Aerosol and Air Quality Research, x: 1–12, xxxx

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2017.09.0331

Commuting in Los Angeles: Cancer and Non-Cancer Health Risks of Roadway, Light-Rail and Subway Transit Routes

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ABSTRACT

Workers within the megacity of Los Angeles are exposed to significant amounts of airborne particulate matter (PM) during their daily commutes, which often exceed 30–60 minutes each way. Chemical species present in roadway and railway PM, including Benzo[*a*]pyrene (BaP) and hexavalent chromium (Cr^{6+}), present substantial cancer and non-cancer health risks. In the current study, PM samples were collected and quantitatively speciated along five major commuter routes, including the METRO red line (subway) and gold line (light rail), the I-110 and I-710 freeways, and high-density surface streets (Sunset and Wilshire Boulevards). Using these concentration data, along with cancer potency (CP) and Reference Dosage (RfD) factors obtained from the United States Environmental Protection Agency (USEPA) and California's Office of Environmental Health Hazard Assessment (OEHHA), cancer and non-cancer health risks were calculated. In contrast to previous research indicating that Polycyclic Aromatic Hydrocarbon (PAH) components of Los Angeles roadway PM (e.g., along the I-710 freeway) led to the greatest cancer risk, the current analysis reveals that exposure to carcinogenic transition metals, particularly hexavalent chromium, which are especially prevalent along the METRO red line, results in the greatest cancer and non-cancer health risks. Based on these data, the best option for commuters is to use above-ground light-rail transportation, which allows for reduced exposure to both traffic-generated PAHs and railway-related metals.

Keywords: Commuter health risk; On-road emissions; Subway; Particulate matter; Los Angeles.

INTRODUCTION

In megacities such as Los Angeles, Seoul, Tokyo, Moscow, Tehran, and São Paulo, whose populations exceed 10 million inhabitants, commuters rely heavily on public transportation, including bus, subway and light-rail transit systems, as well as personal vehicles. All modes of transportation, however, expose the public to varying degrees of air pollution during their daily commute, and the concomitant health risks can be significant. Airborne particulate matter (PM) is considered one of the most toxic forms of air pollution to which commuters are typically exposed, in both roadway and railway environments. $PM_{2.5}$, or fine particulate matter, which includes all PM smaller than 2.5 μm in diameter, is largely the product of condensation and agglomeration of primary ultrafine particles emitted by a variety of combustion sources, and results in more deleterious health effects due to its small size allowing for deep penetration into the lungs and subsequently the bloodstream (Brugge *et al.*, 2007; de Kok *et al.*, 2006; Delfino *et al.*, 2010).

$PM_{2.5}$ is composed of several chemical species, including carbonaceous materials such as elemental and organic carbon (EC/OC), crustal elements, organic compounds, transition metals, hopanes and steranes, and vehicular abrasion detritus. Two classes of compounds commonly found in the airborne PM to which commuters are exposed, polycyclic aromatic hydrocarbons (PAHs) and transition metals, contain species known to be carcinogens and/or pose chronic health risks (Harrison *et al.*, 2004). Polycyclic Aromatic Hydrocarbons (PAHs), such as Benzo[*a*]pyrene (BaP), are formed during incomplete fossil fuel combustion and are typically found in the PM emitted by vehicles. Transition metals, including nickel (Ni), iron (Fe), and hexavalent chromium (Cr^{6+}), often result from the friction-induced wear of railway components, especially steel rails and cables, and thus represent a significant fraction of light-rail and subway PM emissions (Chillrud *et al.*, 2004; Seaton *et al.*, 2005).

Several recent research programs investigating roadway, light-rail and subway PM exposures have been conducted in various megacities and other large urban cities throughout the world. These studies include investigations of airborne

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metals concentrations in the New York subway system (Chillrud *et al.*, 2004; Grass *et al.*, 2010), the measurement of PM_{10} and $PM_{2.5}$ concentrations both on platforms and inside railway cars of above and below ground metro trains in Naples (Carteni *et al.*, 2015), a quantification of $PM_{2.5}$ exposure and metals content in the subways of Helsinki (Aarnio *et al.*, 2005), a comparison of roadway and railway $PM_{2.5}$ exposures in Mexico City (Gomez-Perales *et al.*, 2004) and London (Adams *et al.*, 2001), as well as studies of subway PM exposures in Milan (Colombi *et al.*, 2013), Barcelona (Martins *et al.*, 2015; Moreno *et al.*, 2015), and Shanghai (Lu *et al.*, 2015).

Invariably, higher concentrations of airborne PM have been found in subway systems as compared to above-ground railway systems and roadways. Within the subway systems, PM concentrations were found to be higher at the waiting platforms as compared to within the railway cars, which are often enclosed and well-ventilated. Additionally, studies that evaluated subway and light-rail PM speciation (e.g., Chillrud *et al.*, 2004; Aarnio *et al.*, 2005; Grass *et al.*, 2010; Colombi *et al.*, 2013; Lu *et al.*, 2015; Moreno *et al.*, 2015) found higher concentrations of metals, especially Fe, Mn, Cu, Cr and Ni, in the PM collected on subway lines, compared to particulate collected in above-ground ambient conditions, as well as during light-rail and roadway exposures. The high metal content of subway PM has been attributed to the wear of railway components, including steel cables, wheels, and rails, as well as braking systems, and higher PM concentrations at subway platforms result from the resuspension of "steel dust" and other PM by passing trains.

Los Angeles, historically considered one of the most polluted megacities in the world, has a unique composition of commuters. Consisting of a vast, decentralized urban sprawl with a multitude of business and manufacturing hubs interspersed among numerous residential communities, the city is perfused by workers who utilize an extensive latticework of arterial railways, roadways and freeways to make the daily journey to and from their places of employment. Perhaps more than any other megacity, a large percentage of Los Angeles commuters choose to travel via personal vehicles as well as by public transit. Nearly 90% of the 4.5 million workers in Los Angeles and its surrounding areas spend an average of 60 minutes per day commuting on a roadway or railway (U.S. Census Bureau, 2015 American Community Survey), and the cumulative health risk posed by the airborne particulate matter (PM) to which they are exposed is significant.

