely responsible for the higher concentrations of light MW PAHs.

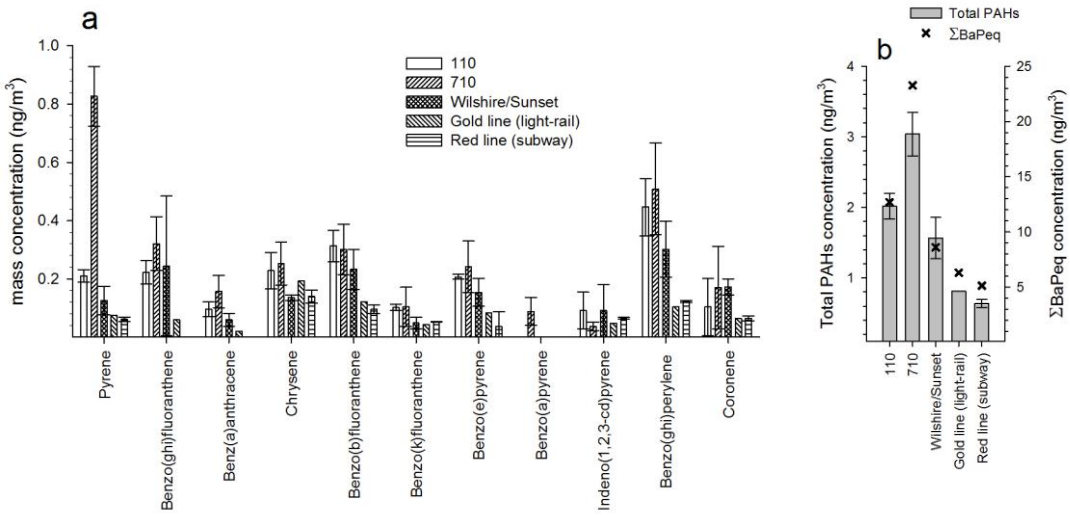

Figure 3. a) Concentrations of 11 PAHs and b) sum of PAHs concentrations and ΣBaPeq for the five commute environments.

An important property of PAHs is their semi-volatile nature. PAHs can be found in the urban environment in the gaseous phase or adsorbed onto particles in the solid phase based on its vapor pressure. Ambient temperatures can also play a role in the presence of particle-bound PAHs. Generally, high MW PAHs have lower vapor pressures than low MW PAHs. Thus, pyrene (MW = 202), can partition between the gas and particle phase depending on ambient temperatures, while indeno(1,2,3-cd)pyrene (MW = 276) and coronene (MW = 300) are found almost entirely in the particle phase. This is consistent with a previous study which found that emission factors for high MW PAH based on roadside sampling at the 110 and 710 were comparable to the reconstructed LDV and HDV emission factors based on tunnel sampling in spite of the different temperatures and dilution conditions, while low MW PAH emission factors differed by over two times (Ning et al. 2008). For the current study, the ambient temperatures for the two campaigns varied from 17 to 24 °C (Table 1). Of the 3 roadway environments,

Wilshire/Sunset exhibited the lowest PAH levels, consistent with the higher observed temperatures. Although the METRO campaign also had higher average ambient temperatures, the PAH levels for the red and gold lines are also influenced by the particle removal efficiency of the subway and train ventilation systems and thus particle penetration into the train.

3.4 Lung cancer risk for commuters

As mentioned earlier, PAHs are a major public health concern due to its carcinogenicity, and more specifically, to lung cancer risk. A number of PAHs identified in this study are classified as priority pollutants under the U.S. EPA. According to the IARC, benzo(a)pyrene, or BaP, is classified as a probable carcinogen (Group 2A). Since BaP has been studied and its cancer potency values have been well established, it is commonly used as the index compound for which potency activity of other PAH compounds and its derivatives are compared to. Relative potency values are referred to as potency equivalent factors (PEFs), for which BaP has a PEF of 1. Benz(a)anthracene has a PEF of 0.1, meaning it has 1/10th the potency of BaP. PEFs for other PAH compounds are from OEHHA. The calculation of lung cancer risk follows the method in Sauvain et al. 2003, and a brief summary follows. The PEFs are multiplied by the corresponding PAH concentration to determine the BaP equivalent concentrations (BaPeq). The sum of the individual BaPeq (ΣBaPeq) is subsequently multiplied by its unit risk factor (μg/m^3)$^{-1}$, which has been determined based on rodent or epidemiology studies (Sauvain et al. 2003). Unit risk factors based on rodent and epidemiology studies are 1.1E-4 and 2.1E-3 (μg/m^3)$^{-1}$, respectively. Figure 3b shows ΣBaPeq as a marker for each of the 5 microenvironments. Since the unit risk factors in Sauvain et al. (2003) are based on occupational continuous exposures (45 years for 8 hr/day), the current unit risk factors are determined by a multiplication factor of 0.18 to account for the lower risk for a commuter's lifetime on the road, which is considered to be 45 years for 5 days/week for 2 hours/day.

