Toronto Subway Air Quality Health Impact Assessment

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Toronto Subway Air Quality Health Impact Assessment Project Summary

Introduction

Toronto's subway is a critical part of the Toronto Transit Commission's (TTC) public transportation network. First opened in 1954, it spans over 77 km of track and 75 stations across the city. On an average weekday over 1,400,000 customer-trips are taken on the subway.

In 2017, Health Canada reported levels of air pollution in the TTC subway system that were elevated compared with outdoor air. The Toronto Board of Health requested that Toronto Public Health (TPH) oversee an independent study to understand the potential health impacts of air quality issues for passengers in the Toronto subway system - The Toronto Subway Air Quality Health Impact Assessment (TSAQ HIA).

The TSAQ HIA takes a holistic approach to assessing how subway use may positively and/or negatively impact the health and well-being of Torontonians. The HIA used a human health risk assessment (HHRA) approach to calculate the potential health risks from exposure to air pollutants in the subway, and the results of the HHRA were incorporated into the HIA.

The TSAQ HIA sought to answer three overarching questions:

1. What is the potential health risk to current passengers from air pollutants in the subway system?

2. What are the potential health benefits to mitigation measures that could be implemented to improve air quality in the TTC subway system?

3. What is the overall impact of the TTC's subway system on the health and well-being of Torontonians?

Results of the Toronto Subway Air Qualty Health Impact Assessment

The TSAQ HIA assessed the overall impact of subway use on the health and well-being of Torontonians. The TSAQ HHRA calculated the potential health risks from exposure to fine particulate matter ($PM_{2.5}$) and associated metals for people who regularly use Toronto's subway system. The following are the conclusions of the TSAQ HIA based on the three overarching study questions posed.

1. What is the potential health risk to current passengers from air pollutants in the subway system?

There have been three monitoring campaigns that have measured airborne concentrations of chemicals in Toronto's subway system (Van Ryswyk, 2017; TTC, 2019; and Health Canada, 2019). They all indicate that there are elevated concentrations of fine particulate matter ($PM_{2.5}$) and some metals on subway station platforms and on the trains, as compared to levels found in Toronto's outdoor air.

Long-term exposure to subway air quality increases an individual's overall annual $PM_{2.5}$ exposure by 5% to 33%. The levels of some metals result in predicted cancer risk above Canadian health authorities risk objectives at times. Short-term exposures to subway air quality, particularly on Line 2, may on occasion, result in transient (i.e., short-lived; passing; not permanent) respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, general asthmatic symptoms) and/or a temporary decline in lung function for children and adults with asthma, adults with chronic obstructive pulmonary disease (COPD), and perhaps even healthy adults.

It was also determined that the levels of $PM_{2.5}$ and associated metals measured in the Toronto subway system were similar to those found in London's Underground system in the United Kingdom and in subway systems across Europe.

Overall, the results of the TSAQ HHRA indicate that the levels of $PM_{2.5}$ are high enough to warrant mitigation, particularly on Line 2. Any reduction in $PM_{2.5}$ platform concentrations would also lower concentrations of associated metals.

2. What are the potential health benefits to mitigation measures that could be implemented to improve air quality in the TTC subway system?

Fine particulate matter ($PM_{2.5}$) is a non-threshold contaminant, meaning that there is some potential for health impact at all levels of exposure. The available research has indicated that although the composition of subway $PM_{2.5}$ is different than that found in outdoor air, its health effects could be similar. The Canadian Council of Ministers of the Environment (CCME) set Canadian Ambient Air Quality Standards (CAAQs) for $PM_{2.5}$ that uses a continuous improvement philosophy to lower the concentrations in outdoor air. In other words, any decrease in $PM_{2.5}$ exposure would result in better health outcomes for those exposed.

Similarly, the results of the TSAQ HHRA cannot provide a specific target of $PM_{2.5}$ to achieve negligible health risk, given that it is likely a non-threshold contaminant. Rather, it is clear that Line 2 $PM_{2.5}$ concentrations are the highest in the subway system and efforts should be made to lower them. Line 1

concentrations are also elevated as compared with outdoor air and as such, a continuous improvement approach to lowering them should be taken. Any decrease in $PM_{2.5}$ levels within Toronto's subway would also improve potential health risks of associated metals.

3. *What is the overall impact of the TTC's subway system on the health and well-being of Torontonians?*

The HIA's assessment of the other environmental and social determinants of health concluded that there are numerous benefits to people's health and well-being from taking the subway. It provides a safer alternative to driving, reduces outdoor air pollution and greenhouse gases, promotes physical activity and provides better access to employment, schooling and social/community services.

Each individual reacts differently to air pollution. Children, seniors and those with heart or lung disease are most sensitive to adverse health effects of air pollution. While mitigation measures are being considered, concerned individuals should self-monitor in determining whether being in the subway is affecting them and decide what mode of transportation best meets their needs at any given time.

Recommendations

Overall, access to the subway system provides a number of positive health benefits to its users. The City of Toronto should continue to encourage the use of the subway, especially as an alternative to personal vehicles, and seek to expand the system to provide greater access to all Torontonians.

A Particulate Matter Reduction Strategy that includes both short and long term measures to improve air quality in the subway is recommended. Further, to reduce the uncertainty in the HHRA it would be beneficial to determine the form of chromium in $PM_{2.5}$.

Although the limited research in the field suggests subway air quality health effects may not be clinically significant, further personal exposure research should be undertaken to reduce the uncertainties identified in the HHRA and to better understand the potential health impacts to Toronto subway users. TPH is encouraged to monitor the scientific literature in this field and continue contact with other health authorities, such as the United Kingdom's Committee on the Medical Effects of Air Pollutants (COMEAP), to determine how new research findings can be applied to Toronto's subway system.

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1 INTRODUCTION

Toronto is the largest city in Canada with a population of 2,731,571 and the fourth largest in North America. From 2011 to 2016 it experienced a growth rate of 4.5% (Canadian Census, 2016). In the 1970s and 1980s the GTA experienced one of the largest growth rates in North America, which was supported by a regional transportation network that was ahead of its time.

Over the past decade there have been a number of public transit initiatives undertaken in Toronto and the Greater Toronto Area (GTA). In 2006, the Government of Ontario created Metrolinx as a regional transportation agency to establish an integrated system to support a higher quality of life, a more prosperous economy and a healthier environment (Metrolinx, 2008). The Toronto Transit Commission (TTC) is an agency of the City of Toronto and is responsible for ensuring the operation and planning of public transit within Toronto. It is estimated that 37% of Toronto residents rely on public transit infrastructure to access work, school and community and social services (City of Toronto, 2018).

Both the TTC and Metrolinx have prioritized greater access to public transportation (Metrolinx, 2008; City of Toronto, 2018). A critical part of TTC's public transportation network is the subway system. First opened in 1954, Toronto's subway system spans 75 stations and over 77 km of track across the city. Numerous studies have been conducted on the public health advantages of accessible public transit over private vehicle use (James et al., 2014; Waheed et al., 2019). These potential health benefits include reduced stress during commute, increased access to employment and services, and increased physical activity (Cole et al., 2019).

Although there are considerable positive health benefits to using public transit, the past decade has seen an increase in research focused on measuring airborne concentrations of particulate matter and associated contaminants in subway systems around the world (Loxham and Nieuwenhuijsen, 2019; Xu and Hao, 2017). Collectively, these findings indicate that subway systems around the globe (i.e., North America, Europe, and Asia) have concentrations of fine particulate matter ($PM_{2.5}$) greater than outdoor urban air (Xu and Hao, 2017; Lovett et al., 2017; COMEAP, 2019; Loxham and Nieuwenhuijsen, 2019).

The Urban Transportation Exposure Study (UTES) was a Health Canada led investigation that measured air pollution exposures across major transportation modes (private vehicles, subway systems, and buses) in Vancouver, Montreal and Toronto. In 2017, they reported the levels of air pollution exposure in the Toronto subway system (Van Ryswyk et al., 2017). Similar to other large city subway systems, UTES reported that fine particulate matter ($PM_{2.5}$) concentrations in the Toronto subway system were at least ten fold greater than $PM_{2.5}$ concentrations observed in the City's ambient outdoor air environment. Unlike ambient particulate, the $PM_{2.5}$ samples taken from within the

Toronto subway system were determined to be comprised of mostly metals (e.g., iron, maganese, chromium, copper, and barium) (Van Ryswyk et al., 2017).

Personal exposure to elevated concentrations of ambient $PM_{2.5}$ is a known health risk and is associated with an increased rate of morbidity and mortality. $PM_{2.5}$ has been classified by the World Health Organization (2013) and Health Canada (2013) as a non-threshold contaminant. This means that there is not a clear level of exposure to $PM_{2.5}$ below which there would be no impact on public health. Health agencies have also identified susceptible or vulnerable populations to $PM_{2.5}$ including children, seniors, and patients with pre-existing health conditions; such as cardiovascular disease (CVD), chronic obstructive pulmonary disease (COPD), and asthma. This is especially true for those exercising when exposed to elevated levels of particulate.

Although there are a significant number of studies that have measured $PM_{2.5}$ concentrations (and associated metals) within different subway systems, there are a limited number of studies that have evaluated the potential human health implications of this exposure for passengers who routinely take the subway system (Loxham and Nieuwenhuijsen, 2019; Xu and Hao, 2017). For example, the UTES study reported the concentrations of Toronto subway airborne contaminants but did not evaluate the potential health risks. Therefore, there is a need to investigate if exposure to these elevated concentrations of $PM_{2.5}$ and associated metals in Toronto's subway system may impact the health of riders.

1.1 Scope of the Investigation of the Toronto Subway Air Quality Health Impact Assessment

In 2018, the Toronto Board of Health requested that Toronto Public Health (TPH) oversee an independent study to understand the potential health impacts for passengers of the air quality issues in the Toronto subway system (Toronto Board of Health, 2017). As described in a subsequent report to the TTC Board (TTC, 2017), the Toronto Subway Air Quality Health Impact Assessment (TSAQ HIA) will use human health risk assessment (HHRA) and health impact assessment (HIA) approaches that are well established and commonly used in the environmental health field. The TTC Board directed the TTC to undertake a separate occupational exposure study (TTC, 2018a). Therefore, occupational exposure was not considered in the TSAQ HIA.

The HIA seeks to answer three overarching questions:

1. What is the potential health risk to current passengers from air pollutants in the subway system?
2. What are the potential health benefits to mitigation measures that could be implemented to improve air quality in the TTC subway system?
3. What is the overall impact of the TTC's subway system on the health and well-being of Torontonians?

Health Canada, through a project called the Subway Air Quality Initiative (SAQI) (Health Canada, 2019) and the TTC (TTC, 2018a) collected air samples throughout 2017/18 to gather data about current air quality in the subway system, and to explore the impacts of potential interventions that the TTC could implement to reduce passenger exposure. The data include concentrations of $PM_{2.5}$, PM_{10}, and various metals, and were used in the TSAQ HHRA.

Ollson Environmental Health Management (OEHM) and Wolf Environmental Science Ltd. (the consultants) were contracted to undertake the TSAQ HIA in collaboration with TPH.

In the early stages of the project, an independent Expert Panel was convened by TPH to provide insight on methodological challenges for the HHRA and approaches that might address these. The Expert Panel was selected by TPH, with advice from their consultants, to ensure inclusion of a diversity of professional experience and technical expertise in areas including exposure assessment, toxicology, human health risk assessment, air quality assessment and health impacts, and environmental epidemiology. The Expert Panel report is provided in Appendix A.

This report presents the results and findings of the TSAQ HIA, which includes the results of the technical HHRA (Appendix B). It addresses the overarching study questions and contributes to the knowledge base in the field by presenting findings on the potential health risks from exposure to particulate for the ridership of Toronto's subway system. It also assesses the overall impact of subway use on the health and well-being of Torontonians.

2 Toronto Subway System

In 1954, Toronto Transit Commission began operation of the Yonge Subway between Union Station and Eglinton Avenue. At the time, the system was comprised of 12 underground stations under Yonge Street. Over the years the subway system has significantly expanded and now spans 75 stations with over 77 km of track (Figure 1). In 2018, the TTC estimated that on an average weekday, over 1,400,000 customer-trips are taken (TTC, 2018).

There are two major lines that comprise the subway system (TTC, 2019):

Line 1 Yonge-University-Spadina: First opened in 1954, it is the longest and most heavily used line in the system with 794,680 weekday customer-trips. The U-shaped line spans 38.8 km with 38 stations, from Union Station to Vaughn Metropolitan Centre in the west and Finch in the east.

Line 2 Bloor-Danforth: First opened in 1966, it is the second most heavily used line in the system with 527,640 weekday customer-trips. Line 2 runs parallel to Bloor Street and Danforth Avenue. With 31 stations, it stretches between Kipling Station, in Etobicoke, and Kennedy Station, in Scarborough.

There are also two shorter lines that complete the subway system (TTC, 2019):

Line 3 Scarborough: First opened in 1985 with 35,090 weekday customer-trips. It is L-shaped with six stations, operating from Eglinton Avenue East and Kennedy Road, north and east to the Scarborough Town Centre, and continues to the area of McCowan Road and Progress Avenue. This line is entirely above ground.

Line 4 Sheppard: First opened in 2002 and has 50,150 weekday customer-trips. It runs east to west along Sheppard Avenue East with four stations. It operates from the area of Yonge Street and Sheppard Avenue, east to the area of Sheppard Avenue East and Don Mills Road.

Figure 1. Map of the Toronto Subway System (TTC, 2019).

2.1 Toronto Subway Trains

There are two types of subway cars, also known as rolling stock, that are currently used by the TTC. The newer generation Toronto Rocket (TR) cars are used on Line 1, while older generation T1 cars are used on Line 2. The following provides details of each of the cars.

Toronto Rocket (TR)

The Toronto Rocket (TR) cars are the newest in the TTC fleet and were first introduced in 2011 to replace older subway cars in the TTC fleet (Figure 2). They are now exclusively used on Line 1. Each of the cars seats 64-68 people, with a 180 maximum person capacity. Each train is comprised of 6 cars, for a total maximum capacity of 1,080 people per train. The TTC estimates that each fully occupied TR train removes the equivalent of 990 personal vehicles from the roads during the rush hour commute (TTC, 2019).

Figure 2. Toronto Rocket (TR) subway cars.

T1 Series

The T1 cars are older than the TR cars and were introduced between 1996 and 2001 and are now exclusively used on Line 2 (Figure 3). Each T1 car seats 66 people with a maximum capacity of 167. Each train is comprised of a 6-car train for a total maximum capacity of 1,000 people per train. The TTC estimates that each fully occupied T1 train is the equivalent of removing 900 personal vehicles from rush hour commute (TTC, 2019).

Figure 3. T1 Series subway cars.

2.2 Use of the Toronto Subway System

In Toronto, a subway user would typically enter a TTC station that is located either above or below ground level. They would then spend time on the platform waiting for the train, followed by time traveling on the train, and finally exiting the train and the station at their final destination. Given that the four subway lines in the Toronto subway system are connected, some users may board a train on a particular line and then switch lines to continue to their destination.

For the TSAQ HIA it is important to understand how long a rider would typically spend waiting on a station platform and riding on the train, as the air quality may differ between these two events. This information is used to develop the exposure scenarios in the HHRA. It also provides valuable information to the HIA on patterns of ridership. The Health Canada UTES and SAQI research program focused their sampling efforts on Line 1 and Line 2, given that they are the oldest of the lines, mostly underground and the most heavily travelled. Although the HHRA focused on these two specific subway lines (i.e., Line 1 and Line 2) due to the availability of air quality data, the broader HIA considered the entire subway system.

Results from the UTES and SAQI studies determined that the highest concentrations of $PM_{2.5}$ and associated metals were found during commuter rush hour on the subway. Therefore, the HHRA focused on these times when the highest number of people are exposed to the highest concentrations of contaminants in the air. The TTC provided TPH with general information on subway use for Line 1 and Line 2 (TTC, 2019a). The peak hours of ridership and the number of riders are provided in Table 1. There is a slight variation between the morning and afternoon peak ridership between the two lines. Ridership on Line 1 is considerably higher than on Line 2. The wait times on platforms on each line were reported to be the same by the TTC. During the peak

commuter times the trains arrive at each station approximately every 2 minutes and 30 seconds. This suggests that very little time is actually spent on the platforms, compared to time spent on trains.

The median time on the subway train for the combined morning and evening commute was considerably lower for Line 1 (18 min) as compared to Line 2 (26 min) (Table 1). However, the length of time for the longest commute (90^{th} percentile or 1 out of every 10 riders) on train per day was similar between Line 1 (59 min) and Line 2 (53 min) and is almost an hour per day.

Table 1. Ridership of Line 1 and Line 2 during weekdays peak hours.