Several recent studies of air pollution along the various commuter pathways, both road and railway, in Los Angeles have examined the composition and characteristics of particulate matter to which commuters are exposed. These studies have focused on vehicular roadways (Kam *et al.*, 2012; Shirmohammadi *et al.*, 2017; Vreeland *et al.*, 2017; Zhu *et al.*, 2007), as well as light-rail and subway transportation systems (Kam *et al.*, 2011a, b), and have also compared the relative PM exposures, compositions, and health risks associated with each mode of transport (Kam *et al.*, 2013). Two factors are key in determining the impact of toxic PM compounds on commuters, as quantified by standard health risk indices such as Extended Life Cancer Risk (ELCR) and the non-cancer Hazard Quotient (HQ): the duration of PM exposure and the inherent PM toxicity as determined by its specific chemical composition.

Kam *et al.* (2013), in examining the cancer risk to Los Angeles commuters posed solely by PAHs, collected samples of filterable particulate matter < 2.5 μm in diameter ($PM_{2.5}$) along five major commuting routes, including an above-ground light-rail train route (METRO gold line), a below-ground subway line (METRO red line), two major freeways with high (11.3%) and low (3.9%) volumes of heavy-duty vehicle (HDV) traffic (I-710 and I-110, respectively), and high traffic volume surface streets (Wilshire and Sunset Boulevards). These authors found that I-710, with its large volume of HDV traffic and corresponding high PAH concentrations in collected $PM_{2.5}$, posed the greatest health risk (i.e. lung cancer risk) to commuters, 1.8–4.5 times higher than that resulting from PM exposure on other commuter routes.

While the research of Kam *et al.* (2013) focused on the cancer risks resulting exclusively from the PAH content of $PM_{2.5}$ to which commuters are exposed, transition metals, such as nickel, chromium and cobalt, also contribute significantly to cancer, as well as non-cancer, health risks. Diesel exhaust particulate (DEP), a specific subset of PM composed largely of PAHs and elemental carbon (EC), or black carbon, presents a significant health risk to commuters as well. While PAH components of PM increase cancer risk due to their mutagenic/carcinogenic properties, the EC fraction contributes to cancer risk by distinct non-genotoxic, tumor-promoting mechanisms such as increased inflammation and reactive oxygen species (ROS) formation (Sauvain *et al.*, 2003). The risks posed by metals and EC were not included in the Kam *et al.* (2011a, b, 2012) studies. However, in the current study, we detail the contributions of both PAHs and transition metals, as well as EC, to both cancer and non-cancer risks, thus presenting a more comprehensive picture of the health hazards to commuters resulting from exposure to toxic species of airborne $PM_{2.5}$ in the megacity of Los Angeles.

EXPERIMENTAL METHODOLOGY

Sampling Methods

The $PM_{2.5}$ data reviewed in the current study were collected along the Los Angeles METRO gold (light-rail) and red (subway) lines during the months of May through August, 2010 (Kam *et al.*, 2011a), and on two major freeways (I-110 & I-710) and surface streets (Wilshire/Sunset) during the months of March through May, 2011 (Kam *et al.*, 2012). All $PM_{2.5}$ samples were collected using Personal Cascade Impact Samplers, or PCISs (SKC Inc., Eighty-Four, PA; Misra *et al.*, 2002; Singh *et al.*, 2003), in conjunction with Leland Legacy portable pumps (SKC Inc., Eighty-Four, PA) set at an air intake flow rate of 9 liters per minute (lpm). $PM_{2.5}$ samples were collected for chemical speciation on either Teflon (PTFE) filters (Pall Life Sciences, Ann Arbor, MI) or quartz microfiber filters (Whatman International

Ltd., Maidstone, England) placed downstream of the 2.5 μm cut-point impactor stage in each PCIS.

Two separate sets of filters samples were collected along each of the five sampling routes (2 freeway, 2 railway, 1 surface street) for chemical analysis. For the on-road sampling campaign, 6 PCISs were utilized (3 equipped with Teflon filters, 3 with quartz filters) per set. Sampling at each location was conducted over 5 consecutive weekdays, from 6:00 AM to 5:00 PM each day, using a 2011 Honda Insight Hybrid as a mobile test vehicle. Ambient air intake to the 6 PCISs was through a 3/8-inch diameter stainless steel inlet nozzle affixed to the vehicle, with the opening positioned towards the front (i.e., directly into oncoming roadway air flow). Due to variable driving speeds, depending on traffic conditions, roadway sampling was necessarily anisokinetic. However, as discussed in Kam *et al.* (2012), $PM_{2.5}$ sampling at typical roadway driving speeds of 10–50 mph is not significantly affected by any corresponding deviations from isokineticity.

For the light-rail and subway sampling, 3 PCISs were employed by each experimenter (2 with Teflon filters, 1 with a quartz filter). Each set of filter samples was collected over 7 weekdays, from 9:30 AM to 1:00 PM, while experimenters spent approximately 25% of this time on the railway platform and 75% of the time riding the train. To collect ambient air samples during their commute, each experimenter was equipped with a carry-on suitcase containing the 3 PCISs and 3 pumps. Commutes included stopping at two stations along the route, which varied week-to-week, for platform sampling. Full experimental details are reported in Kam *et al.* (2011a).

Sampling Locations and Route Descriptions

An overview of the five commuter routes along which samples were collected is presented in Fig. 1, with relevant route parameters presented in Table 1. More detailed descriptions of the METRO train routes and sampling protocol have been detailed in Kam *et al.* (2011a), while the specifics of roadway sampling on the freeways and surface streets have been described in Kam *et al.* (2012).

Briefly, the two METRO lines discussed in the present study are electric-powered, third-rail train lines linking downtown Los Angeles to outlying areas of the city. The METRO gold line is an above-ground light-rail train line running between East Los Angeles, Downtown, and Pasadena to the north, with 21 stations scattered along its 32 kilometer length. The METRO red line is a below-ground subway line connecting downtown Los Angeles to North Hollywood, with 14 stations along its 26.4 kilometer length. Unlike other subway systems in the world, the subway and light-rail trains in LA operate with mandatory closed windows the train cabins and are mechanically ventilated. Thus, the METRO trains represent the most protective travel configuration for commuter PM exposures.