	ΣBaPeq (ng/m^3)	lung cancer risk (x10^{-6})	
		rodent	epidemiology
110	12.7	1.4	27.1
710	23.3	2.7	49.7
Wilshire/Sunset	8.6	1.0	18.4
Gold line (light-rail)	6.3	0.7	13.5
Red line (subway)	5.1	0.6	11.0

Table 2. Lung cancer risk calculations based on a commuter lifetime of 45 years, 2 hours/day, and 5 days/week. Unit risk factors for rodent and epidemiology are 1.1E-4 and 2.1E-3 (μg/m^3)$^{-1}$, respectively.

Table 2 shows the concentrations of ΣBaPeq and corresponding unit risk factors and lung cancer risk based on earlier rodent and epidemiology studies. Note that the unit risk factors between the rodent and epidemiology studies differ by approximately 19 times, yielding cancer risk values that differ by the same factor. Overall, the 710 exhibits the highest cancer risk. The 710 is greater than the two METRO lines by an average of 4.2 times, and is greater than the 110 and Wilshire/Sunset by 1.9 and 2.7 times, respectively. Although the results offer meaningful insight into the cancer risk that various commuters face on a daily basis, the authors acknowledge that there are relatively large uncertainties associated with the results as seen with the differences in unit risk factors between the rodent and epidemiology studies. In addition, concentrations of PAHs may exhibit temporal variation. For example, a previous study in Wilmington, CA, which is located between the 110 and 710 and in the proximity of the Ports of Los Angeles and Long Beach found that lung cancer risk is highest during rush hour traffic (around 8:00AM) and lowest in the late afternoon (around 5:00PM) (Polidori et al. 2008), whereas the current study represents results based on time-integrated samples from 6:00AM to 5:00PM. Nonetheless, results from this study are substantive in assessing the lung cancer risk for commuters on light-rail, subway, freeway, and surface street environments in Los Angeles.

4. Conclusion

This study compares the major PM components (EC, OC, WSOC), metals and trace elements, and PAHs in $PM_{2.5}$ for public and private commuters in five differential environments: subway (METRO red line), light-rail (METRO gold line), surface street (Wilshire/Sunset), and two freeways which represent the highest (710) and lowest (110) truck compositions in Los Angeles.

The 710 exhibited the highest EC and OC levels most likely due to its higher volume of HDVs, while the two METRO lines had the lowest EC and OC levels. Metals and trace elements quantified in this study are derived from a variety of sources depending on the commute environment. Substantially high levels of Fe and other steel-associated elements (Mn, Mo, Ba, Cr, Co, Ni, and Cd) were observed on the red line (subway) and substantially low levels were observed on the gold line (light-rail). Major sources in the rail environment are steel abrasion and wear of parts. Another group of elements (Ca, Ti, Sn, Sb, and Pb) was identified to be associated with urban traffic sources only, which are generated from vehicular wear processes and emitted from motor oil additives. Additionally, a number of the elements are primarily of crustal (i.e. Mg, Al) or sea salt (Na) origins. In the roadway environment, PAHs are primarily derived from vehicular emissions and were found to be substantially higher on the 710. Lastly, lung cancer risk was estimated and the 710 was determined to have the greatest cancer risk, while the two METRO lines had the lowest risk. Since the gold line (light-rail) was observed to have low concentrations of both PAHs and metals and trace elements, this suggests that commuting on a light-rail may have potential health benefits due to lower PM exposure levels as opposed to driving on freeways and major roadways. Results from this study are especially important for understanding $PM_{2.5}$ exposure for daily commuters, residents, and pedestrians in the proximity of roadways, who can be subjected to these pollutants and its inherent health risks.

5. References

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