Line	Time	Daily Number of Riders During Peak Times	Minutes on Train (per day)		Minutes on Platform (per day)	
			Median	90^{th} Percentile	Median	Maximum
Line 1	8:15 to 9:15 17:00 to 18:00	174,464 170,143	18	59	2.5	5.0
Line 2	8:00 to 9:00 16:45 to 17:45	110,107 113,891	26	53	2.5	5.0

2.3 Air Quality Studies Conducted in the Toronto Subway System

A cornerstone of the TSAQ HIA is understanding the levels of contaminants within the Toronto subway system. There have been three main studies conducted over the past decade on air quality in the Toronto subway system. The first and only published study, known as the Urban Transportation Exposure Study (UTES), was conducted by Health Canada between 2010 and 2011 (Van Ryswyk et al., 2017). In 2017, the TTC hired OHE Consultants to conduct air monitoring for an occupational assessment of TTC workers between 2017 and 2018 (TTC, 2019). Health Canada initiated further monitoring campaign of Line 1 and Line 2 underground subway stations under the Subway Air Quality Initiative (SAQI) between 2017 and 2019 (Health Canada, 2019).

The data and findings for the three studies were reviewed for relevance and use in the TSAQ HIA, specifically in the HHRA. Further details of the monitoring campaign results and their use in the HHRA are found in Appendix B.

2.3.1 Urban Transportation Exposure Study (UTES) 2010 to 2013

From 2010 to 2013, Health Canada characterized air pollution resulting from emissions from private vehicles, metro systems, and buses in major Canadian urban centers. Sampling of $PM_{2.5}$ and its metal composition was conducted in the Toronto subway system to compare the concentrations with ambient air levels.

Sampling was conducted over three weeks in the summer of 2010 and winter of 2011. For on-train sampling, three technicians were outfitted with personal sampling backpacks and assigned segments of Line 1 and Line 2 of the subway system.

Sampling was completed during commuting hours on weekday mornings (7 am to 10 am) and evenings (3 pm to 6 pm), recording air pollution levels when they boarded and disembarked at each station. Continuous monitoring on station platforms was carried out for $PM_{2.5}$ using a standard instrument (TSI DustTrak 8520 samplers).

Elevated concentrations of $PM_{2.5}$ (compared to previously measured outdoor ambient air levels) were documented on both the platforms and trains. The subway $PM_{2.5}$ was comprised largely of metals (iron, aluminum, barium, chromium, copper, manganese, molybdenum, and nickel) and was different than the composition of ambient outdoor $PM_{2.5}$ in Toronto, which is largely comprised of sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water (Van Ryswyk et al., 2017). The authors estimated that a typical commuter would receive an average of 21% of their daily exposure to $PM_{2.5}$ from the subway.

2.3.2 Toronto Transit Commission Subway Air Quality Study 2017 – 2018

The Occupational Hygiene and Environment Section of the TTC initiated its own Subway Air Quality Study in the summer of 2017. Interim results were published in March 2018 (TTC, 2018a).

The stated purpose of the study was to:

- Provide current information on the air quality in the underground portions of the subway during revenue service;
- Determine employee exposures to airborne contaminants and verify compliance with Ontario Regulation 833 – Control of Exposure to Biological or Chemical Agents, made under the Occupational Health and Safety Act (OHSA);
- Evaluate the effectiveness of current controls;
- Make recommendations regarding both compliance with OHSA and opportunities for general improvement.

The airborne contaminants studied were:

> Asbestos; Respirable dust and crystalline silica; respirable metals; total metals; hexavalent chromium; PM_4; diesel exhaust markers (carbon monoxide (CO) and nitrogen dioxide (NO_2)); and carbon dioxide (CO_2).

The study concluded:

> *"None of the 40 sample sets collected to date exceeded the Occupational Exposure Limits (OELs) specified in Reg. 833. Based on the interim sampling results, the subway air quality is not expected to affect the health of employees in work positions assessed who do not have pre-existing serious respiratory conditions."*

Although the TTC study provided information relevant for workers, occupational data are collected in a manner that is specific for occupational exposure under Ontario

Regulation (O.Reg. 833) and may not be appropriate for use in a human health risk assessment. Data from the TTC study (TTC, 2018a) was provided to TPH and the study consultants for informational purposes (Appendix B).

2.3.3 Subway Air Quality Initiative (SAQI) 2017-2018

The Subway Air Quality Initiative (SAQI) is a Health Canada-led follow-on monitoring campaign of the UTES study. It is focused solely on better understanding the concentrations of $PM_{2.5}$ and associated metal constituents in the Toronto subway system. Monitoring of the subway system and outdoor ambient air began in December of 2017 and was completed by August 2018. Subway platforms on Line 1 and Line 2 were sampled, three to five platforms at a time, for periods ranging from several days to weeks (Figure 4). A second round of sampling involved the collection and analysis of outdoor ambient air at two locations in Toronto (Health Canada, 2019).

Samples were collected at subway station locations using a stationary monitor that collected total $PM_{2.5}$ over a 12-hour period (6 am to 6 pm). Ambient conditions were monitored over seven days in parallel with the subway samples, at locations close to the subway system (Health Canada, 2019). The concentrations of metals in the $PM_{2.5}$ were analyzed in the laboratory using x-ray fluorescence (XRF).

Continuous $PM_{2.5}$ data, among other parameters, were also collected at subway platforms. Continuous measurements of $PM_{2.5}$ were made using the TSI DustTrak II equipment. Continuous air quality data were collected from 31 subway stations for $PM_{2.5}$ and from 22 stations for stationary monitors. At each subway platform, data were collected for anywhere from 2 to 39 days.

In addition to the data described above, Health Canada (2019) also provided a personal exposure monitoring (PEM) dataset, containing continuous $PM_{2.5}$ data collected using the same approach as the UTES. The PEM dataset, collected in 2018, allows for the determination of $PM_{2.5}$ concentrations while riding on the subway trains and while waiting on platforms.

Health Canada provided their SAQI monitoring campaign data to TPH for use in the TSAQ HIA. This was the primary data used in the HHRA and further details on the monitoring campaign methodology and reports are provided in Appendix B. At the time of publication of this TSAQ HIA, the results of the Health Canada SAQI monitoring program had not been published or made publically available.

Figure 4. Location of Subway Platform Monitoring in SAQI (Health Canada, 2019)

3 HEALTH IMPACT ASSESSMENT METHODOLOGY

The World Health Organization (WHO) defines health as "*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*" (WHO, 1948). It is challenging to measure or predict the impact of projects or policies using this broad and wide-ranging definition of health. Health Impact Assessment (HIA) has been used as a means of assessing the potential health impacts of policies, plans and projects in diverse economic sectors using a variety of quantitative and qualitative techniques (WHO, 2019). The outcome of an HIA can aid decision-makers and stakeholders in making choices about alternatives, mitigation measures and/or improvements that could reduce risk and prevent illness/injury while actively promoting health and well-being.

Health status or outcomes are dependent on a broad range of personal, social, economic and environmental factors that determine individual and population health. These are collectively referred to as the "determinants of health" (Figure 5). The practice of HIA is intended to assess a project or policy's potential impact on a wide range of health determinants, including environmental factors and the social determinants of health.

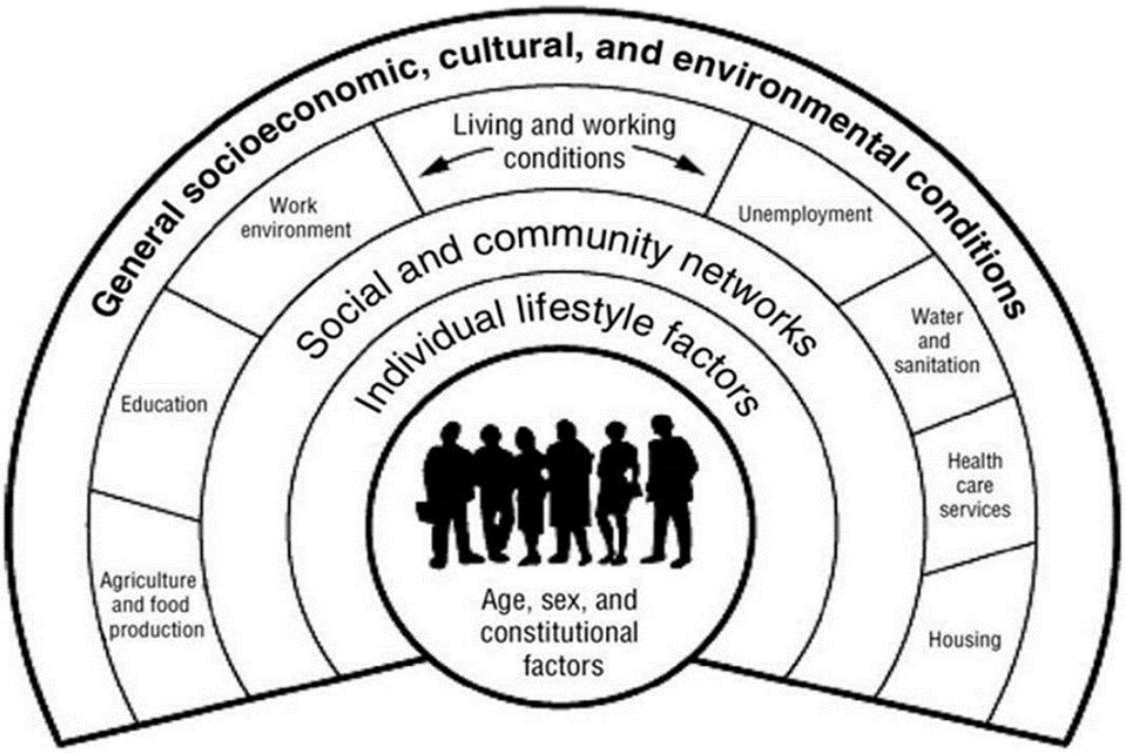

Figure 5. The conditions that comprise the quality of health of a population, known as the 'determinants of health' (from Dahlgren and Whitehead, 1991).

In 2004, Health Canada released guidance on conducting HIA in Canada (Health Canada, 2004). This four-volume document provided a general overview of health concepts that could be applied to a wide range of projects. In 2008, TPH developed their Health Impact Assessment Framework that provided an approach and set of tools for conducting HIA for infrastructure projects in Toronto (TPH, 2008). The HIA framework was updated in 2014 (TPH, 2014) and most recently in 2019 (TPH, 2019). The latest update to the TPH HIA framework is an internal document that is currently in development and it is anticipated that it will be publicly released at a later date. It will be referenced throughout this document as (TPH, 2019).

3.1 Steps of an HIA

There are seven steps that comprise an HIA (Figure 6), including:

Screening: The first step of any HIA process is screening to determine whether this type of assessment is warranted based on a review of available evidence. Key questions that are answered in this step include: Is an HIA feasible and necessary? What form should it take and how much effort will be required?

Scoping: Scoping the HIA properly ensures that the highest priority determinants of health are included in the assessment (based on established evidence and stakeholder input). The scoping step plans and focuses the overall approach to the HIA including methods, contents and logistics. It also identifies the populations to be assessed and sets the geographic and temporal boundaries.

Assessment: The assessment step characterizes potential impacts (positive or negative) on the determinants of health and identifies the likelihood of their occurrence based on available evidence. It can employ a combination of quantitative and qualitative assessment approaches.

Recommendations: Based on the findings of the assessment, recommendations are made to enhance potential positive impacts and mitigate potential negative health outcomes.

Reporting: The assessment of potential health impacts and recommendations to improve the project are reported. Reporting should take the form of a technical document, written summary for public consumption and an oral/visual presentation.

Monitoring: After the HIA is complete a monitoring plan should be developed. It provides measurable indicators to determine how mitigation or enhancement measures are improving health outcomes.

Evaluation: Once the HIA is complete, a retrospective review should be conducted of the HIA process and/or impact to determine areas for improvement.

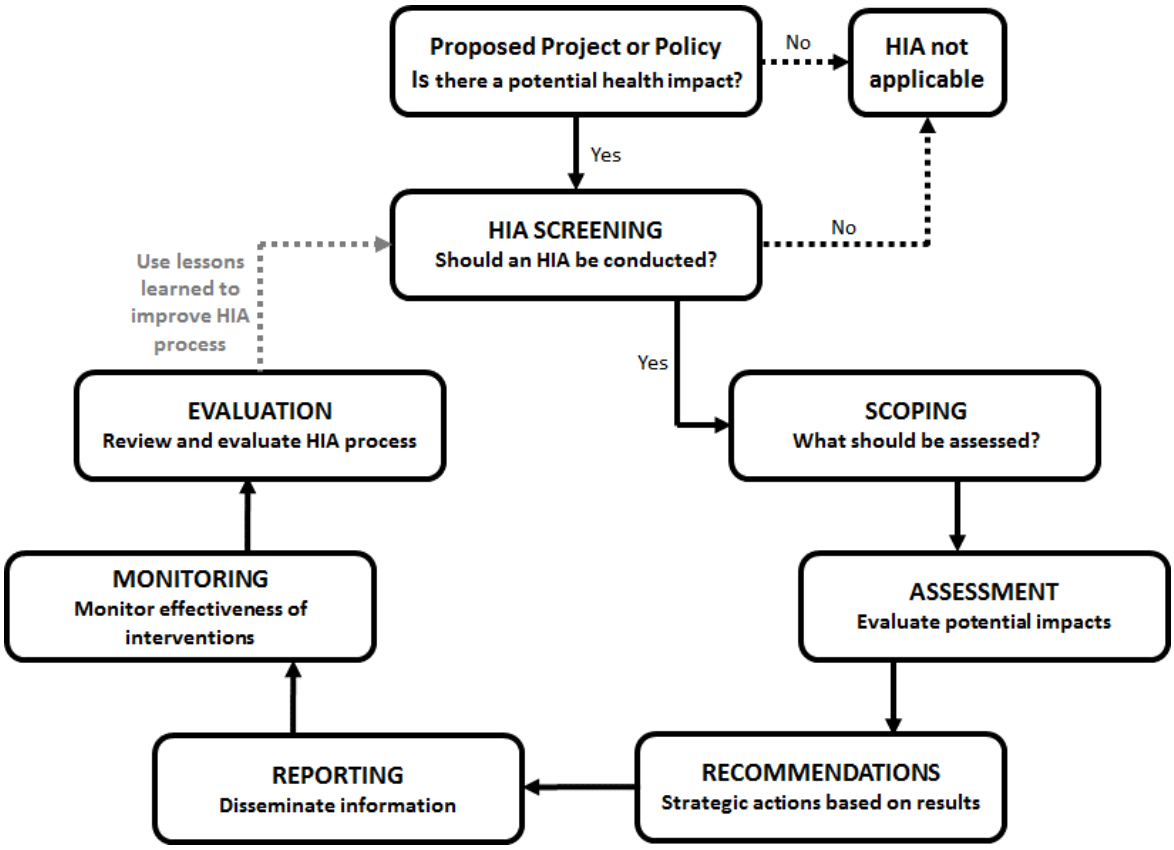

Figure 6. The HIA Assessment Process (McCallum et al., 2015).

Specific approaches and methodology used in each of the steps for the TSAQ HIA are presented in their respective sections in this report.

In addition, there are three general types of HIA – Rapid, Intermediate, and Comprehensive - that are based on the depth of analysis, scope of the assessment, complexity of the issues, available data and information, and available resources. The TSAQ HIA is best classified as an Intermediate HIA that includes a comprehensive quantitative HHRA.

The quantitative HHRA is being conducted specifically on the air quality in the Toronto subway system. An overview of the HHRA methodology is provided in the HIA assessment Section 6.1, with a detailed methodology section provided in Appendix B. The results of the HHRA are used in the assessment section of the HIA (Section 7.1.1).

3.2 Health Equity

A fundamental tenet of an HIA is the consideration of health equity in the assessment of determinants of health. The 2019 TPH HIA guidance states:

> *Equity in health means that everyone should have a fair opportunity to attain their full health potential, and that no one should be disadvantaged from achieving this potential due to their ability, age, culture, ethnicity, family status, gender, language, race, religion, sex, or socioeconomic status (WHO, 1999; NCCDH, 2013; Whitehead and Dahlgreen, 2007). Health inequities are defined as differences in health and health determinants that are considered socially produced and systematic and are thus unnecessary, avoidable, unfair and unjust (Whitehead et al., 2007; World Health Organization, n.d.; Solar and Irwin, 2010; Povall, Haigh, Abrahams, & Scott-Samuel, 2013).*
>
> (TPH, 2019)

Equity is an important consideration in an HIA when examining the social, economic and environmental factors that relate to a specific health issue and outcome. HIA attempts to address equity issues through the identification of 'Vulnerable Populations' for each health determinant, some of which are due to social produced and systematic differences, and provides recommendations for measures to reduce inequities. For example, environmental pollutants may have a disproportionate impact on youth, seniors and those with pre-existing medical conditions. Analysis of health inequities also considers the distribution of project/policy impacts across a population to understand whether any underlying factors contribute to a disproportionate burden of impacts on specific groups.

> **Vulnerable Populations:** those that are more susceptible to a change in a determinant of health, created by a project or policy, that could lead to a disproportionately negative health outcome compared to the general population.