The I-110 and I-710 Los Angeles freeways are both high-density roadways that connect commuters living in outlying communities to the urban hub of downtown Los Angeles (DTLA) as well as other major business districts. I-110 is a 51-kilometer north-south freeway connecting San Pedro and the Port of Los Angeles in the south to Pasadena in the north, passing along the western edge of DTLA. I-710 (also known as the Long Beach Freeway) is a 43-kilometer north-south freeway, parallel to and east of I-110, that begins in Long Beach at its southern end and ends in Pasadena to the north, running along the eastern edge of DTLA. The I-710 freeway experiences a lower volume of traffic (4247 vehicles per hour) as compared to the I-110 (6378 vehicles per hour), however the I-710 freeway traffic consists of a higher percentage of heavy-duty trucks (11.3%) as compared to the I-110 freeway (3.9%). Wilshire and Sunset Boulevards are major east-west surface streets with a moderate vehicle density (1839 vehicles per hour, with negligible truck traffic). During the roadway sampling campaign, a 48-km route was traversed along these streets, passing through the communities of Beverly Hills, Hollywood, Echo Park, Koreatown, and DTLA.

As a quasi-control condition, PM emissions and composition were also determined at a stationary urban site in central Los Angeles, adjacent to the main campus of USC. Filter samples were collected utilizing 3 PCISs (2 with Teflon filters, 1 with a quartz filter), as described previously, at a stationary laboratory near DTLA, the USC Particle Instrumentation Unit (PIU). These filter samples were collected concurrently during the time periods of both the roadway and railway sampling campaigns, using the same procedures, and underwent the same chemical analyses, as is further detailed in Kam *et al.* (2011a, 2012).

Sample Analysis

Gravimetric analysis consisted of weighing all filters pre- and post-sampling with an MT5 Microbalance (Mettler-Toledo Inc., Columbus, OH) to determine mass loading. PM total metals content was determined by analyzing the Teflon filters using a high resolution, double-focusing magnetic sector field Inductively Coupled Plasma Mass Spectroscopy (HR-ICPMS; Finnigan Element 2) after acid extraction, as detailed in Zhang *et al.* (2008). To determine the PAH species present in the collected PM samples, gas chromatography/mass spectroscopy analysis was performed on the quartz filter samples (Mazurek *et al.*, 1987; Schauer *et al.*, 1999). Quartz filters were also analyzed for elemental carbon (EC) using Thermal Evolution/Optical Transmittance analysis (Birch and Cary, 1996).

Cancer and Non-Cancer Risk Calculations

While several PAHs encountered by commuters are carcinogenic, as discussed in Kam *et al.* (2012), this type of airborne particulate matter is also composed of several transition metals that present a significant cancer risk (Klein, 1996), particularly hexavalent chromium (Cr^{6+}), which is the oxidation state of chromium that has been shown to dominate airborne PM emissions resulting from high temperature processes such as welding and combustion (Shi *et al.*, 1994; Edme *et al.*, 1997). In the current study, we examined and quantified the cancer risk associated with exposure to both PAHs and metals, as well as the chronic health hazards such materials pose. Additionally, we assessed the cancer risk posed by Diesel Exhaust Particulate (DEP)

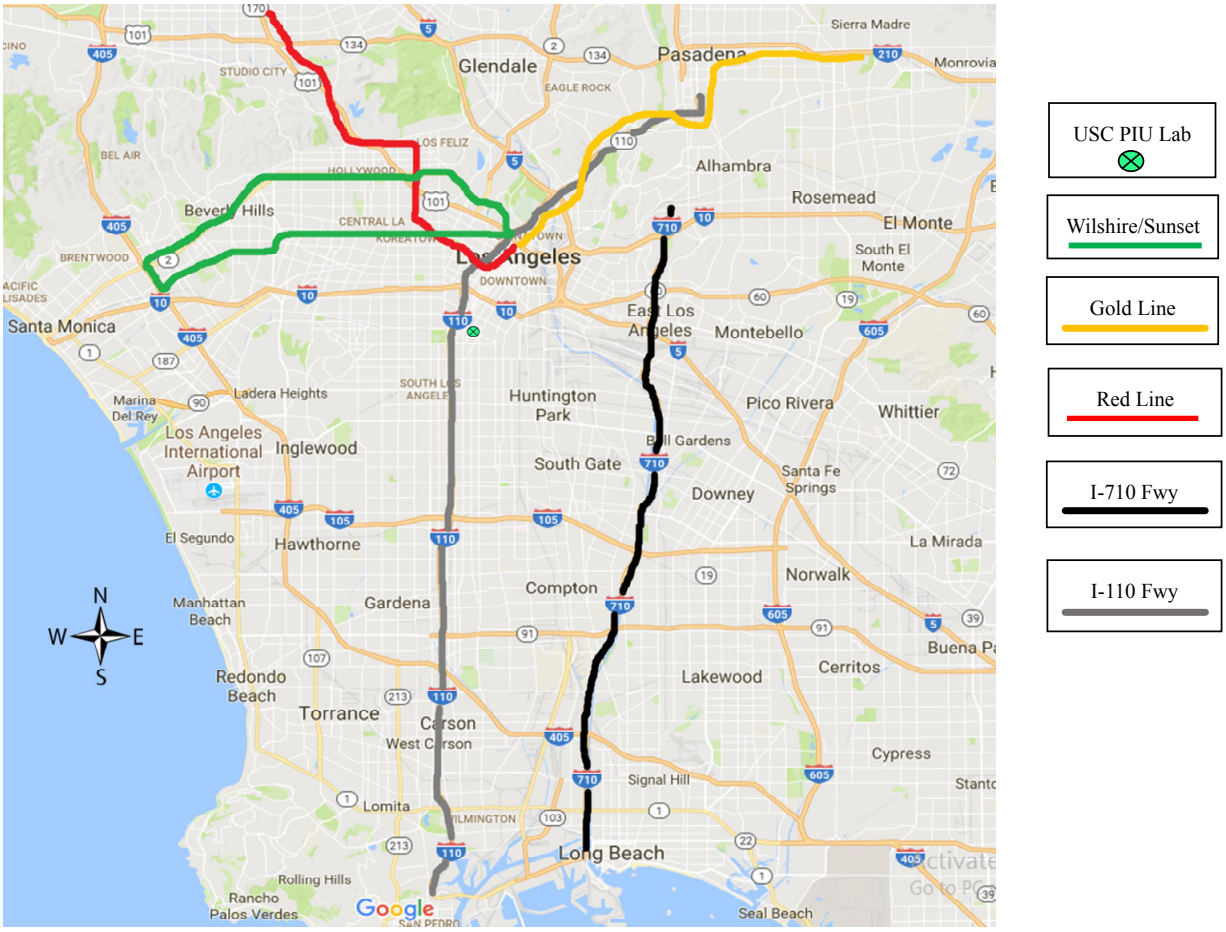

Fig. 1. Commuter Routes.