TPH HIA guidance (TPH, 2019) includes five critical steps that should be completed to ensure the incorporation of health equity in HIA:

> ***Step 1:*** *Consider equity when conducting HIA screening. If it is anticipated that the health of certain populations, communities or groups will be disproportionately impacted by a policy, program or project, then conducting an HIA should be considered a favourable option;*
>
> ***Step 2:*** *Analyzing the impact on health equity should be identified as one of the objectives of the HIA;*
>
> ***Step 3:*** *During the scoping phase, the equity metrics should be reviewed to assist with developing a plan for including equity in the HIA process;*
>
> ***Step 4:*** *During assessment, disproportionately impacted communities/groups should be identified and where possible, assessment of impacts on these groups should be completed;*

> ***Step 5:*** *During recommendations, equity should be a key factor in developing the recommended actions to either mitigate negative impacts or enhance positive impacts for specific communities or groups;*
>
> *Through HIA reporting, these equity-focused steps should be identified, described and clearly articulated.*

3.3 Stakeholder Engagement

The nature and amount of stakeholder engagement in an HIA is dependent on the level of assessment being conducted and the stage of the overall project. Rapid or intermediate HIAs are typically conducted using both qualitative and quantitative approaches and may include some stakeholder and/or public consultation. A detailed discussion regarding the stakeholders that were engaged as part of the TSAQ HIA study is provided in Section 5.1.3.

4 SCREENING

In 2017, the Toronto Board of Health directed TPH to oversee an independent study to understand the potential health impacts for passengers of air quality in the Toronto subway system. As described in a September 2017 report to the TTC Board (TTC Staff Report, 2017), TPH determined that the most appropriate way to address this issue was through an HIA that includes a comprehensive quantitative HHRA.

The project team held initial meetings on the approach to undertaking the TSAQ HIA. The TPH HIA Screening Tool (TPH, 2019) was completed and confirmed that:

> *An HIA is the appropriate lens through which the potential negative impact of subway air quality chemical exposure can be assessed and weighed against the positive health aspects of subway use.*

During the Screening step it was determined that the technical and air-quality focused HHRA report should be included as an appendix to the HIA. Subway air quality would be included as one determinant of health within the broader HIA.

5 SCOPING

The purpose of the Scoping step was to plan the overall approach and identify the determinants to be evaluated in the TSAQ HIA. Scoping was undertaken using the approach from Prioritizing Health: A Systematic Approach to Scoping Determinants in Health Impact Assessment (McCallum et al., 2016) and TPH HIA Guidance (2019).

5.1 Scope Overview

5.1.1 The Goal and Anticipated Use of the HIA

Goal of the TSAQ HIA

The objective of the TSAQ HIA is to answer the following questions:

1. What is the potential health risk to current passengers from air pollutants in the subway system?
2. What are the potential health benefits to mitigation measures that could be implemented to improve air quality in the TTC subway system?
3. What is the overall impact of the TTC's subway system on the health and well-being of Torontonians?

Anticipated Use of the TSAQ HIA Outcome

The HIA was prepared to provide information about the potential impacts of air quality on the health of individuals using the subway, as well as providing information about the broader impacts to health of using the system.

5.1.2 The HIA Team and Roles and Responsibilities

The consultants, Dr. Christopher Ollson of OEHM led the HIA and Christopher Bacigalupo of Wolf Environmental led the HHRA. TPH staff provided project management oversight, support and information to the consultants.

The TTC provided information on ridership statistics and studies being conducted for occupational health. Mr. Keith Van Ryswyk, the primary contact from Health Canada, provided air quality data, statistical support for the analysis and details on methodology and collection of data for the SAQI program.

5.1.3 Stakeholder Engagement

Given the unique nature of conducting the HHRA component of the TSAQ HIA, an Expert Panel was convened to ensure that: (i) the novel aspects are thoughtfully considered; (ii) the analytical approach used is valid and defensible; and (iii) any limitations are well-understood. The Panel provided insight on methodological challenges and approaches that could be considered to overcome them.

The Expert Panel was selected by TPH, with advice from the consultants, to ensure inclusion of a diversity of professional experience and technical expertise in areas including exposure assessment, toxicology, human health risk assessment, air quality assessment and health impacts, and environmental epidemiology. The Expert Panel workshop summary report and recommendations are provided in Appendix A.

In addition, TPH engaged with the TTC throughout the project to better understand the subway system and its ridership, to obtain system information needed to inform both the HHRA and HIA, and to discuss air quality mitigation measures.

TPH and the consultants also held a teleconference on October 9, 2019 with some members of the Committee on the Medical Effects of Air Pollutants (COMEAP). This committee was responsible for investigation and health risk reporting on the United Kingdom's London Underground system air quality. The objective of the call was to

better understand their experience in reporting and communicating the results of their investigation and to understand additional work that is planned or underway.

5.2 Selection of the TSAQ HIA Determinants of Health

The determinants of health to be included in the TSAQ HIA were developed through consultation with TPH staff. An Excel-based spreadsheet scoping tool (McCallum et al, 2016) was used to support selection of the determinant list and assign priority ranking. The Excel-based tool allows for priority ranking of a comprehensive list of determinants of health and allows for consideration of applicability to the project, stakeholder interest and available data and information.

Consensus on the final list of determinants was reached amongst the consultant and HIA team. The following sections identify determinants of health that were considered relevant for the TSAQ HIA and were carried forward for assessment.

5.2.1 Environmental Factors

Physical and chemical environmental determinants of health are exposures that are often difficult to avoid and could negatively impact health in the context of the subway system.

Subway Air Quality: A detailed quantitative HHRA was completed to assess the potential for adverse health impacts on the subway ridership (Appendix B), with the results carried forward for HIA assessment.

Traffic Volume: Transit systems are intended to help alleviate traffic congestion by moving large numbers of people; avoided use of personal vehicles due to the subway system could impact levels of **air pollution** and **greenhouse gas (GHG)** emissions.

5.2.2 Social, Economic and Other Factors

The following social, economic and other factors were determined to be the most important determinants of health that could potentially impact the health of subway ridership.

Physical Activity: Subway use could impact the physical activity level of those who access the system as compared with those who use personal vehicles.

Mental Health and Wellness: Access to the subway may affect mental health and well-being, including stress, associated with travel in Toronto.

Employment, Education and Household Income: Access to the subway may affect access to wider employment and education opportunities, which may also potentially impact household income.

Access to Services: The subway may affect how efficient and economical it is for Torontonians to access essential government and health care services.

Safety and Security: Taking the subway over other modes of transportation may have an impact on certain safety and security considerations.

Tourism and Recreation: The subway may impact tourists and Torontonians ability to access recreation and leisure activities.

5.3 Temporal and Geographic Boundaries

It is important to clearly define the temporal and geographic boundaries that are included in the TSAQ HIA. These are important factors in the assessment phase to characterize the impact of the subway system on health determinants.

5.3.1 Temporal Boundaries

Health Canada has been studying air quality in the Toronto subway system since 2010 under the UTES program. However, there have been potentially significant changes in the system with respect to rolling stock (i.e., the types of trains) on individual lines, and potential changes in track cleaning and ventilation made by the TTC over the past decade. Health Canada informed TPH that there are significant differences in the airborne chemical concentrations between the two study periods (Personal Communication, Van Ryswick, 2019). Therefore, the TSAQ HIA relies on the most recently collected Health Canada SAQI data from 2018 to 2019, which represents the current exposure scenario.

It was also determined in the HHRA (Appendix B) that the highest concentrations of airborne contaminants were during the morning rush hours 6 am to 9 am and the afternoon highest commute times between 3 pm to 6 pm. These periods of time became the focus of the HHRA.

In addition, the TSAQ HIA only considers the current state of the subway system configuration and operations and does not include any consideration of a future state or proposed expansion or changes that the TTC may be considering for the system. The potential for such changes is discussed in the limitations and recommendations sections of this report.

5.3.2 Geographic Boundaries

During the UTES study, Health Canada determined that the highest concentrations of airborne contaminants were found on the underground platforms of Line 1 (Yonge-University-Spadina) and Line 2 (Bloor-Danforth) and focused the SAQI sampling on these lines. Therefore, the HHRA use of SAQI data represents the highest concentrations on all lines and platforms within the subway system.

The remainder of the determinants of health considered in the HIA are inclusive of the entire Toronto subway system, all lines and all stations. This is because the impact on these determinants of health can be evaluated for the system as a whole. The assessment of commuters who may use other forms of TTC public transport (e.g.,

GOTrain, bus, car, walking and street car) and then transfer to the subway is outside the scope of the TSAQ HIA. Therefore, given that the study is focused on the Toronto subway system, the geographic boundary is largely limited to this system, its trains and platforms, and the aboveground areas and amenities that are located in the vicinity of the system.

5.4 Data Sources and Availability

The HHRA was based on the latest unpublished sampling results from the Health Canada SAQI project. These are representative of the most current data for subway rider's exposure in Toronto.

Where available, information for assessing the remaining determinants of health was based on Toronto-specific data. This was supplemented with other relevant peer-reviewed scientific articles and government reports specific to subway systems and evaluated modes of transportation. In some instances, only a qualitative assessment could be made based on the availability of data or information. It was determined that sufficient data was available to evaluate health outcomes related to the determinants selected for the HIA.

5.5 Summary of HIA Scoping

The scoping of the TSAQ HIA provided clear goals and objectives for the assessment. Determinants of health to be evaluated were established through consultation with TPH staff, and include:

- Air Quality
- Traffic (Air Pollution and GHG)
- Physical Activity
- Mental Health and Wellness
- Employment, Education and Household Income
- Access to Services
- Safety and Security
- Tourism and Recreation

Vulnerable populations were identified and included in the assessment of each of the determinants of health to better understand the potential distribution of impacts. The temporal boundary of the HIA will be the current condition of the subway (as per Health Canada's SAQI data) and TTC commuter times. The geographic boundary for the HHRA (air quality study) focuses on Line 1 and Line 2, while the remainder of the determinants of health in the HIA includes consideration of the entire system and its surface-level areas and amenities.

6 POPULATION PROFILE

It is important to understand the demographics of the Toronto subway ridership to focus the assessment of the environmental and other determinants of health. The data and information in this section is recent (2018) and was provided by the TTC based on a specific data request in support of the TSAQ HIA (TTC, 2019a).

On an average weekday (Monday to Friday) there are over 1,400,000 customer-trips made each day on Toronto's subway system (TTC, 2018). Line 1 (Yonge-University-Spadina) and Line 2 (Bloor-Danforth) are the most heavily used in the system (Figure 7).

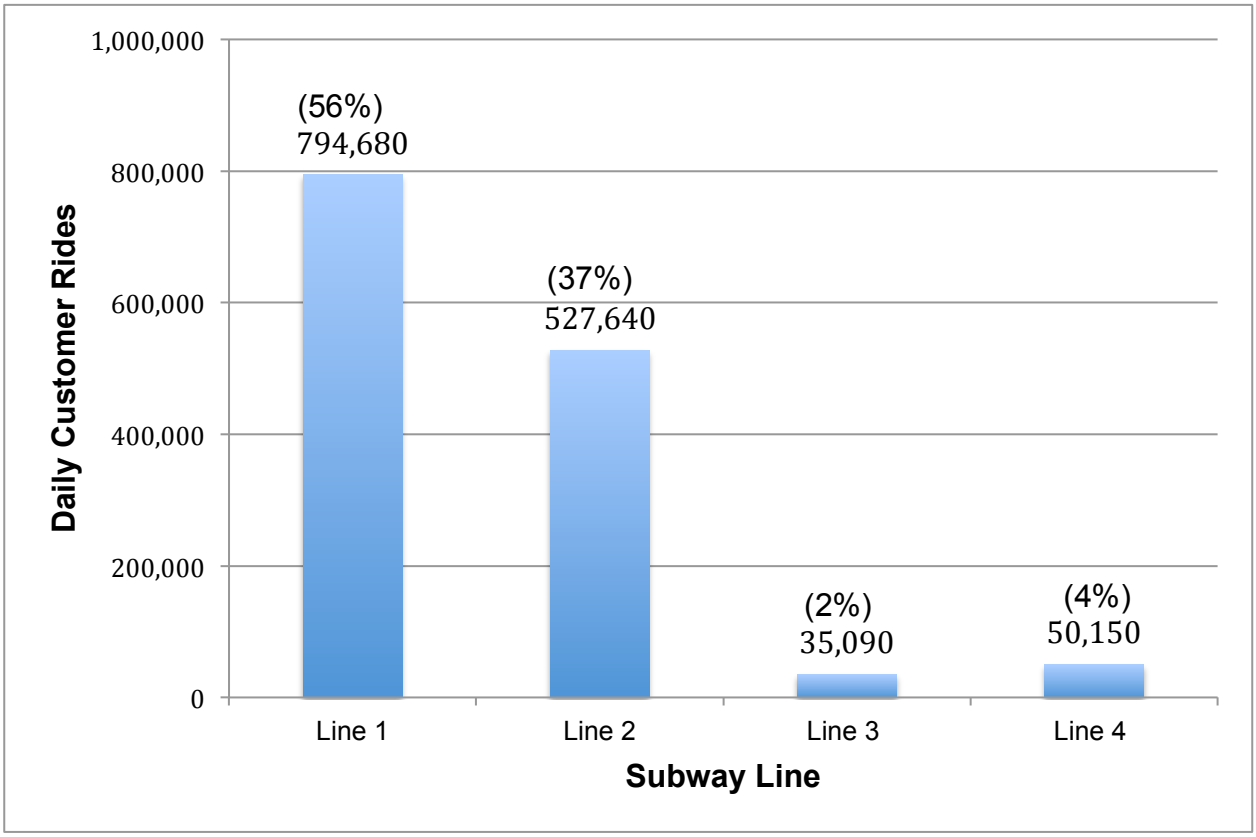

Figure 7. The Number of Weekday Customer-trips Taken on Toronto's Subway System (2018).

Forty-three percent of all weekday customer-trips on Line 1 and Line 2 are during peak morning and evening commute times. The vast majority of subway riders live in Toronto (89%), with surrounding regions of York, Durham and Halton comprising the remainder of the subway users (Figure 8).

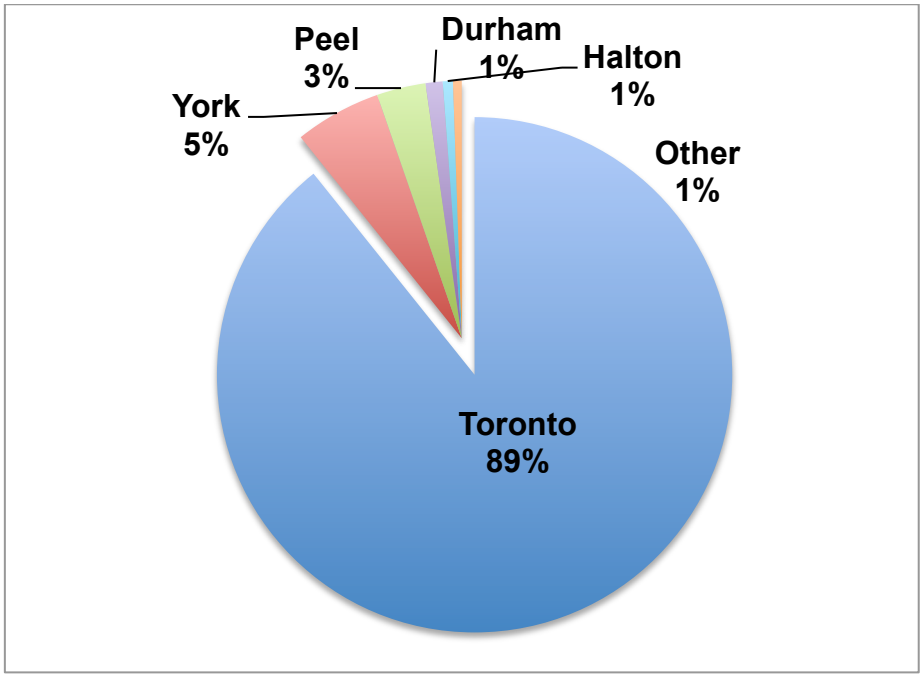

Figure 8. Place of Residence of Subway Users (2018).

According to the 2016 Census data, 51.5% of Torontonians identify as a visible minority (Canadian Census, 2016). However, 59% of the Toronto subway ridership are visible minorities (Figure 9).

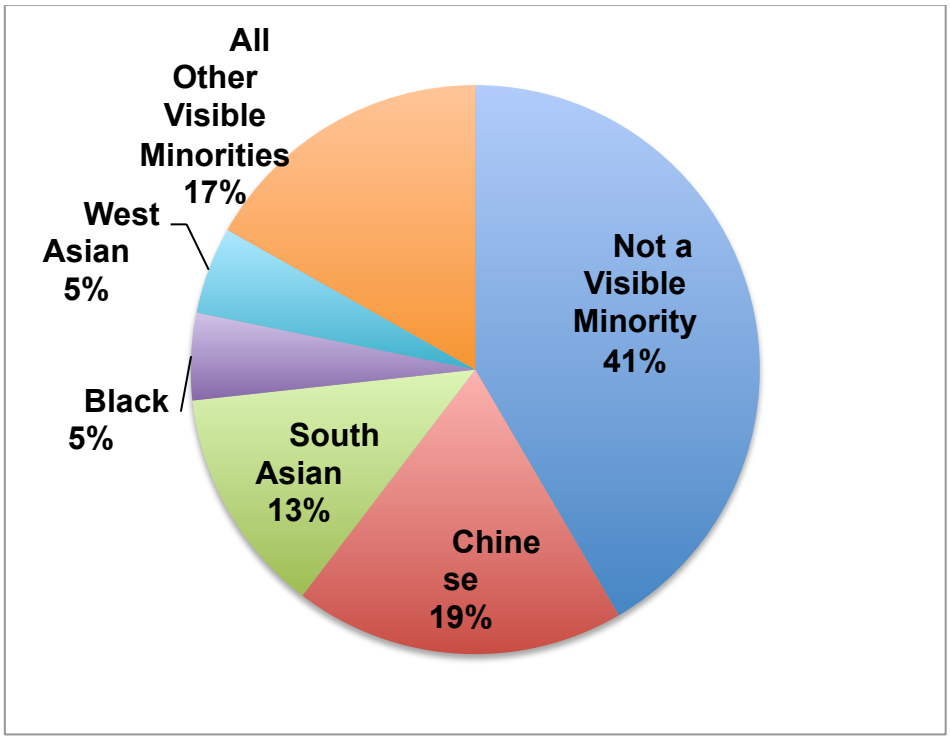

Figure 9. Ethnicity of Toronto Subway Ridership (2018).

As shown in Figure 10, the vast majority (91%) of customer trips are home-based, meaning that riders use the subway to travel to and from their homes, with only 9% of customer trips for destinations between subway platforms (e.g., going from work to a doctor's appointment). Almost 50% of subway riders use the system to commute to and from work, while 21% of riders use the system to go to school. Similarly, 21% of subway trips are taken to and from home for discretionary purposes (e.g., access to services and recreation).

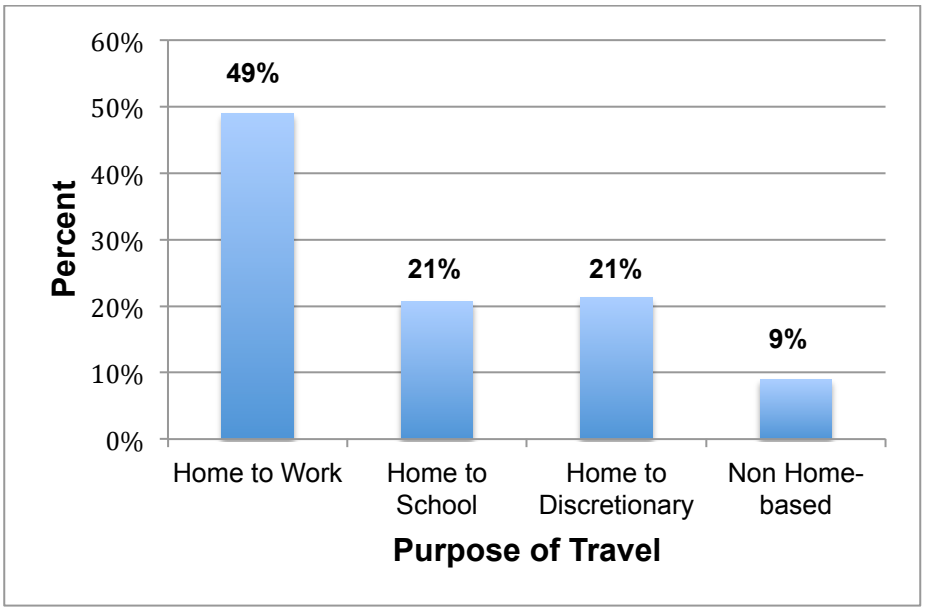

Figure 10. Purpose of Travel by Toronto Subway Ridership (2018).

According to the TTC, those who self-identify as female use the subway more in Toronto compared to males (56% vs. 44%) (Figure 11). The majority of subway users were 25 to 64 years of age (65%), and ridership was highest among 25 to 44 year olds (40%) (Figure 11). Over two-thirds of riders were employed either full-time or part-time (Figure 11).

The proportion of subway ridership is lower between riders with the lowest household income (25%) and those with the highest household income (32%) for those who reported their household income. The household income pattern for subway users is markedly different than what was reported for TTC public transit users (including streetcar and bus routes) as a whole.

In 2013, TPH reported that the lowest income commuters were 1.6 times more likely to use some form of public transit to get to work compared to the highest income commuters (TPH, 2013). One possible explanation for this variation is that the subway system traverses neighbourhoods with higher home values and provides an efficient means of accessing Toronto's downtown district.

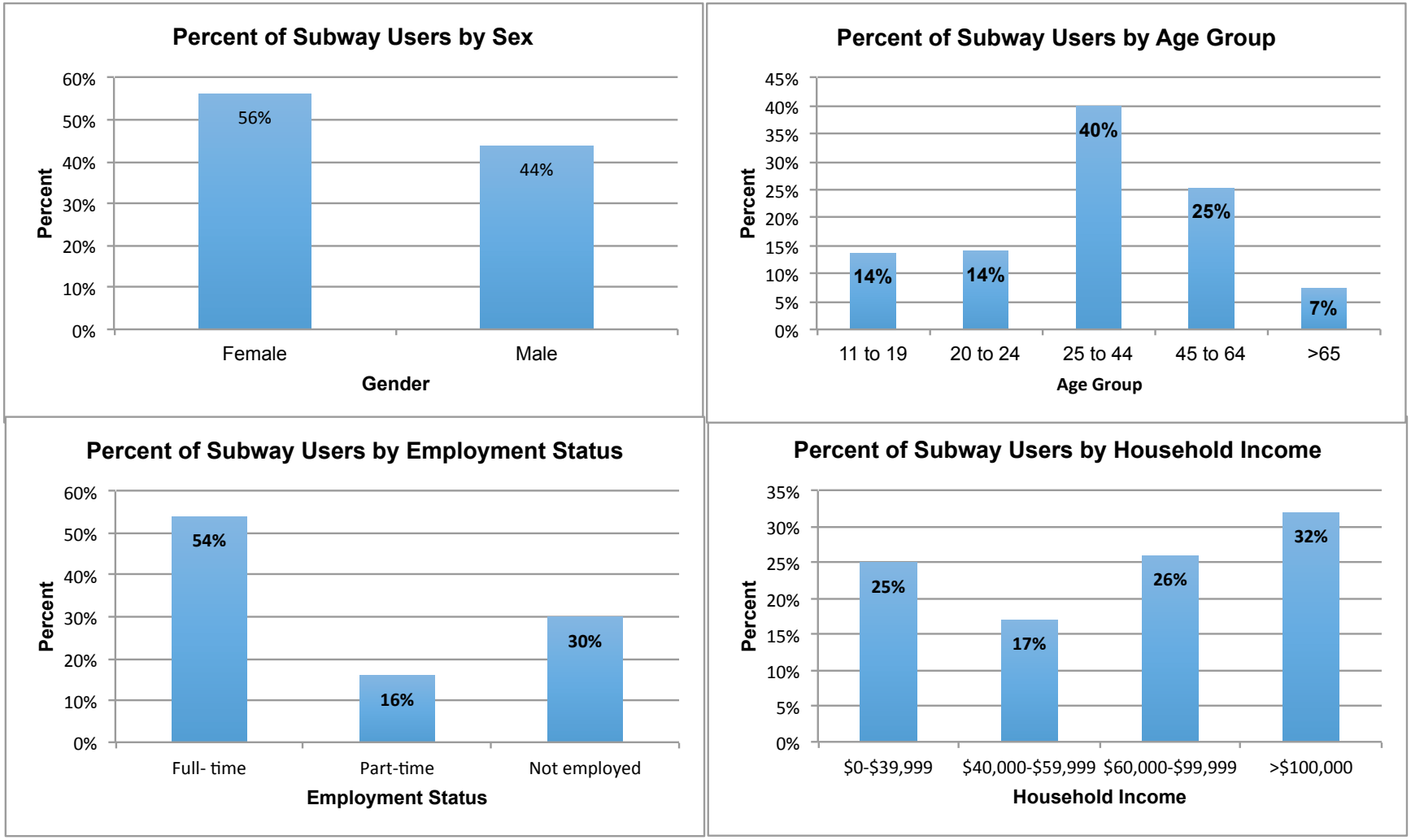

Figure 11. Select Socio-Economic and Demographic Characteristics to Subway Ridership (2018).

6.1 Vulnerable Populations and Health Equity

A key step in conducting any HIA is identifying the potential vulnerable or sensitive populations that may be disproportionately impacted, either positively or negatively, by the project; in this case, subway use or access to the system. Vulnerable populations were identified based on how the selected determinants of health could impact groups differently. Health equity is also assessed for each determinant of health to evaluate whether a particular vulnerable population or community is disproportionately impacted in terms of negative health outcomes.

For the HHRA, it was important to consider how air contaminant exposure could adversely affect the health of sensitive (vulnerable) populations that may react to airborne contaminants differently than the general population. This was determined through a review of the individual contaminants and the available research that identifies sensitive populations impacted by exposure to these contaminants. This included consideration of children and populations with pre-existing health conditions that can be exacerbated by airborne pollutant exposure, particularly to $PM_{2.5}$ (HHRA, Section 5.1, Appendix B).

Some people within the subway ridership populations are particularly vulnerable to certain health effects, because of their age, social/economic situation, or health status. In addition to the socio-economic factors previously identified, another group considered in the HIA included those residing in neighbourhoods in Toronto that are remote (not walkable) to the subway. They may not be able to easily access the many employment opportunities and services are located along the subway system. Table 2 provides a summary of the vulnerable groups considered in the HIA and the availability of data specific to those groups in relation to the subway system.

Table 2. Vulnerable Populations in the Subway Ridership Considered in the HIA Assessment.

Vulnerable Group	Vulnerabilities of Concern	TTC Ridership
Children (<11 years old)	Air pollution, physical activity	No data available
Teens (<20 years old)	Air pollution, mobility, physical activity, personal security	14%
Seniors (> 65y years old)	Mobility, physical activity, social isolation, personal security, access to health and social services	7%
Women	Personal security	56%
Low Income Families	Mobility, employment, access to health and social services	24%
Homeless	Mobility, employment, social isolation, personal security, access to health and social services	No data available
Those without Direct Access to the Subway System	Mobility, employment, access to health and social services	No data available.
Adults with Disability	Mobility, social isolation	No data available

Vulnerable Group	Vulnerabilities of Concern	TTC Ridership
Preexisting Medical Conditions Children with Asthma Children with special healthcare needs Adults with pulmonary or cardiovascular diseases	Air pollution	No data available

7 ASSESSMENT

Based on the available evidence, the assessment step characterizes potential impacts (positive or negative) of subway use and access on the determinants of health that were identified in the scoping step (Section 5.2). For the TSAQ HIA, the potential health impacts of exposure to airborne contaminants was assessed quantitatively in the HHRA (Appendix B). There was sufficient data to conduct a scientifically defensible detailed quantitative air quality health risk assessment. The health impacts for the remaining determinants of health were assessed qualitatively based on both local Toronto-based data and broader available evidence from the scientific literature. Each determinant of health was evaluated to assess:

- Potential health outcome;
- Vulnerable populations;
- Outcome of the assessment; and,
- Equity/distribution of impacts.

The results of the assessment for each determinant of health were captured in a summary table at the end of each section. The individual tables are then collated in the conclusions sections of the TSAQ HIA (Section 7.1.4 and 7.2.7). This qualitative approach to conducting HIA assessment is standard practice when project-specific data is not collected or not available for each determinant of health. Rather, the assessor relies on published sources of information that can serve to inform about how determinants of health for the project may be impacted. Although this approach often requires subjective professional judgment to be applied by the HIA practitioner, it allows for consistency and transparency in how effects on health are evaluated. It allows stakeholders and decision makers to examine how assessment of health impacts was made by clearly identifying the evidence used and rationale.

The TSAQ HIA is somewhat unique as it is evaluating an existing condition of subway use. There is no evaluation of a proposed project or policy alternative being undertaken in comparison to status quo. Therefore, it was determined that the TSAQ HIA should assess potential health outcomes specifically related to current subway use and not to compare it to a baseline or a future state.

In some instances the evaluation also included, for comparative purposes, consideration of what the potential outcome would be in the absence of subway system access. For example, if subway users were in a position of relying on an alternative mode of transportation such as the use of personal vehicles. The assessors wish to emphasize that there is no indication this may occur and was done for comparative purposes only to put the potential positive and negative impacts of subway use into a broader context for interpretation. Given the scope of the TSAQ HIA it is not feasible, nor was it ever within the scope of the assessment, to analyze and conduct a detailed comparison of the myriad of alternative modes of transportation to that of subway use. It is acknowledged that subway use could be compared to other modes including walking,

cycling, taking the bus or train and others; however, it was determined that the alternative for comparison within this HIA would be personal vehicle use in the absence of subway use for context and comparison purposes.

7.1 Environmental Determinants of Health

This section focuses on the potential health impacts of the measured concentrations of airborne contaminants in the subway on ridership. It also provides some consideration of potential impacts on Toronto's environment if subway ridership did not displace personal vehicle use as it does currently.

Toronto's population is currently 2.93 million and is projected to reach 3.9 million by 2041 (Ontario Ministry of Finance, 2018). This growing population continues to place a strain on its road network infrastructure. Although traffic congestion cannot be completely eliminated due to the increasing number of people living, working and doing business in Toronto, it can be managed through public transit and other initiatives. Traffic congestion negatively impacts air quality, increases greenhouse gas (GHG) emissions, and can affect a host of determinants of health. This section provides an overview of traffic related issues in Toronto that will be referenced in the individual assessments of the determinants of health.

In an effort to manage and reduce traffic congestion City Council approved a four-year Congestion Management Plan 2016-2020 (City of Toronto, 2016). This plan identified that it is not practical to build enough roads and infrastructure to accommodate the daily vehicle demand. The plan identified the important role that public transportation plays in reducing the number of vehicles on the road and the need to encourage its use to mitigate traffic congestion and related impacts (City of Toronto, 2016). Based on subway train loading standards, and passenger vehicle occupancy of 1.11 people for inbound trips to the city of Toronto during the morning rush hour, TTC estimates that each T1 Train replaces 900 personal vehicles and each TR Train replaces 990 personal vehicles (TTC, 2018a). Therefore, use of the subway system displaces tens of thousands of personal vehicles that might otherwise be used on Toronto's roads each day.

7.1.1 Assessment of Subway Air Quality Impact on Health

Over the past decade, three air quality measurement monitoring campaigns have demonstrated that Toronto's subway system contains elevated concentrations of $PM_{2.5}$ (and associated metals) over that typically found in an urban outdoor environment (Van Ryswyk et al., 2017; TTC, 2018a; Health Canada, 2019). A detailed quantitative HHRA was undertaken to ascertain the potential health risk to subway riders from exposure to these airborne contaminants (Appendix B). This section provides a summary of findings and conclusions of the HHRA. For further details, readers may refer to Appendix B that provides the complete HHRA technical report.

7.1.1.1 HHRA Methodology

Health Canada and the United States Environmental Protection Agency (US EPA) define a Human Health Risk Assessment (HHRA) as a process used to approximate the nature and likelihood (or probability) of adverse human health effects occurring among individuals who may be exposed to chemicals in the surrounding environment either now or in the future (US EPA, 2012; Health Canada, 2010a)

More specifically, an HHRA evaluates the frequency and extent to which humans (receptors) may be exposed to chemicals present in various environmental media (e.g., air, soil, water, food, etc.) through one or more exposure pathways (e.g., inhalation of air, direct dermal contact, ingestion of food or water, etc.). An estimate of human (or receptor) exposure to a specific chemical is then compared to information concerning its inherent hazards (or toxicity).

Ideally, an HHRA would rely entirely on strong, complete, and reproducible data. In practice, data are often limited, resulting in the need for approximations, professional judgement, and assumptions during the development of an HHRA. As such, a certain level of uncertainty is inherently introduced into human health risk estimates (US EPA, 2012). Presenting these uncertainties in a clear and transparent manner is an important component of any HHRA (US EPA, 2012; Health Canada, 2010a).

Although HHRA guidance can vary among different regulatory agencies, it is widely accepted that the HHRA framework typically consists of four key components or steps — Problem Formulation, Exposure Assessment, Hazard (Toxicity) Assessment, and Risk Characterization. This HHRA framework is a well-established and accepted approach to examining the potential health risks from exposure to contaminants.

The HHRA was conducted in accordance with accepted HHRA methods and guidance documents published by various regulatory agencies including Health Canada (2010a; 2010b; 2012), the Ontario Ministry of the Environment, Conservation and Parks (MECP; previously referred to as Ontario Ministry of the Environment and Climate Change, (MOE, 2005a, 2011)), the California Office of Environmental Health Hazard Assessment (Cal OEHHA), the Texas Commission on Environmental Quality (TCEQ), and guidance provided by the United States Environmental Protection Agency (US EPA, 2011, 2012).