Table 1. General characteristics of the investigated sampling routes.

Characteristics	METRO Gold line	METRO Red line	I-110 Freeway	I-710 Freeway	Wilshire/Sunset
Length of sampling route	32 km	26 km	51 km	43 km	48 km
Sampling dates	May–Aug 2010	May–Aug 2010	March–April 2011	March–April 2011	March–May 2011
Traffic flow (vehicles hr^{-1})	-	-	6378	4247	1839
Percentage of HDVs (%)	-	-	3.9	11.3	-
Sampling type	Platform & in-train	Platform & in-train	Vehicle-based	Vehicle-based	Vehicle-based

using Elemental Carbon (EC) concentration as a surrogate index of DEP concentration as described in Sauvain *et al.* (2003).

To calculate the cancer risk to humans, quantified as Excess Lifetime Cancer Risk (ELCR), as well as the chronic non-cancer risk, quantified as the Hazard Quotient (HQ), we first calculated the Chronic Daily Intake (CDI) of each compound at each sampling location. The CDI, in units of mg kg^{-1} day^{-1}, was calculated from the toxin concentration (mg m^{-3}), daily intake rate based on a 1-hour daily commute (20 m^3 day^{-1} × (1 hr/24 hr)), days of exposure per lifetime (5 days $week^{-1}$ × 50 weeks $year^{-1}$ × 30 years of employment), average human body weight (70 kg), and average human lifetime (70 years), as detailed in Eq. (1).

Chronic Daily Intake (CDI):

$$CDI = (\text{Concentration (mg m}^{-3}) \times \text{Intake Rate (m}^3\text{ day}^{-1}) \times \text{Exposure (days life}^{-1})) / (\text{Body Weight (kg)} \times 70\text{ (years life}^{-1}) \times 365\text{ (days year}^{-1})) \quad (1)$$

Intake rate: 20 m^3 day^{-1} × 1 hr day^{-1} commute × day 24 hrs^{-1} = 0.833 m^3 day^{-1}
Exposure: 5 days $week^{-1}$ × 50 weeks $year^{-1}$ × 30 years = 7500 days $life^{-1}$
Body weight: 70 kg

Excess Lifetime Cancer Risk (ELCR):

The CDI for each compound was then multiplied by its

Cancer Potency (CP) factor, in units of (mg kg^{-1} $day^{-1})^{-1}$, to calculate lifetime cancer risk, or ELCR, as detailed in Eq. (2).

$$ELCR = \text{CDI (mg kg}^{-1}\text{ day}^{-1}) \times \text{potency factor (mg kg}^{-1}\text{ day}^{-1})^{-1} \quad (2)$$

There is some discrepancy in CP factors between those provided by the United States Environmental Protection Agency (USEPA), which are listed in their Integrated Risk Information System (IRIS) database, and those provided by California's Office of Environmental Health Hazard Assessment (OEHHA). In the current study, distinct ELCR values were calculated for each compound using both the USEPA and OEHHA CP factors. If only a single CP factor was available (from either agency) that value was used in both calculations. CP factors from both the USEPA and OEHHA are presented in Table 2.

Individual ELCRs for each species, both metals and PAHs, were summed to generate a Total ELCR value for each sampling location. As with individual ELCR values, Total ELCR values were calculated from both the USEPA- and OEHHA-based ELCR values and reported separately. A Maximum Total ELCR value was calculated for each location by summing only the higher of the two individual ELCR values for each compound. The Maximum Total ELCR value for each site also includes the calculated cancer risk due to DEP. The threshold for acceptable cancer risk is generally defined as 1 in a million, or 10^{-6}, per most governmental health and environmental organizations, e.g., the World Health Organization (WHO), USEPA, OEHHA, and the South Coast Air Quality Management District (SCAQMD), the regional air quality regulatory agency with jurisdiction over Los Angeles county and adjoining areas.

Cancer risk due to DEP exposure (using EC as a surrogate of DEP, as noted earlier) was calculated using the method described in Sauvain *et al.* (2003) and Stayner *et al.* (1998). In this method, the EC concentration is multiplied by the Inhalation Unit Risk (IUR) factor to give cancer risk. An IUR value is defined by the USEPA's Integrated Risk Information System (IRIS) as "The upper-bound excess lifetime cancer risk estimated to result from continuous exposure to an agent at a concentration of 1 μg m^{-3} in air," (https://www.epa.gov/iris). To calculate cancer risk resulting from occupational DEP (EC) exposure over an 8-hour work day, Sauvain *et al.* (2003) used an IUR of 2.8×10^{-6} $(\mu g\ m^{-3})^{-1}$ based on rodent exposure toxicology data and corrected for an 8-hour workday and 45-year working period. For use in calculating commuter exposure risk, we divided this value by eight, resulting in a 1-hour commuter IUR of 3.5×10^{-7} $(\mu g\ m^{-3})^{-1}$.

Cancer risk calculated using IUR values represents the upper-limit of risk and does not take into account body weight, which is factored into the cancer potency values used to calculate ELCR. Additionally, it should be noted that unit risk values vary widely based on epidemiological and toxicological studies, as discussed in Stayner *et al.* (1998), and no best method of determining IUR values has been agreed upon. Calculating ELCR using cancer potency values provided by OEHHA and USEPA, along with the CDI value, which incorporates several exposure factors such as body weight and breathing rate, is a more robust method of cancer risk determination. Sharma and Balasubramanian (2017) in their paper examining wildfire smoke haze-related

Table 2. Cancer Potency (CP), Reference Concentration (RfC) and Reference Exposure Level (REL) for Selected PAHs and Metals.