7.1.1.2 HHRA Problem Formulation

The objective of the problem formulation stage is the development of a conceptual model that clearly outlines the scope of the HHRA by identifying the chemicals of potential concern (e.g., $PM_{2.5}$ and metals), the human receptors of interest (i.e., subway riders), and the relevant exposure pathways (i.e., inhalation). The goal of the problem formulation is to focus the HHRA on the chemicals, exposure pathways, and receptors that have the greatest potential to contribute to human health risks (HC, 2010a).

Identification and Selection of Chemicals of Potential Concern

In addition to evaluating health risks associated with exposure to $PM_{2.5}$ in the Toronto subway system, the health risks associated with exposure to a number of key metals of interest (identified as constituents of the subway $PM_{2.5}$) were also evaluated. Measurements of $PM_{2.5}$ and metals (found within subway $PM_{2.5}$) were available for Line 1 (Yonge-University-Spadina) and Line 2 (Bloor-Danforth). A relative toxic potency screening was completed to focus the HHRA on those metals (identified in subway $PM_{2.5}$) that have the greatest potential to impact human health.

In addition to $PM_{2.5}$, the following nine metals in subway $PM_{2.5}$ were identified for further evaluation in the HHRA:

arsenic, barium, cadmium, chromium, cobalt, iron, manganese, nickel and silver

Receptor Identification

A receptor is an individual who may come into contact, either directly or indirectly, with subway $PM_{2.5}$ and the associated metals of interest. Those individuals that are most susceptible to subway particulate matter ($PM_{2.5}$) and associated metals, due to having the greatest probability of exposure, should be identified and selected for assessment in the HHRA.

The HHRA selected the subway user who is consistently in the subway system as part of their daily routine during morning and afternoon peak hours as the receptor of interest. The subway user may represent all individuals (including adults and children) who may rely on the subway for their daily commute to and from work or school.

The evaluation of this highest user group of subway riders ensures that risks for occasional users of the subway system are also captured, and in fact overestimated. There was no indication during the development of the problem formulation that there would be a group of Toronto subway users that would use the system with greater frequency than daily commuters.

There are vulnerable populations (e.g., children, pregnant women, seniors, individuals with pre-existing respiratory conditions) within the ridership who may be more sensitive to $PM_{2.5}$ and/or metals than others. This type of susceptibility (i.e., a heightened sensitivity to specific types of substances) is addressed in the toxicity assessment of the HHRA (Appendix B, Section 5.0).

The HHRA focused on the direct exposure resulting from the inhalation of $PM_{2.5}$ and associated metals measured from within the subway system (i.e., the inhalation exposure pathway). The concept of microenvironments was used in the development of both acute (short-term: a single subway ride) and chronic (long-term: continued annual use) exposure scenarios. Depending on the scenario being evaluated, individuals were

assigned different exposure durations under each microenvironment based on ridership data provided by the TTC (2019a). The three key microenvironments included: the subway platform environment; the on-train environment; and ambient (outdoor) air.

In addition to characterizing chronic (or long-term) exposures among individuals who regularly use the subway, the HHRA also evaluated, as a point of reference, chronic exposures among individuals who do not use the subway system (i.e., exposure under ambient conditions alone).

Three short-term (or acute) exposure scenarios were also evaluated for each subway line, and the system as a whole, during weekday peak hours of operation or transit use. The acute scenarios were designed to evaluate one-off exposure events (single subway ride), assumed to last anywhere from approximately a half hour to an hour in duration, during peak hours of operation or transit use.

7.1.1.3 Exposure Assessment

Subway $PM_{2.5}$ and Metal Concentrations by Microenvironment

The mean $PM_{2.5}$ concentrations on Toronto subway platforms over all operational hours on Line 1 (138 µg/m^3) and Line 2 (291 µg/m^3) fall within the range of $PM_{2.5}$ concentrations found in other subway systems around the world (Moreno, 2017 and COMEAP, 2018). The mean $PM_{2.5}$ subway platform concentration on Line 2 (of 291 µg/m^3) is near the upper limit of the range presented by Moreno (2017).

Continuous (minute-by-minute) sampling of subway platforms during peak weekday hours (6am– 9am and 3pm–7pm) resulted in $PM_{2.5}$ concentrations (expressed the 95th UCLM - upper confidence limit on the mean) of 165 µg/m^3 (Line 1), 385 µg/m^3 (Line 2), and 303 µg/m^3 (entire system). As illustrated in Figure 12, mean $PM_{2.5}$ platform concentrations measured over peak weekday hours or transit operation were observed to be approximately two times greater than platform concentrations measured during late evening (10pm–1am) and overnight periods (1:30am–5:30am) combined (i.e., combined E/O). The concentrations for peak weekday hours were used in the HHRA to approximate the exposure point concentration.

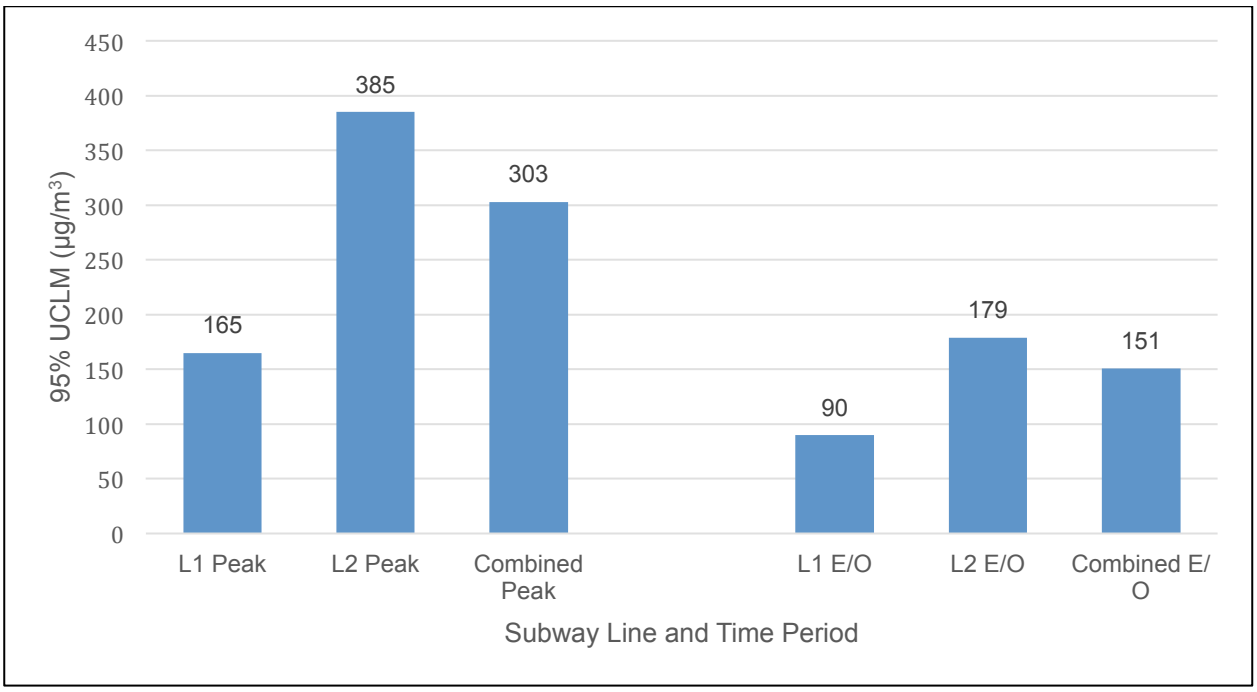

Figure 12. $PM_{2.5}$ Subway Platform Concentrations During Peak and Evening/Overnight (E/O) Hours on Line 1, Line 2, and the Combined System.

On-Train Chemical Concentrations

The TTC (2019a) data indicated that a significant proportion of an individual's time in the subway system is spent riding within the subway train. As such, the concentrations of $PM_{2.5}$ and associated metals found within the subway train cars (as opposed to on the platform) are critical to approximating overall exposure while taking the subway.

The Health Canada SAQI personal exposure monitoring dataset allowed for the development of on-train-to-platform concentration ratios. Median on-train concentrations of $PM_{2.5}$ were observed to be 39% to 47% lower than $PM_{2.5}$ concentrations measured on platforms. These data were used to develop on-train chemical concentrations.

Concentrations for Metals in $PM_{2.5}$

The SAQI dataset included an analysis of 189 individual PM samples for laboratory analysis of their metal concentrations. Summary statistics of abundance ratio (AR) values, defined as the concentration of a specific metal in $PM_{2.5}$ (expressed as $\mu g/m^3$) divided by the concentration of $PM_{2.5}$ (expressed as $\mu g/m^3$) were calculated and an appropriate 95 percent upper confidence limit on the arithmetic mean (95% UCLM) was derived. This was done to derive concentrations of metals for both on-platform and on-train scenarios. The resulting metal concentrations are found in the HHRA (Appendix B).

Concentrations of $PM_{2.5}$ and Metals in Ambient Air

As part of the SAQI, a second sampling campaign was completed that involved the collection and analysis of $PM_{2.5}$ in ambient air (Health Canada, 2019). Ambient air samplers were situated at two different monitoring locations (i.e., 200 College Street and 4905 Dufferin Rd.) between May and August of 2018. A total of twenty-three 7-day samples comprised the SAQI ambient dataset. $PM_{2.5}$ samples were also analyzed for their metal concentrations (Health Canada, 2019). The ambient air quality dataset collected as part of the SAQI was considered the most appropriate dataset to use to characterize ambient levels of $PM_{2.5}$ and metals for the HHRA, as subway and ambient data were collected in parallel with one another, there was consistency in the methods used to collect $PM_{2.5}$ samples in subway and ambient air as well as consistency in the methods used to analyze the metal composition.

Development of Exposure Point Concentrations (EPCs)

One of the most critical steps to quantifying human exposure is to develop chemical- and media-specific EPCs. An EPC represents an approximation of a subway user's daily exposure to a chemical of concern. To approximate a subway user's exposure to $PM_{2.5}$ and associated metals, the concentration and time spent within each microenvironment (i.e., on the platform, riding the subway train, and time spent under ambient conditions) was considered. As such, a series of time-weighted average EPCs was developed to facilitate the approximation of acute (i.e., ½-hour to 1-hour single ride) and chronic (i.e., yearly) EPC values.

Time-activity patterns (i.e., time waiting on platforms, riding on trains, and time spent under ambient conditions) were used in conjunction with microenvironment-specific concentrations to develop a series of time-weighted chronic EPCs.

The TTC (2019a) data indicated that most subway users spend approximately one hour in the subway system on any given travel day (i.e., approximately a ½-hour each way). Most of this time is spent on the subway train, with up to five (5) minutes a day (in total for both directions) spent waiting on the platform. As such, exposure to subway $PM_{2.5}$ and associated metals of interest over a ½-hour to 1-hour averaging time would be considered relevant to characterizing acute human health risks. Acute EPCs were derived in a similar fashion to the chronic daily EPCs, with the exception that time-weighted subway exposures were averaged over the time spent only within the subway system.

7.1.1.4 Toxicity Assessment

The HHRA selected inhalation toxicity reference values (TRVs) to assist in the characterization of health risks as a result of exposure to subway $PM_{2.5}$ and associated metals of interest. The Expert Panel (Appendix A) recommended that the evaluation of the individual airborne metals in subway PM be undertaken quantitatively using

international TRVs, where available, and that TRVs should be sourced from the United States Environmental Protection Agency (US EPA), Health Canada, World Health Organization, and California EPA. Neither the US EPA or Health Canada (Health Canada, 2010b) report acute TRVs. Therefore, TRVs published by the Texas Commission on Environmental Quality (TCEQ) were included for consideration. Full details concerning the TRVs selected for use are found in Section 5 of the HHRA (Appendix B).

Toxicity of $PM_{2.5}$

The chemical parameter of primary concern in the Toronto subway system is airborne particulate matter (PM) (Figure 13). Particulate matter is a term used to represent a mixture of very small solid particles and liquid droplets in air. PM is a concern, as it is associated with a variety of serious health effects and premature death (US EPA, 2019a). The composition of PM is complex, with some particles (e.g., dust, soot, smoke, etc.) being large and/or dark enough to be visible with the naked eye, while other particles can only be detected using an electron microscope (US EPA, 2019b).

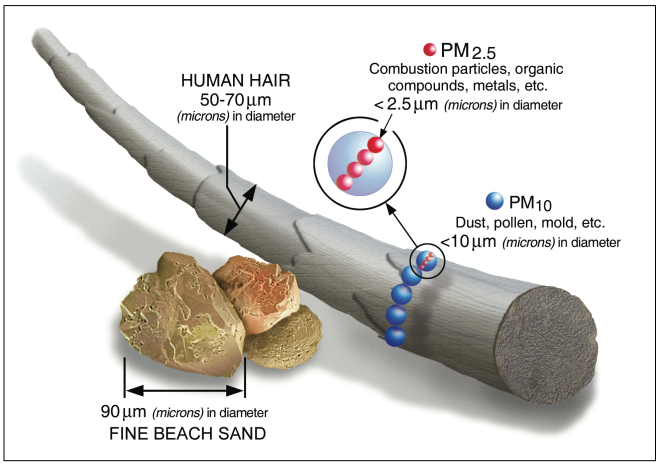

Figure 13. Relative Size of Fine Particulate ($PM_{2.5}$) (US EPA, 2019b).

$PM_{2.5}$, often referred to as fine PM, is approximately 35 times smaller than the diameter of fine beach sand or about 30 times smaller than the diameter of the average human hair (US EPA, 2009; 2019). $PM_{2.5}$ represents the greatest risk to human health (relative to other PM size fractions), as $PM_{2.5}$ can be deposited deep within the lungs and can, in some instances, enter the bloodstream (US EPA 2019a).The body of scientific evidence gathered to date indicates that exposure to $PM_{2.5}$ is associated with a variety of serious adverse health effects, including premature death, where no discernable effects threshold has been identified. The TSAQ HIA Expert Panel Workshop Report (Appendix A) also concluded that both Health Canada and international health agencies agree that $PM_{2.5}$, regardless of its composition, is a non-threshold health hazard, meaning that exposure to any level of $PM_{2.5}$ poses some potential detriment to health.

Acute exposure studies involving individuals participating in normal activities under ambient conditions have shown that short-term exposures to $PM_{2.5}$ are associated with multiple effects, including increased respiratory symptoms (*e.g.,* cough, chest tightness, shortness of breath general asthma symptoms), decrements in lung function (as measured by decreased forced exploratory volume, for example), and pulmonary

inflammation. Asthmatic children and adults with COPD appear to be most susceptible to these effects; however, limited evidence indicates that healthy children and adults may also be at an increased risk due to acute exposure (Health Canada, 2013).

To-date, TRVs that are specific to subway $PM_{2.5}$ exposure have not been developed. In their review of the subway $PM_{2.5}$ literature Loxham and Nieuwenhuijsen (2019) concluded that although the toxicological effects of subway $PM_{2.5}$ exposure may be different from the effects associated with ambient $PM_{2.5}$ (likely due to the unique characteristics of subway $PM_{2.5}$), they are not likely greater than the effects associated with ambient $PM_{2.5}$. Canadian and international guidelines for ambient $PM_{2.5}$ are predicated on the fact that PM is a non-threshold contaminant, meaning there is no level below which adverse health effects are not expected to occur (WHO, 2006a; HC, 2013). Therefore, the HHRA assumed, in agreement with the Expert Panel, that the subway $PM_{2.5}$ has similar toxicity to ambient PM and as such, used the WHO (2006a) annual (chronic) and daily (acute) health-based benchmarks to place subway PM concentrations into context.

7.1.1.5 Risk Characterization Results

The results of the TSAQ HHRA indicate that concentrations of $PM_{2.5}$ are elevated throughout Toronto's subway system. The mean $PM_{2.5}$ concentrations on Toronto subway platforms recorded during weekday peak hours (when ridership is at its greatest) on Line 2 (385 $\mu g/m^3$) are 2.3 times greater than on Line 1 (165 $\mu g/m^3$). In comparison, the annual average ambient $PM_{2.5}$ concentration in Toronto's outdoor environment has been recorded to range anywhere from 7.5 $\mu g/m^3$ at the NAPS stations to 10.5 $\mu g/m^3$ from the SAQI monitoring campaign.

Similar to other subway systems around the world that employ the use of a conventional steel-wheel steel rail arrangement known to generate steel 'rail dust' through friction (Bukowiecki, et al., 2007), the airborne $PM_{2.5}$ is largely comprised of metals (e.g., iron, barium, chromium, cobalt, manganese, nickel, etc.). As such, the metal enriched $PM_{2.5}$ found in Toronto's subway differs greatly in composition from the PM found in a typical ambient urban environment (e.g., water-soluble ionic species - $SO4^{2-}$, $NO3^{-}$, Cl^{-}, $NH4^{+}$ and carbonaceous species – organic carbon, elemental carbon, etc.).

Risk Assessment Results for Subway $PM_{2.5}$

Chronic

The WHO (2006) provides a series of interim targets and guidelines for annual (or chronic) exposure to $PM_{2.5}$. They range from an air quality guideline (AQG) of 10 $\mu g/m^3$ to an interim target (IT-3) of 15 $\mu g/m^3$. When annualized $PM_{2.5}$ exposures of subway ridership on Line 1 and Line 2 were combined with exposures from ambient air, it was determined that Line 1 exposure estimates were largely consistent with the WHO (2006a) AQG, while Line 2 estimates were between the AGQ (10 $\mu g/m^3$) and the IT-3 (15 $\mu g/m^3$) (Figure 14).

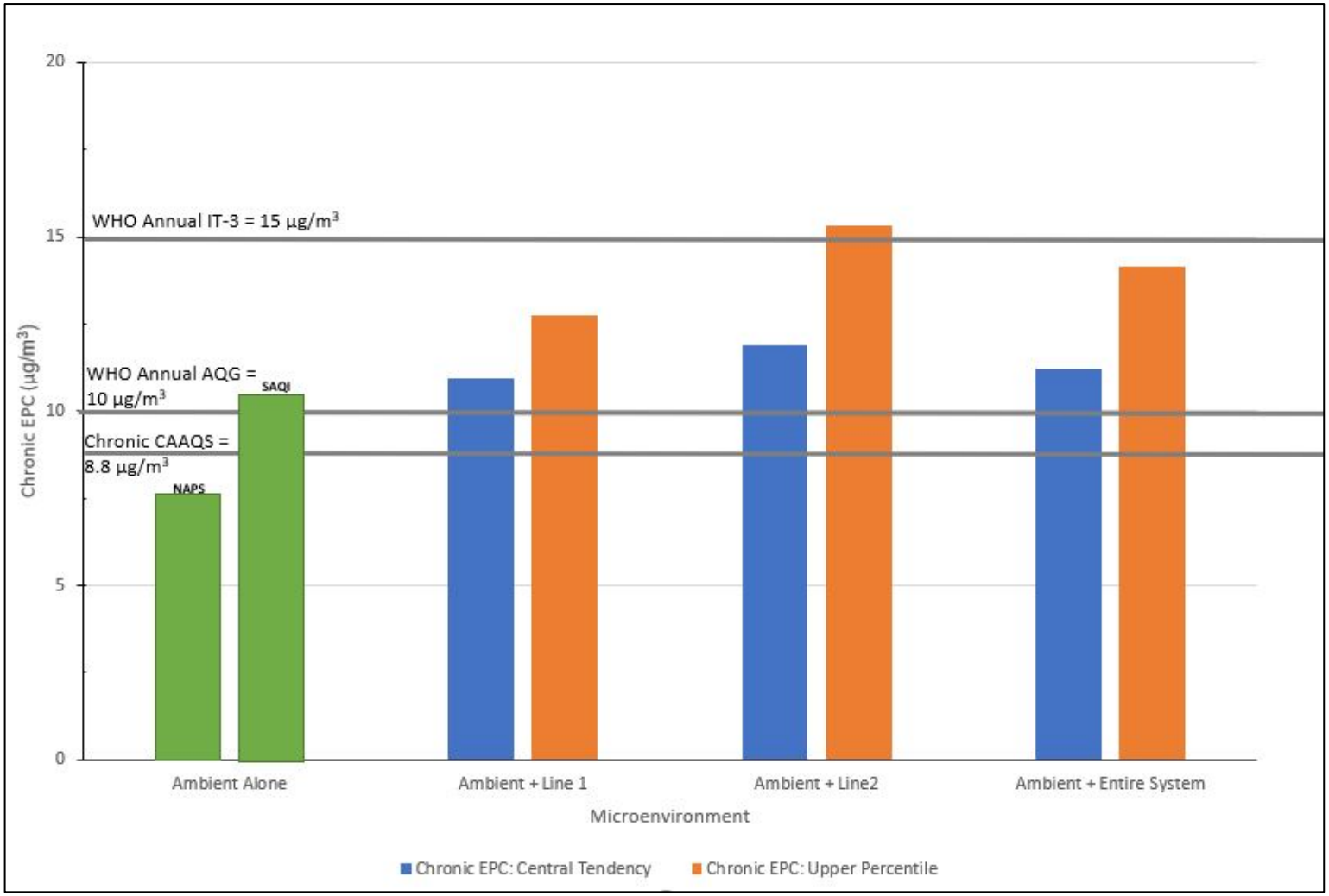

Figure 14. Chronic $PM_{2.5}$ Exposure Point Concentration Estimates (µg/m^3) under Ambient Alone and Ambient + Subway Lines.

Acute

The HHRA used an approach similar to that of Moreno (2017) to benchmark acute $PM_{2.5}$ exposure (over an individual subway ride) against the WHO (2006a) $PM_{2.5}$ 24-hr guideline and interim targets. The acute $PM_{2.5}$ exposure estimate for Line 1 was similar to the WHO IT-1 (75 µg/m^3); however, the Line 2 $PM_{2.5}$ exposure estimate was approximately 2.5-times greater than the WHO IT-1 and Line 1 exposure estimate (Figure 15). The $PM_{2.5}$ exposure estimates on both lines are considerably higher than the concentrations measured in Toronto's ambient air.

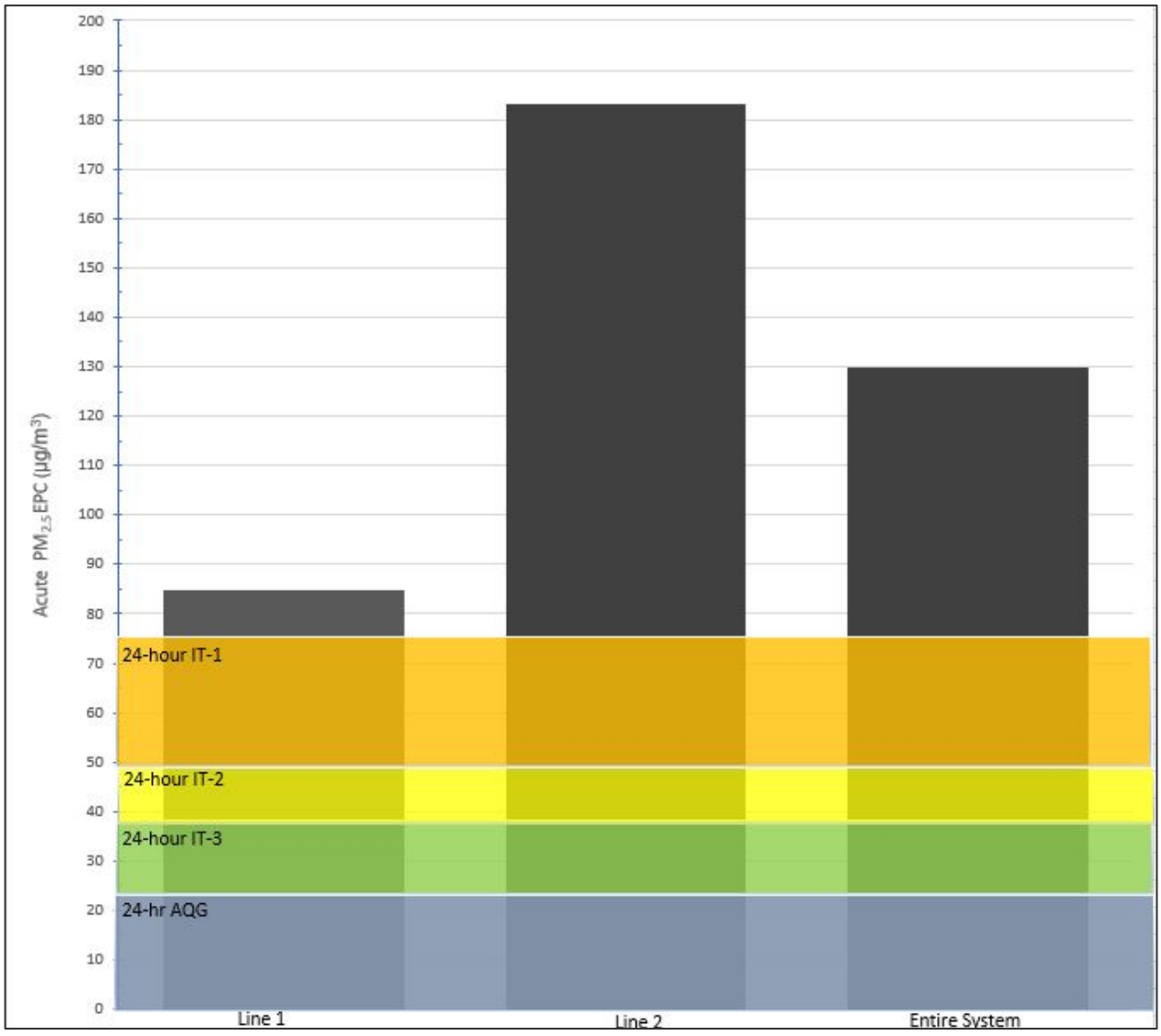

Figure 15. Acute $PM_{2.5}$ Exposure Point Concentrations (µg/m^3) by Subway Line During Peak Weekday Hours (6am to 9am and 3pm to 7pm)

Acute exposures to ambient $PM_{2.5}$ has been shown to result in an increase in respiratory and cardiovascular related effects. The US EPA (2009) and Health Canada

(2013) indicate that multiple lines of evidence exist to conclude that there is likely a causal relationship between respiratory effects (i.e., lung function decrements, respiratory symptoms, and lung inflammation) and acute $PM_{2.5}$ exposure. Exposure to ambient $PM_{2.5}$ levels can result in increased respiratory emergency room visits and hospital admissions (Health Canada, 2013). A reduction of Line 2 $PM_{2.5}$ levels would be expected to decrease the potential for transient respiratory effects and symptoms among the subway ridership.

Risk Assessment Results for Individual Metals

Chronic Exposure

Non-Cancer Health Risks

International regulatory agencies have published inhalation TRVs for the metals of interest identified in the HHRA that allow for a quantitative evaluation of non-cancer health risks (e.g. cardiovascular or respiratory) from exposure to individual metals of interest. Long-term (or chronic) exposure estimates to airborne metal concentrations (in the $PM_{2.5}$ size fraction) on both Line 1 and Line 2 were below their respective toxicity reference values (meaning a HQ<1.0). Figure 16 provides the non-cancer risk results for ambient air and Line 2.

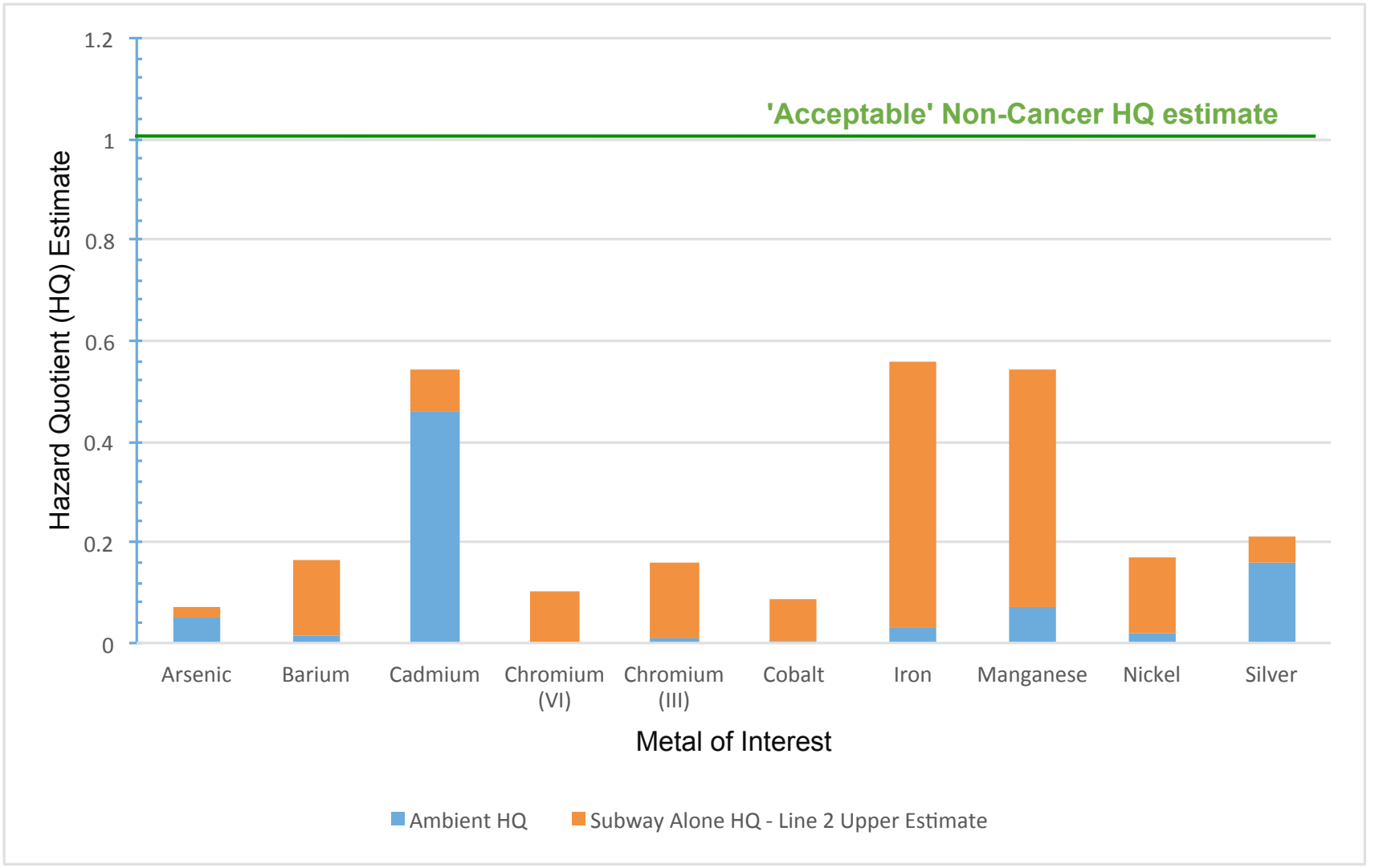

Figure 16. Non-Cancer Health Effect Hazard Quotients for Ambient Air and Line 2 Exposures to Metals.

Cancer Health Risks

The probability of Torontonians developing cancer in their lifetime is approximately 40% (40% or 0.4E-01) (Health Canada, 2010). In other words, 4 out of every 10 Torontonians will develop some form of cancer as a result of their genetic make-up, dietary choices and a host of social and environmental factors.

For exposure to individual environmental chemicals that may cause cancer Health Canada, and many other provincial jurisdictions, set an acceptable incremental (additional over background) lifetime cancer risk of 1 in 100,000 (1E-05) (Health Canada, 2010). However, the MECP has set a policy-based 'acceptable' or de minimis level of incremental lifetime cancer risk of 1 in 1,000,000 people exposed (1.0E-06), while TPH uses this target for both background (LCR) and ILCR risk estimates for environmental chemical exposure. A risk of one in a million means that one out of every million people exposed would be expected to develop cancer during their lifetime. Toronto Public Health encourages actions to reduce exposures when the risk is above one in a million (TPH, 2014b).

Nickel LCR (ambient air alone) and ILCR (subway alone) cancer risks were all below the stringent TPH acceptable cancer limit (Figure 17). Lifetime cancer risks for Torontonians breathing outdoor air were above the TPH acceptable limit for arsenic and cadmium, with subway exposure to these metals adding very little to the overall cancer risk for these metals. The subway Line 2 alone chromium (VI) ILCR was 4.9E-05, which exceeds both the acceptable levels of TPH (1.0E-06) and Health Canada (1.0E-05) (Figure 17). As such, an ILCR of 4.9E-05 (associated with chromium (VI) on Line 2) increases a subway user's lifetime probability of getting cancer risk from 40% to 40.005%.

Although the TTC (2018) occupational study was unable to detect chromium (VI) in subway particulate matter (above the analytical method of quantification), the HHRA conservatively assumed that 100% of all chromium measured in subway $PM_{2.5}$ existed as chromium (VI). As such, the subway ILCR estimates associated with chromium (VI) may over-estimate actual chromium-related health risks.

Summing the cancer risks for those metals that cause lung cancer (arsenic, cadmium, chromium (VI) and nickel) result in levels above the negligible range, although it is dominated by chromium (VI).

These findings are consistent with other subway air quality risk assessments that have reported that carcinogenic risk for individuals metals was at times reported to be above the negligible risk range (Lovett et al., 2017 and COMEAP, 2018).