Compound	CAS No.	CP (USEPA) (mg kg^{-1} $day^{-1})^{-1}$	CP (OEHHA) (mg kg^{-1} $day^{-1})^{-1}$	RfC (EPA) (mg m^{-3})	REL (OEHHA) (mg m^{-3})
PAHs					
Benz(a)Anthracene	56-55-3	NA[a]	0.39	NA	NA
Benzo(a)Pyrene (BaP)	50-32-8	2.1	3.9	2.0×10^{-6}	NA
Benzo(b)Fluoranthene	205-99-2	NA	0.39	NA	NA
Benzo(j)Fluoranthene	205-82-3	NA	0.39	NA	NA
Benzo(k)Fluoranthene	207-08-9	NA	0.39	NA	NA
Chrysene	218-01-9	NA	0.039	NA	NA
Dibenz(ah)Anthracene	53-70-3	NA	4.1	NA	NA
Dibenzo(ae)Pyrene	192-65-4	NA	3.9	NA	NA
Indeno(1,2,3-cd)Pyrene	193-39-5	NA	0.39	NA	NA
Metals					
Aluminum	7429-90-5	NA	NA	5.0×10^{-3}	NA
Arsenic, inorganic	7440-38-2	15.05	12.0	NA	1.5×10^{-5}
Cadmium	7440-43-9	6.3	15.0	2.0×10^{-6}	2.0×10^{-5}
Chromium(VI)	18540-29-9	42.0	510	1.0×10^{-4}	2.0×10^{-4}
Cobalt	7440-48-4	31.5	NA	NA	NA
Copper	7440-50-8	NA	NA	NA	NA
Lead	7439-92-1	0.040	0.042	1.5×10^{-4}	NA
Manganese	7439-96-5	NA	NA	5.0×10^{-5}	9.0×10^{-5}
Nickel	7440-02-0	0.84	0.91	NA	1.4×10^{-5}

[a] NA: Not assessed.

$PM_{2.5}$ health risks in Southeast Asia, in both indoor and outdoor environments, also use this method of calculating ELCR values and calculate cancer risks. Their results (e.g., a 3.4 to 5.8 × 10^{-6} cancer risk due to the Cr component of $PM_{2.5}$ during outdoor haze exposures) are comparable in magnitude to the findings of the current study.

Hazard Quotient (HQ):

To calculate the chronic (lifetime) non-cancer risk, or Hazard Quotient (HQ), the same CDI used for cancer risk calculations is divided by the Reference Dosage (RfD), in units of mg kg^{-1} day^{-1}, as shown in Equation (3). The RfD is calculated from either the inhalation exposure Reference Concentration (RfC) values provided by the USEPA, or the chronic Reference Exposure Level (REL) values provided by OEHHA. Both RfC and REL concentration values are provided in units of mg m^{-3}. To calculate RfD values, the RfC or REL is multiplied by the human daily inhalation rate of 20 m^3 day^{-1} and divided by the average human body weight of 70 kg. As with ELCR values, in calculating non-cancer health hazard values, the available RfC or REL value was used, or, when both were available, two distinct HQ values were determined, one using the USEPA RfC and one using the OEHHA REL. RfC and REL values are presented in Table 2.

$$HQ = \frac{\text{CDI (mg kg}^{-1}\text{ day}^{-1})}{\text{RfD (mg kg}^{-1}\text{ day}^{-1})} \quad (3)$$

EPA: RfD = RfC (mg m^{-3}) × Inhalation Rate (20 m^3 day^{-1})/ Body Weight (70 kg)
OEHHA: RfD = REL (mg m^{-3}) × Inhalation Rate (20 m^3 day^{-1})/Body Weight (70 kg)

RESULTS AND DISCUSSION

Particulate Matter Composition at Sampling Sites

General parameters of the various sampling routes and collection periods are presented in Table 1. While the total volume of vehicular traffic along the I-110 freeway (6378 vehicles hr^{-1}) was larger than that along the I-710 freeway (4247 vehicles hr^{-1}), the percentage of HDV trucks on the I-710 (11.3%) was significantly higher than on the I-110 freeway (3.9%).

Transition metals posing a cancer risk to commuters that were detected in measurable concentrations at any of the test sites include As, Co, Cd, Cr, Pb and Ni, while the detectable metals contributing to non-cancer risk include Al, As, Cd, Cr, Ni, Pb and Mn. Airborne PAHs having an associated cancer risk that were detected along any of the commuter sampling routes include Benz(a)Anthracene, Benzo(a)Pyrene, Benzo(b)Fluoranthene, Benzo(k)Fluoranthene, Chrysene and Indeno(1,2,3-cd)Pyrene. The only detected PAH with an associated non-cancer health hazard risk was BaP, however this compound was only found in PM samples collected along the I-710 freeway.

Concentrations (ng m^{-3}) of relevant transition metal and PAH species contained in PM captured at these sampling sites are presented in Table 3. As seen in Table 3, the highest concentrations of transition metals, particularly manganese (84.9 ± 13.1 ng m^{-3}), copper (64.8 ± 11.3 ng m^{-3}), and chromium (23.1 ± 4.7 ng m^{-3}), were found in PM samples collected along the METRO red line commuter pathway. These values are lower but comparable to those found by Chillrud *et al.* (2004) for manganese (240 ng m^{-3}) and chromium (84 ng m^{-3}) during their study of the New York City subway system. The assumption made by Chillrud *et al.* (2004) that all detected chromium is hexavalent chromium, an assumption we also make in this paper, is reasonable given the high temperatures in which railway dust is formed, and allows us to determine a more conservative health risk estimate. These authors note that while the manganese and chromium (VI) concentrations measured are much lower than the permissible exposure levels (PELs) set by the Occupational Safety and Health Administration (OSHA), namely 5,000 ng m^{-3} for Cr (VI) and 200,000 ng m^{-3} for Mn (8-hr averages), the calculated total excess lifetime cancer risk at the measured concentrations is greater than 10^{-5}, clearly posing a substantial cancer risk that exceeds the ELCR safety threshold of 10^{-6}. While the OSHA PEL concentration threshold thus seems excessively high based on these calculated cancer risks, it should be noted that this prima facie discrepancy arises because the PEL pertains to acute exposures (< 8 hrs day^{-1}), while the calculated ELCR is based on a 70-year lifetime of daily exposures. To put the measured chromium (VI) concentrations in perspective, as of 2010, the average ambient chromium (VI) concentrations in California were found to be approximately 0.04–0.06 ng m^{-3} (Propper *et al.*, 2015), which is 2–3 orders of magnitude lower than the concentrations found within the subway environments.

The highest concentrations of total PAHs with an associated health risk (0.940 ± 0.346 ng m^{-3}) were found along the I-710 freeway, which was also the only sampling route with a detectable concentration of BaP (0.0886 ± 0.0479 ng m^{-3}). Higher PAH concentrations observed along the I-710 freeway result from a higher percentage of HDVs, which emit more PAHs than do LDVs (Phuleria *et al.*, 2006; Ning *et al.*, 2008). Additionally, a higher proportion of HDVs, which are primarily diesel-fueled, on the I-710 freeway, resulted in a higher concentration of DEP, as indexed by EC. The concentration of EC measured along the I-710 was 2016 ± 115 ng m^{-3}, as compared to 1036 ± 164 ng m^{-3} along the I-110 freeway.