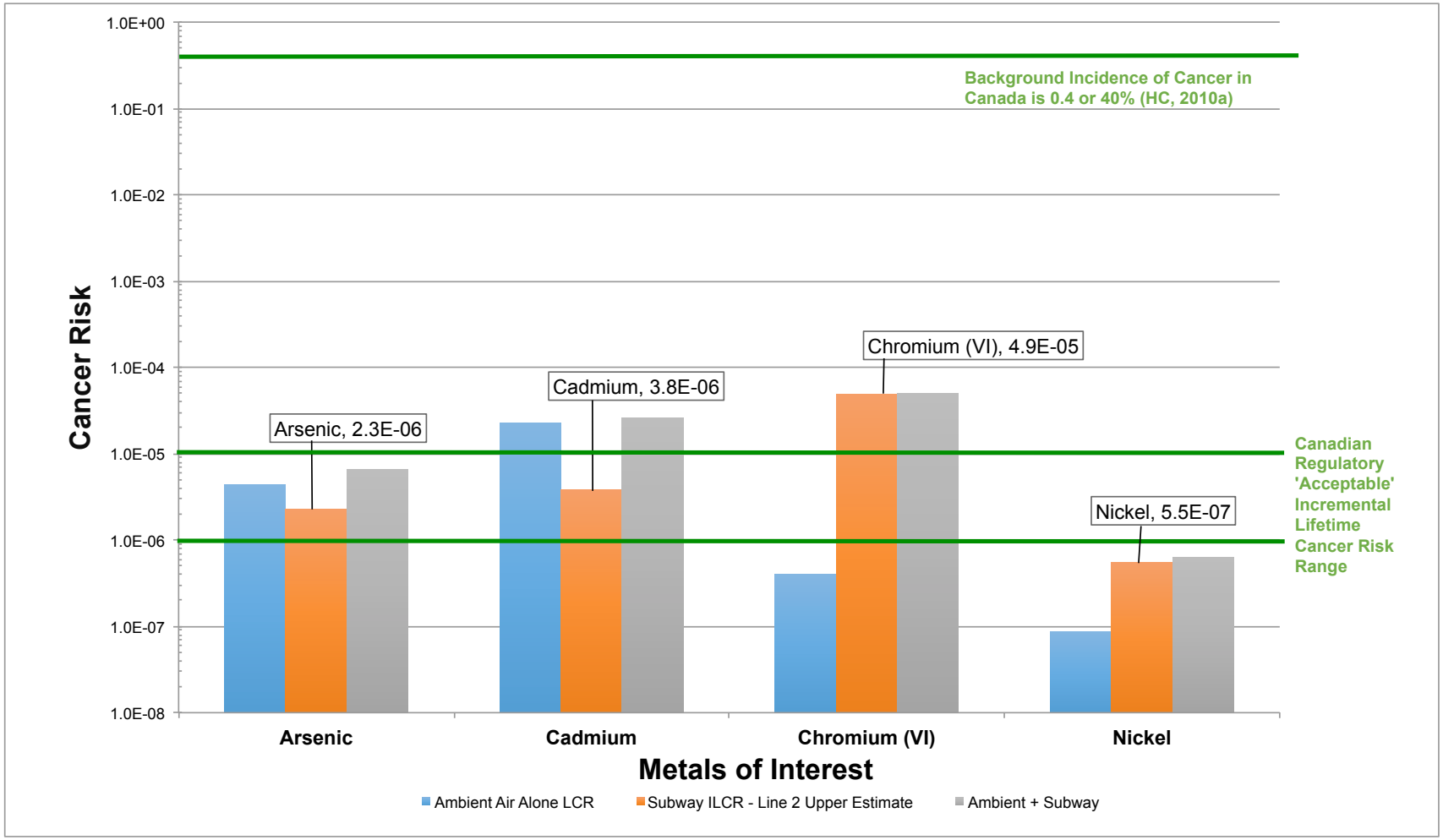

Figure 17. Cancer Risks Associated with Ambient Air and Subway Air Exposure.

Overall, long-term (or annual) exposure to individual metals found in subway $PM_{2.5}$ is unlikely to pose an undue health risk to subway riders. However, when all metals that have respiratory effects are considered together, the findings indicate a hazard marginally above the tolerable range.

Acute Exposure

Acute exposures to $PM_{2.5}$, and the associated mixture of metals that may occur over an individual ride, particularly on Line 2, are great enough that transient (i.e., short-lived, passing or not permanent) respiratory effects and/or symptoms may be experienced among some vulnerable individuals (Figure 18). More specifically, it is possible that transient respiratory effects (breathing problems) could be experienced among asthmatics, those with COPD, and even potentially in healthy adults. The effects may include detectable differences in lung function and/or respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, rhinitis and general asthmatic symptoms).

It may also be possible that one could detect the biomarkers of lung inflammation (Loxham and Nieuwenhuijsen, 2019). The high iron content in subway $PM_{2.5}$ appears to dominate acute non-cancer health risks associated with exposures to mixtures of metals in $PM_{2.5}$

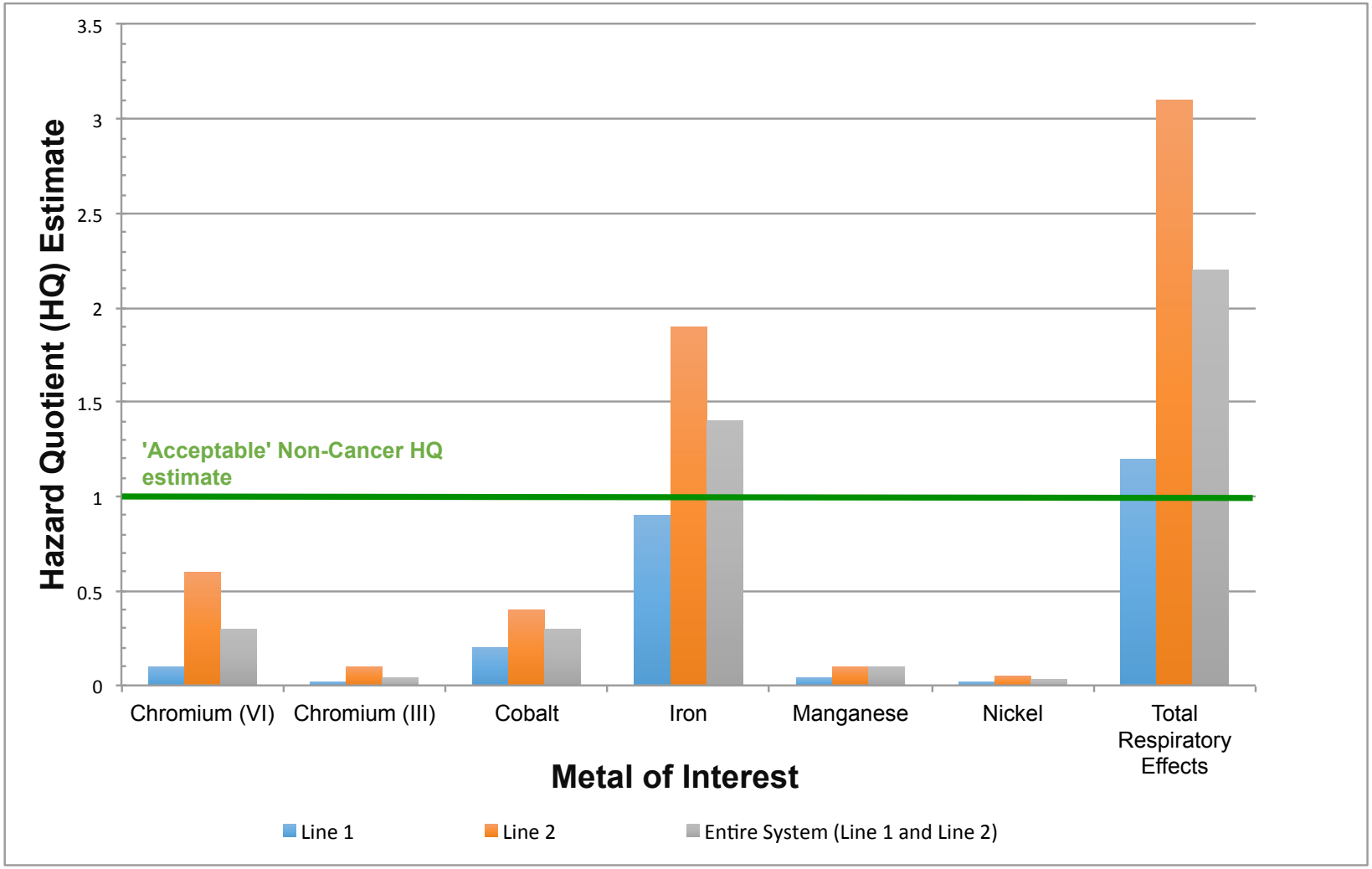

Figure 18. Acute Exposure (Individual Subway Ride) to Individual Metals and Their Cumulative Respiratory Effe

7.1.1.6 HHRA Conclusions and Discussion

The area of scientific investigation of potential health risks from exposure to subway air quality is still in its infancy. Although there is a decade's worth of measurements illustrating the elevated concentration of $PM_{2.5}$ in subway systems around the world, there is a lack of epidemiological *in vivo* (health monitoring of individuals using subway) and *in vitro* (laboratory studies) research to determine the actual health risks posed by subway air quality.

Loxham and Niewenhuijsen (2019) conducted a recent systematic review of the available literature on the *Health Effects of Particulate Matter in Air Pollution in Underground Railway Systems – a Critical Review of the Evidence.* This article identifies the peer-reviewed scientific research in the field, provides critical review and synthesis of the findings in the field, and allows for the TSAQ to be placed into context with the available international research.

The weight of scientific evidence suggests that while measurable effects on some endpoints have been observed across several in person (in vivo) studies, there is a general lack of evidence for the effects being as clinically significant as laboratory (in vitro) studies suggest could happen (Loxham and Nieuwenhuijsen, 2019). However, Line 2 $PM_{2.5}$ concentrations appear to be higher than those reported in the systematic review and, as such, caution should be exercised as to how this literature can be used to draw conclusions concerning health impacts associated with Line 2 exposures.

Overall, the results of the TSAQ HHRA indicate that the levels of $PM_{2.5}$ are high enough to warrant mitigation, particularly on Line 2. Any reduction in subway $PM_{2.5}$ concentrations would also be beneficial in lowering concentrations of associated metals. Long-term exposure to subway air quality marginally increases an individual's overall annual exposure to $PM_{2.5}$. The chromium (VI) subway incremental lifetime cancer risk estimates, which are associated with a high degree of uncertainty due to the lack of speciation data, was found to be the most elevated above the TPH target risk level. Short-term exposures to subway air quality, particularly on Line 2, may on occasion, result in transient (i.e., short-lived; passing; not permanent) respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, general asthmatic symptoms) and/or a temporary decline in lung function for children and adults with asthma, adults with COPD, and perhaps even healthy adults (Table 3).

Given the results of the TSAQ HHRA, the lack of studies assessing the human health effects of subway particulate exposure, and the strong link between adverse health effects and exposure to ambient particulate, it is reasonable to conclude that health risks associated with exposure to Toronto's subway air quality are elevated. Similar conclusions have been reached for the London Underground in the UK (COMEAP, 2019) and the Metro red line (subway) in Los Angeles (Lovett et al., 2017).

At this time there is a limited amount of research that has been done that suggests these effects may not be clinically significant (does not actually change lung function or result in breathing problems) (Loxham and Niewenhuijsen, 2019). Although these preliminary findings are encouraging, this work is in its infancy and may not have captured concentrations of particulate as high as that found in the Toronto subway systems. Therefore, further personal exposure research is needed to reduce the uncertainties identified in the HHRA and to better understand the potential health impacts to Toronto subway users. In addition, TPH is encouraged to monitor the scientific literature in this field and continue collaborating with other health authorities, such as COMEAP, to determine how new research findings can be applied to Toronto's subway system.

Table 3. Summary of Assessment of Subway Air Quality Impact on Health

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Subway Air Quality	Morbidity and mortality	Children, seniors and those with preexisting pulmonary and cardiovascular conditions	It is likely that there is some level of health risk associated with exposure to Toronto's subway air quality. It is possible that transient respiratory effects (breathing problems) could be experienced among asthmatics, those with COPD, seniors, children and even potentially in healthy adults. The effects may include detectable temporary differences in lung function, respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, rhinitis and general asthmatic symptoms).	Effects of subway PM could disproportionately impact subway riders over those using alternative forms of transportation; however, comparative risk analysis of air pollution and various modes of transportation was not completed.

7.1.2 Assessment of Traffic-Related Air Pollution Health Risk with Increased Personal Vehicle Use

Globally, air pollution represents the greatest environmental risk to population health (WHO, 2018). Traffic-related air pollution (TRAP) is the major local contributor to air pollution in Toronto (TPH, 2017). It is important to understand how the use of the subway may help to offset health issues that arise as a result of personal vehicle use in the City.

Exposure to ambient air pollution increases the potential risk of premature mortality from heart disease, stroke and lung cancer and contributes to increasing the risk to numerous diseases; such as asthma, pulmonary and cardiovascular diseases (Health Canada, 2019a). In the 2014 *Path to Healthier Air: Toronto Air Pollution Burden of Illness Update*, vehicle emissions were predicted to account for approximately 280 premature deaths and 1,090 hospitalizations in the City each year (TPH, 2014a), or 42% of premature deaths and 55% of hospitalizations related to air pollution exposure in Toronto.

Vulnerable populations that are at greatest risk from TRAP related health impacts are children, seniors and those with preexisting cardiovascular and pulmonary medical conditions. TPH (2017) also identified vulnerable communities or sensitive sites as residential neighborhoods, schools, child-care centres and long-term care facilities that are located in close proximity to TRAP exposure zones (e.g., adjacent to major roads and highways).

Jeong et al. (2019) found that residing within 300 m of a high-density road in Toronto results in elevated exposure to traffic related air pollution inside residences. This is consistent with the 1999-2011 Canadian Census Health and Environment Cohort (CanCHEC) that found those living near major traffic and higher density roads were at increased risk of mortality from cerebrovascular and cardiovascular disease, ischemic heart disease, chronic obstructive pulmonary disorder (COPD), respiratory disease, and lung cancer (Cakmak et al., 2019).

If current subway riders did not have access to a subway system and had to choose personal vehicles for their transportation, it could result in an increase of tens of thousands of vehicles daily on Toronto's roads. This could result in an increase in TRAP exposure for drivers, pedestrians, and cyclists and those living in vulnerable communities, and therefore an increase in morbidity and mortality across the population. Exposures would disproportionately impact those living in close proximity to major roads and highways in Toronto.

Daily commuters using the subway ensure that tens of thousands of personal vehicles are not contributing to Toronto's traffic-related air pollution. Subway users are a major contributor to supporting the objective of reducing vehicle-related air pollution, which in turn has a positive influence on health of all Torontonians (Table 4).

Table 4. Summary of Assessment of TRAP Health Risk with Increased Personal Vehicle Use

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Traffic-Related Air Pollution	Morbidity and mortality	Children, seniors, those with preexisting pulmonary and cardiovascular conditions, those living in residential neighborhoods, schools, child-care centres and long-term care facilities that are located in close proximity to TRAP exposure zones.	The current use of the subway over personal vehicles results in less ambient pollution, especially in proximity to high volume roadways. This reduces the amount of traffic-related air pollutants and the negative impacts on population health.	Impact would disproportionately impact those living closest to major roadways and highways.

7.1.3 Assessment of a Potential Increase in Greenhouse Gas Health Risk with Increased Personal Vehicle Use

Greenhouse gas (GHG) emissions contribute to the threat of global climate change. Public health researchers have been reporting on potential adverse health impacts that climate change will cause for over a decade (Haines, 2006). In 2015, TPH reported on the potential health concerns related to climate change in *A Climate of Concern: Climate Change and Health Strategy for Toronto* (TPH, 2015). The potential negative health impacts of climate change for Torontonians include:

- Increased incidence of heat/cold-related illness and premature death;
- Severe weather resulting in direct impacts such as injury and indirect impacts such as water-borne diseases;
- Increase in vector-borne diseases;
- Food system impacts including food insecurity and food-borne illness; and
- Degraded air quality increasing cardiovascular and respiratory illness.

The increase in severe weather events and natural disasters also has an impact on individual and community mental health (Rossati, 2017).

Vulnerable populations of particular concern are those that would be at greatest risk to GHG related adverse health outcomes include children, those with chronic disease, seniors, those who have a low income, those experiencing homelessness, and those who work outside.

In July 2017, Toronto City Council approved an ambitious climate action strategy (TransformTO, 2017). This strategy provides long-term, low-carbon goals and strategies to achieve a reduction in local GHG emissions. Toronto has targeted an 80% reduction of 1990 levels by 2050. Toronto releases an annual inventory of major community-wide contributors to GHG emissions. There has been a 44% reduction of Toronto's GHG emissions between 1990 and 2017. In 2017, 30% of Toronto's GHG emissions were from personal vehicle use (City of Toronto, 2017).