Cancer and Non-Cancer Health Risks along Commuter Pathways

Figs. 2(a) and 2(b) present the cancer risk (ELCR) posed by individual metal and PAH species, respectively, of particulate matter collected at the five different sampling locations. As can be seen in the data presented in Fig. 2(a), chromium led to the greatest cancer risk of all metals (ELCR = 4.1 × 10^{-5} at the METRO red line), by at least one order of magnitude, at all sampling locations. Elemental Carbon (EC), as a surrogate for DEP, also presented a substantial contribution to cancer risk (METRO red line

Table 3. Summary statistics of the concentrations (ng m^{-3}) of chemical components (metals, PAHs, and EC) measured in each sampling campaign

Category	Species	Gold line		Red line		I-110		I-710		Wilshire/Sunset		USC	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Metals	Al	61.7	54.6	151	47.5	197	ND	182	ND	170	ND	136	11.0
	As	0.382	0.191	0.877	0.0833	0.659	ND	0.394	ND	0.491	ND	0.453	0.0725
	Cd	0.127	0.0674	0.985	0.113	0.153	ND	0.113	ND	0.136	ND	0.0865	0.0170
	Cr	2.14	0.932	23.1	4.75	4.13	ND	3.44	ND	3.27	ND	3.03	1.54
	Co	0.102	0.0257	1.24	0.219	0.164	ND	0.167	ND	0.158	ND	0.132	0.0324
	Cu	37.5	2.52	64.8	11.3	60.4	ND	36.8	ND	43.3	ND	14.4	0.760
	Pb	2.37	1.13	2.89	0.350	4.73	ND	3.99	ND	4.92	ND	3.35	0.786
	Mn	5.81	2.15	84.9	13.1	9.97	ND	9.16	ND	7.45	ND	5.10	0.632
	Ni	1.42	0.482	11.9	2.56	1.74	ND	1.61	ND	0.912	ND	2.47	1.31
PAHs	Benz(a)Anthracene	0.0208	ND[a]	NA	--	0.0955	0.0251	0.157	0.0557	0.0590	0.0218	0.0137	0.0122
	Benzo(a)Pyrene	NA[b]	--	NA	--	NA	--	0.0886	0.0479	NA	--	NA	--
	Benzo(b)Fluoranthene	0.122	ND	0.0958	0.0148	0.313	0.0538	0.300	0.0870	0.233	0.0689	0.0945	0.0600
	Benzo(j)Fluoranthene	NA	--	NA	--	NA	--	NA	--	NA	--	NA	--
	Benzo(k)Fluoranthene	0.0440	ND	0.0523	0.0002	0.102	0.0114	0.104	0.0675	0.0485	0.0193	0.0308	0.0211
	Chrysene	0.194	ND	0.140	0.0224	0.228	0.0621	0.253	0.0738	0.135	0.0100	0.0911	0.0757
	Dibenz(ah)Anthracene	NA	--	NA	--	NA	--	NA	--	NA	--	NA	--
	Dibenzo(ae)Pyrene	NA	--	NA	--	NA	--	NA	--	NA	--	NA	--
	Indeno(1,2,3-cd)Pyrene	0.0475	ND	0.0649	0.0032	0.0916	0.0626	0.0371	0.0143	0.0911	0.0903	0.0345	0.0153
Elemental Carbon	DEP Surrogate	1046	ND	760	10.0	1036	164	2016	115	616	18.6	650	285

[a] ND: Not determined.
[b] NA: Not available.

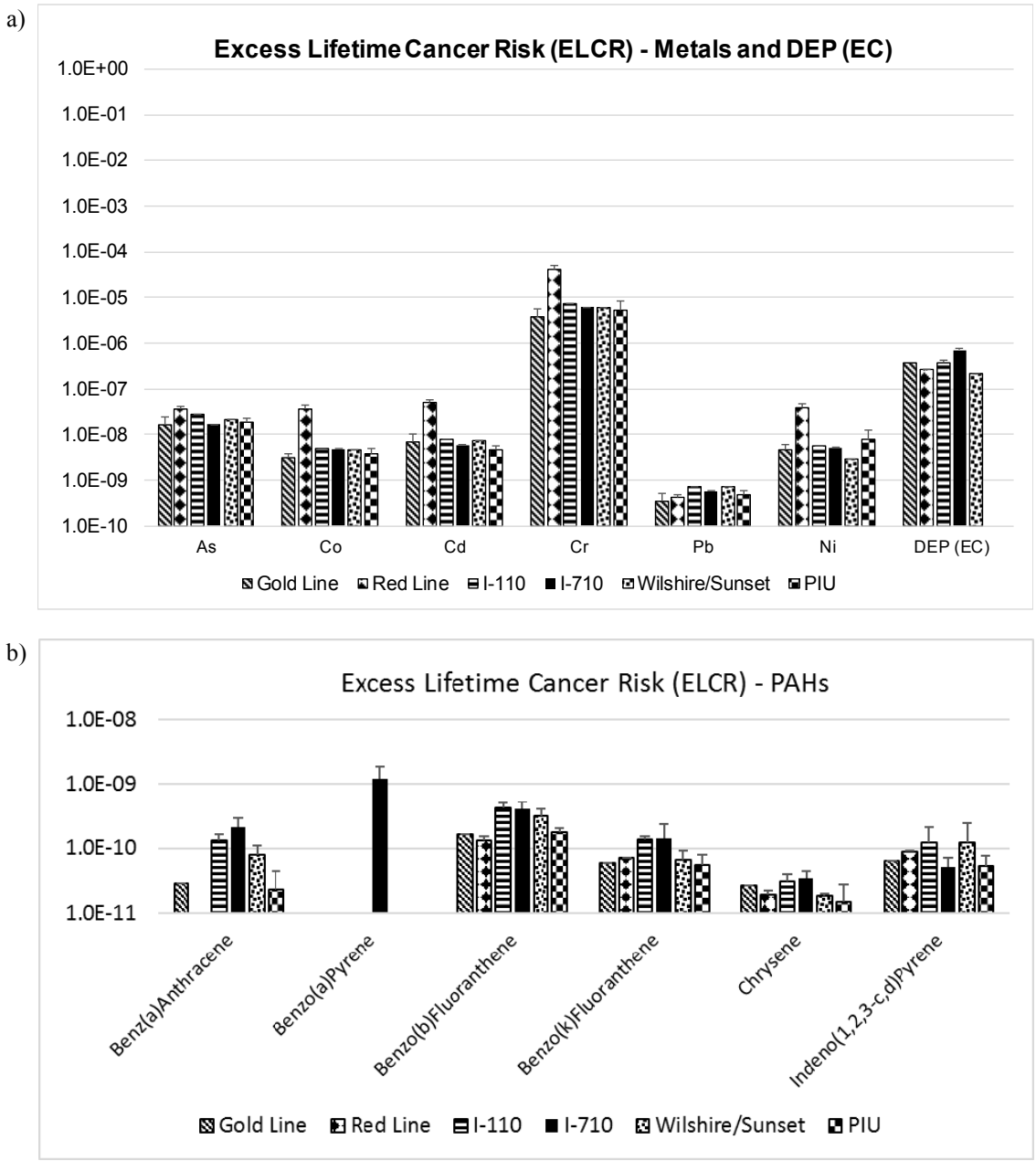

Fig. 2. a) Cancer Risk (ELCR) for Metals. b) Cancer Risk (ELCR) for PAHs.

ELCR = 2.7×10^{-7}). Fig. 2(b) reveals that among the PAHs, BaP poses the greatest cancer risk (ELCR = 1.2×10^{-9}) though it was only detected along the I-710 freeway. While the cancer risk of BaP is not trivial, it makes an insignificant contribution to overall risk in an environment (e.g., a subway system) where emissions of metallic carcinogens such as hexavalent chromium dominate.

Of the metals present in both subway and roadway environments, hexavalent chromium, with an exceptionally high cancer potency factor of 42.0 (USEPA) or 510 (OEHHA) (mg kg^{-1} $day^{-1})^{-1}$, is the largest contributor to overall cancer risk. Thus, the high concentrations of airborne metals measured in the subway setting (METRO red line) of the current study, as well as in the Chillrud *et al.* (2004) study of the New York City subway system, should be of special concern to commuters.

Fig. 3 presents the chronic non-cancer health hazard risk (HQ) posed by relevant transition metals. The greatest non-cancer risk along the METRO red line was due to Cd (HQ = 6.0×10^{-3}), Cr (HQ = 2.8×10^{-3}), Ni (HQ = 1.0×10^{-2}), and Mn (HQ = 2.1×10^{-2}), while generally, across all sampling locations, Ni and Mn produced the greatest health hazards compared to other metals, as can be seen in Fig. 3. Note that an RfC value was available to calculate the HQ for only one PAH (BaP), therefore it is not included with the metals HQ results depicted in Fig. 3.

Figs. 4(a) and 4(b) present the Total ELCR (cancer risk) and HQ (non-cancer risk) values, respectively, at each of the various sampling sites, calculated as the sum of individual ELCR and HQ values of all relevant metals and PAHs

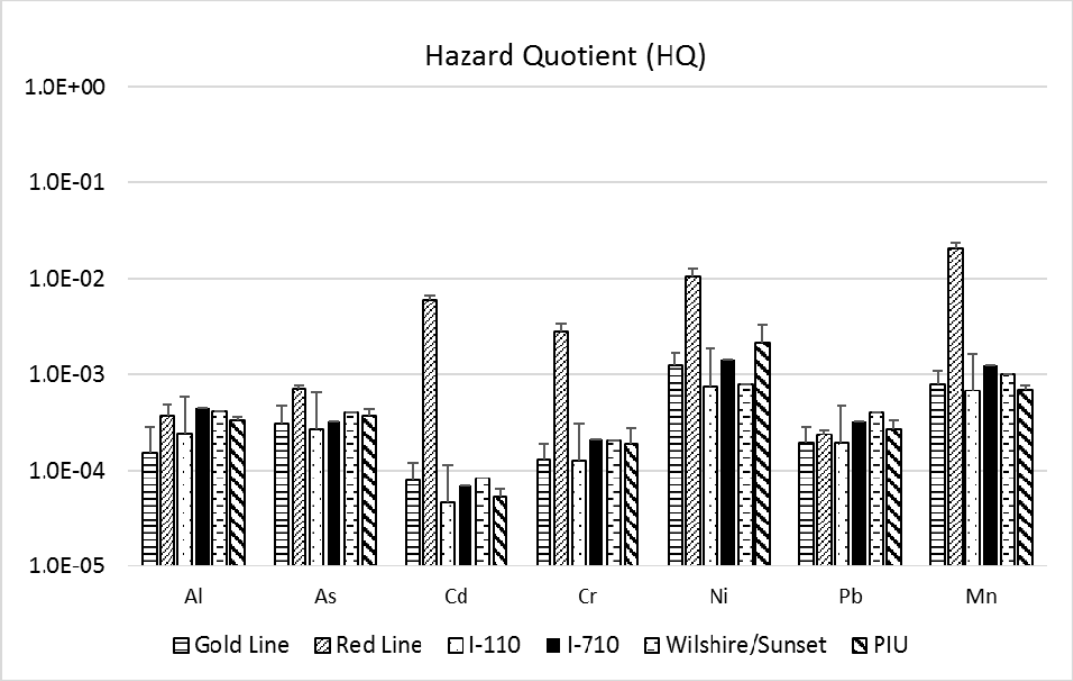

Fig. 3. Non-Cancer Risk (Hazard Quotient).

present at each site. Total values were calculated based on the CP and RfC/REL values provide by the USEPA and OEHHA, however if only one value was available for any individual metal or PAH, it was used in both calculations. A depiction of the Maximum ELCR or HQ at each site, along with the total values calculated using USEPA and OEHHA factors alone, is also included in Figs. 4(a) and 4(b) based on using the higher CP or RfC/REL values.

While the results of risk calculations in Kam *et al.* (2013) indicated that traveling on the I-710 freeway posed the greatest cancer risk to commuters due to PAH-laden roadway PM, the current analysis indicates that commuters riding the METRO red line train in fact experience a greater cumulative cancer risk (4.2×10^{-5}) due to the presence of carcinogenic metals in the airborne PM to which they are exposed. METRO red line travelers are also subjected to the greatest cumulative non-cancer chronic health risk (4.1×10^{-2}), though non-cancer risk values determined at all sites were well below the accepted safety threshold of 1.0.

The maximum calculated ELCRs associated with the other commuter routes examined were all lower than that of the METRO red line, but did not differ significantly from each other. The cancer risk of riding the METRO gold line (4.2×10^{-6}) was comparable to that of driving on the I-110 (4.1×10^{-6}) and I-710 (3.8×10^{-6}) freeways, as well as the risk inherent in utilizing the surface streets Wilshire and Sunset (3.2×10^{-6}). Additionally, the non-cancer risk of riding the METRO gold line was the second lowest of the five commuting options (2.9×10^{-3}), a miniscule amount above the I-110 value (2.3×10^{-3}). It would thus seem that freeway commuting is a safer option for commuters, by a small margin. However, it should be kept in mind that other hazards exist on roadways and freeways including non-particulate air pollution exposures (e.g., carbon monoxide, nitrogen oxides, and gas-phase volatile organic compounds – which are not accounted for in the current study) as well as the immediate and significant risk of vehicle collisions, which may outweigh the slight cancer risk advantage.

Based on these data, we can conclude that the best option for commuters, provided there are routes available to bring them near their workplace, is to use above-ground light-rail transit when possible. Greater ventilation provides for lower concentrations of both metals and PAHs, and the use of freeways or surface streets is obviated along with the danger of motor vehicle collisions, resulting in the least health risk overall.

CONCLUSIONS

Commuters in Los Angeles, whether traveling by light rail, subway, or motor vehicle, are exposed to particulate matter that contains significant concentrations of PAHs and transition metals on a daily basis. In this comparative study of the corresponding health risks, both cancerous and non-cancerous, of various modes of transportation, both roadway- and railway-based, we determined that commuters riding the METRO red line experience the most significant health risks, and that these risks, both cancer and non-cancer, are driven largely by the hexavalent chromium content of the PM. While freeway commuters are not risk-free, due to PAH exposures as well as non-pollution related hazards, there is lower exposure to carcinogenic transition metals. Above-ground light-rail trains offer the best of both worlds, in that riders are removed from much of the traffic-generated PAHs which plague freeways, while the open air and greater circulation at railway platforms mitigates exposure to airborne metals associated with railways.

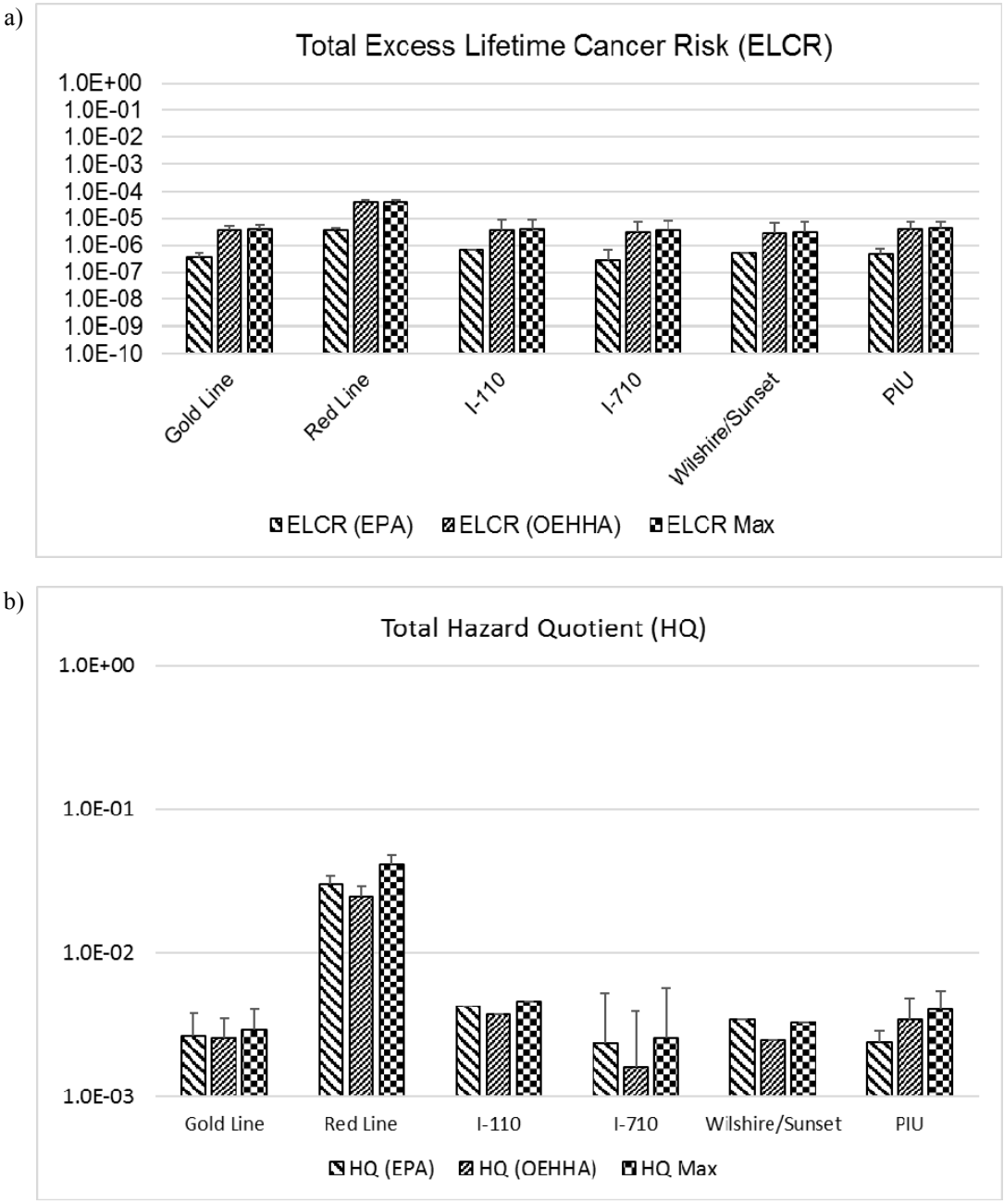

Fig. 4. a) Cancer Risk Totals (ELCR) by Site. b) Non-Cancer Risk (Health Quotient) by Site.

ACKNOWLEDGMENTS

This study was supported in part by the University of Southern California Viterbi Dean's Ph.D. Fellowship.

DISCLAIMER

Reference to any companies, manufacturers, or specific commercial products does not constitute endorsement on the authors' behalf.

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Received for review, September 22, 2017
Revised, November 2, 2017
Accepted, November 5, 2017