Under TransformTO the City has also established the Modeling Advisory Group (MAG) to identify where high-impact carbon reduction action coincides with opportunities to create multiple community benefits (MAG, 2017). Two key actions identified by the MAG were:

> *"Planning policies, guided by Toronto's Official Plan, that support complete communities and public transit/active transportation infrastructure lead to reduced emissions. Ensuring the successful application of these existing plans is essential."*
>
> *"MAG members identified public transit, active transportation, and land use changes as the most important opportunities the City has to achieve emission reductions that at the same time deliver other public benefits."*

Daily commuters using the subway ensure that tens of thousands of vehicles are not contributing to Toronto's GHG emissions. Without access to the subway system, the use of personal vehicles would result in an increase in Toronto's GHG emissions. This would impede Toronto in achieving their GHG reduction goals through TransformTO and would be counter to the objective of reducing its contribution to this global health threat (Table 5).

Table 5. Summary of Assessment of Personal Vehicle Traffic Volume

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
GHG	Numerous biological and physical adverse health impacts	Children, those with chronic disease, seniors, those with low income, those experiencing homelessness, those working outside.	Subway use over personal vehicle use decreases GHG production and aides in Toronto's GHG reduction strategy.	Would impact all Torontonians. Risks are greater for vulnerable populations.

7.1.4 Summary of Environmental Determinants of Health

A summary of the HIA environmental assessment is provided in Table 6. Overall, it was determined health risks associated with exposure to Toronto's subway air quality are elevated. Further research of personal exposure to subway air quality would allow for more meaningful conclusions to be made on the nature and significance of these potential health impacts. TPH is also encouraged to monitor the international scientific literature for any new developments in the field and how they can be applied to Toronto's subway system.

It was determined that use of the subway system results in a significant reduction in personal vehicle use in the City. The direct impact of the subway system is a reduction in potential emissions of traffic-related air pollution and GHG emissions. The presence of the subway offsets these emissions and potential negative impacts on the health of all Torontonians.

Table 6. Summary of the Assessment of Environmental Determinants of Health

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Subway Air Quality	Morbidity and mortality	Children, seniors and those with preexisting pulmonary and cardiovascular conditions	It is likely that there is some level of health risk associated with exposure to Toronto's subway air quality. It is possible that transient respiratory effects (breathing problems) could be experienced among asthmatics, those with COPD, seniors, children and even potentially in healthy adults. The effects may include detectable temporary differences in lung function, respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, rhinitis and general asthmatic symptoms).	Effects of subway PM could disproportionately impact subway riders over those using alternative forms of transportation; however, comparative risk analysis of air pollution and various modes of transportation was not completed.

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Traffic-Related Air Pollution	Morbidity and mortality	Children, seniors, those with preexisting pulmonary and cardiovascular conditions, those living in residential neighborhoods, schools, child-care centres and long-term care facilities that are located in close proximity to TRAP exposure zones.	The current use of the subway over personal vehicles results in less ambient pollution, especially in proximity to high volume roadways. This reduces the amount of traffic-related air pollutants and the negative impacts on population health.	Impact would disproportionately impact those living closest to major roadways and highways.
GHG	Numerous biological and physical adverse health impacts	Children, those with chronic disease, seniors, those with low income, those experiencing homelessness, those working outside.	Subway use over personal vehicle use decreases GHG production and aides in Toronto's GHG reduction strategy.	Would impact all Torontonians. Risks are greater for vulnerable populations.

7.2 Social, Economic and Other Determinants of Health

This section assesses the potential health impacts of Toronto's subway ridership on the social and economic determinants of health.

7.2.1 Assessment of Physical Activity and Physical Health Related to Subway Use

Physical activity is critical to ensuring overall physical health. Lack of physical activity has been linked to a host of poor health outcomes, such as, overall mortality, cardiovascular diseases, diabetes, colon cancer, and hypertension (US DHHS, 1996). This section assesses the potential increase for physical activity from walking to the subway station when compared with personal vehicle use for commuting to work or school.

The use of personal vehicles that likely involves longer commute times to work over that of the subway results in less physical activity and a higher prevalence of obesity as compared to use of public transportation. A study comparing daily walking distance between car commuters and those using commuter train from home in New Jersey to work in New York found that train commuters walked on average 30% more steps per day (Wener and Evans, 2007). They were four times more likely to walk 10,000 steps per day than car commuters, which is the recommended daily target. Lindstrom (2008) investigated the association between means of transportation to work and its correlation to overweight and obesity in commuters in Sweden. In this study the odds ratio of overweight and obesity was lower among men using public transportation over those who commuted by car.

There have been several studies on walkability access to the Toronto subway system. Alshalafah and Shalaby (2007) investigated the relationship between walk access distance to a Toronto subway station and use of the system during weekday peak commute time from 6 am to 9 am. The results indicated that the dense subway network in the downtown area resulted in lower walk access distance than other parts of the city. Approximately 60% of subway users live within 300 m (airline distances), while 80% live within 500 m of a subway station. The median access distance for both school and work was 346 m. However, they also reported that people in Toronto are willing to walk further to access the subway than previously thought (Alshalafah and Shalaby, 2007). This means that on average people are walking an additional 700 m a day while taking the subway and not using their personal vehicles.

Crowley et al. (2009) studied the walkability access of Greater Toronto Area residents of North York City Center to Line 1 of the subway system. In terms of walking distance, 36% of those living within 200 m of a station used the subway system. There was only a slight decrease to 32% who reside within 200 m to 400 m walking distance to the closest subway station. However, there was a rapid decline to only 17% use for those living 400 m to 800 m to the closest station and only 3% for those living beyond 800 m from the subway. Crowley et al. (2009), also determined even if residents owned vehicles, they are less likely to use them over the subway for commuting during peak periods if they live close to the subway.

The US Surgeon General reported that 30 minutes of walking a day can lead to demonstrated health benefits through this moderate level of activity (US DHHS, 1996). In a study of transit users in the U.S., those who rode the bus and train reported a median of 19 minutes of walking per day as part of their commute (Besser & Dannenberg, 2005). It takes the average healthy person 12.5 minutes to walk a kilometer. Given the results of the Toronto walkability to subway station studies (Alshalafah and Shalaby, 2007; Crowley et al., 2009) it is likely that subway users are experiencing positive health outcomes from their commute compared to commuters in personal vehicles. Therefore, vulnerable populations would include those that do not have a reasonable walking distance of less than 800 m to a subway station or an alternative form of public transportation.

Overall, walking to subway stations likely results in an increase in physical activity and better health outcomes over choosing to use personal vehicles or living beyond a reasonable walking distance to the subway system. Therefore, many subway users experience these physical health benefits (Table 7).

Table 7. Summary of Assessment of Physical Activity as it Relates to Subway Use

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Physical Activity	Numerous biological and physical adverse health impacts, including obesity and chronic disease.	Those without a reasonable walkability distance to a subway station.	Those who walk to the subway have a greater level of physical activity and lower rates of being overweight and obesity than personal vehicle commuters.	There is an inequitable distribution of impact on those who do not have walkable access to the subway or other means of public transportation.

7.2.2 Assessment of Mental Health and Well-being Related to Subway Use

One of the largest challenges facing the working public is time spent commuting. Both the total time of the commute and the nature and mode of transportation of the commute play a role in mental health and well-being. There are two main areas for commuter well-being that need to be evaluated. The first is stress caused by the mode of commuting and the second is the well-being that may be associated with commute time.

The average working Canadian commutes 68 minutes round trip a day to work, with over 50% of those by personal vehicles (Canadian Census, 2016). Statistics Canada identified that over 1.5 million Canadians have a long commute, meaning that they spend more than 2 hours a day commuting to work. The majority of these trips are in personal vehicles (Statistics Canada, 2018). Regardless of the mode of transportation selected, peak commuting times to and from home to work and school in Toronto are from 6 am to 9 am, and from 3 pm to 6 pm.

Hilbrecht et al. (2014) examined how commute time affected time spent on activities beneficial to well-being and self-assessed well-being in Canadians. They reported that time spent commuting was correlated with lower levels of life satisfaction and an increased sense of time pressure. This left commuters with reduced time for physical actively and leisure.

Data was not available to determine how much commuting time the average Torontonian saves using the subway versus road travel from the same location. The highest percentage of people using public transit in Toronto was for those having to commute less than 5 km to work (58%). The dominant form of transportation for those commuting greater than 5 km to work is use of personal vehicles. The median commute time for subway users of Line 1 (18 min) and Line 2 (26 min) is lower than those using personal vehicles (TTC, 2019). Although interruption to subway service occurs, in general, daily commute times via the subway are also relatively fixed in duration and less susceptible to unpredictable increases than personal vehicle commutes in congestion.

For 2018, the average Torontonian using a car with a one-way travel time of 30 minutes (without congestion) was delayed an extra 16 minutes in the morning and 20 minutes in the evening, or a total of 36 minutes a day (TomTom, 2018). This is an additional three

hours of time spent commuting in one's personal vehicle per week or over 150 additional hours a year due to traffic volume. This will continue to be an ongoing issue for Toronto, and will worsen with the anticipated continued population increase. This additional time spent commuting takes away from other personal enjoyment activities; such as recreation, time spent with family, exercise and hobbies.

Stress levels are reported to be markedly higher for those who drive over those that use the subway. A study comparing stress levels among those who drove or took the train from New Jersey to New York City found that personal vehicle commuters showed significantly higher levels of self-reported stress, more negative mood, indicated the trip was significantly more effort, and reported that their travel time was significantly less predictable as compared with train commuters (Wener and Evans, 2011).

A survey conducted of commuters to McGill University in Montreal also reported that driving is the most stressful mode of transportation when compared with taking the subway, train or bus (Legrain et al., 2015).

Based on the available evidence, it is clear that shorter commute times and use of the subway as a chosen mode of transportation are associated with a decrease in stress levels and an increase in well-being over those using personal vehicles with longer commute times (Table 8). Access to social and other services via the subway system can also lead to positive mental health and well-being outcomes, which are further detailed in Section 7.2.4.

Table 8. Summary of Assessment of Mental Health and Wellness as it Relates to Subway Use

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Mental Health and Well-being	Stress and feeling of personal well-being.	Those without reasonable walkability distance to subway station.	Subway commuters generally have shorter commute times, lower stress levels and an increase in overall sense of well-being over personal vehicle commuters. They are also typically able to enjoy more personal time.	There is an inequitable distribution of impact on those who do not have walkabie access to the subway or other means of public transportation.

7.2.3 Assessment of Employment, Education and Household Income Related to Subway Use

Access to affordable and reliable public transportation is critical to ensuring access to employment opportunities and education. A higher family income and socio-economic status results in better overall health outcomes (TPH, 2015a). Stable employment is also a known factor for someone to maintain good mental health and is an important factor for recovery for those that have developed a mental health problem (NHS, 2017).

The proportion of subway ridership is fairly equally distributed between riders with the lowest household income (25%; <$40,000) and those with the highest household

income (32%; >$100,000). This demonstrates that the subway is critically important to accessing employment (and other services) for those across the full range of income distribution within the City of Toronto (i.e., used equally by high and low income individuals).

Lower income commuters (vulnerable population) are more dependent on public transport to get to work than higher income earners. This is because they are less likely to own an automobile. In 2010, only 44% of Torontonians with a household income of <$24,000 reported owning a vehicle compared to 71% vehicle ownership for those with household incomes >$40,000 (TPH, 2010).

As described in Section 7.2.1, walkability to the subway platform from home increases the likelihood of commuting to work or school. However, housing and condo prices within a reasonable walking distance (800 m) of a Toronto subway platform are expensive. In 2018, the average Toronto house price was $776,221 and condo was $571,415. Zoocasa (real estate website) reported the average 2018 sold prices near all 75 subway stations (Zoocasa, 2019). The most affordable homes are located near Line 3 (Scarborough) at $740,000, while homes near Line 1 average over $3,000,000. The lowest condo prices were located in the east end of Toronto near Lines 2 and 3 with an average price of $329,530 near Kennedy station. There was no information available for average rental prices. It is clear that real estate is more expensive closer to the core of the city along the subway lines.

Although the broader TTC system reaches many areas of Toronto not accessible by the subway, it may be perceived as being faster and more efficient as compared with surface transit (*e.g.* buses and streetcars). Therefore, extending the subway, or other forms of rapid and accessible public transit, into lower socio-economic areas may improve access to employment (and other services) for more low income families across the City.

Levels of educational attainment and skills development are fundamental social determinants of health, which is an upstream cause of health outcomes (Hann et al., 2015). The TTC (2019) reported that 21% of subway rides are from home to school. Although not broken down in the data, it is assumed that school included both public school and access to higher education. Across Canada, higher levels of education tend to be correlated with higher levels of income (Canada Census, 2010). In 2010, one in four Canadians who obtained a university degree was in the top 10% of income earners (Canada Census, 2010). Toronto's subway provides access to numerous universities and colleges across the city.

In a 2012 survey, public transportation was the most commonly used mode of transportation to employment and skills training (66%) and language training (49%) amongst Toronto's immigrant and refugee population (Ontario Council of Agencies Serving Immigrants, 2012). The lack of access to public transportation was identified as the most common barrier to accessing training (Ontario Council of Agencies Serving

Immigrants, 2012). Therefore, the subway provides vital access to these services for those immigrants and refugees living along the system.

Toronto's subway allows people greater access to employment opportunities, public schools and institutes of higher education, skills and language training programs and reduces the need to own a vehicle. This may translate into higher household incomes and overall better health outcomes (Table 9).

Table 9. Summary of Assessment of Employment, Education and Household Income as it Relates to Subway Use

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Household Income	Overall Health Status	Families and individuals of low income household.	Access to better employment opportunities, education and skills training can lead to higher household incomes that translates to overall positive health outcomes, including mental health.	There is an inequitable distribution of impact in lower house hold income families that may not have access to the subway or other forms of rapid public transit.

7.2.4 Assessment of Access to Government and Social Services Related to Subway Use

Public transportation provides a vital link to access numerous services; such as health care, healthy food options, childcare, recreation and cultural programs. Inaccessibility to these basic services can result in both poorer physical health and mental health outcomes (TPH, 2013).

Low income families, seniors and people with disabilities are more reliant on public transportation (subway) to access basic services than those who are middle or higher income (Victoria Transport Policy Institute, 2018; TPH, 2013). As previously discussed, 25% of subway riders are from low income households and access to affordable public transportation is essential, especially for those without vehicles.

Seniors (>65 years old) make up 7% of Toronto subway users. Key factors in determining mode of transportation selected by seniors are having a valid driver's license, living with a partner, and the specific age range over 65 years. The loss of a driver's license and/or partner is reported to be major contributors to social isolation for those without adequate access to public transport (Heshner, 2007).

There was no information available on the percent of subway users with a disability. Although all of the subway trains are accessible for people with a physical disability, only half of the stations have elevators (TTC, 2018).

Access to health services ensures health promotion and disease prevention, and contributes to overall health and well-being. However, limited access to affordable public transit (subway) can be a barrier to accessing health services (TPH, 2011). This

is especially the case for those without access to a vehicle and low income families. Access to health services is particularly important for the management of children's health. In 2011, a TPH study concluded that lack of access or affordability of public transit for low income families resulted in missed doctor/specialist, dental care, vaccination and developmental service appointments for their children (TPH, 2011). It is postulated that access to the subway would also affect the ability of senior and those living with a disability to access to health services.

Healthy eating is essential for maintaining health, especially for a healthy pregnancy and child development (PHAC, 2018). It also decreases the risk of heart disease, diabetes, obesity, certain type of cancer and osteoporosis (City of Toronto, 2019). TPH leads the Toronto Food Strategy (TFS), which was established in 2010. The TFS aims to encourage a food system that positively impacts human and environmental health (TPH, 2018). The TFS recognizes the importance of access to healthy foods to improve the lives of all Toronto residents.

In Toronto, income is the biggest determinant of food access. Many people live in neighborhoods with few sources of healthy and diverse foods and have to travel more than 1 km to purchase fresh produce (City of Toronto, 2019). Access to the subway allows people greater access to affordable, healthy foods that meet their cultural or religious beliefs (TPH, 2010). It also may allow for better access to food banks for low income families.

Affordable public transportation, including subway access, is important for low-income families to help them access recreational and cultural programs that promote children's health and well-being. Restricted access to free or subsidized recreational activities can result in both a decrease to physical and mental health (TPH, 2011), especially amongst children.

Social connectivity and access to cultural and social resources are important dimensions of being socially inclusive and have been associated with positive physical and mental health outcomes (TPH and Wellesley Institute, 2019). Neighbourhoods that have poor public transit can limit the capacity of residents to connect with others (TPH and Wellesley Institute, 2019). Affordable subway access to cultural and social resources may increase individual and community social cohesion. Allowing for better access to places of worship, cultural events and social events would allow seniors, those with a low income and living with a disability broader opportunities for social participation.

Overall, Toronto's subway system provides an efficient and effective way to access a broad range of health and social services (Table 10). The City should continue to explore measures that increase affordability and accessibility to the subway system. Access to all stations for people with physical disabilities is important and the TTC is encourage to continue with these ongoing efforts. The City should consider expansion

of the subway system, or other forms of rapid transit, to reach more low income families to provide greater access to services.

Table 10. Summary of Assessment of Access to Services as it Relates to Subway Use

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Access to Services	Physical and mental well-being	Low income household Seniors Children Teens Adults with Disabilties or mobility issues	Access to affordable subway use provides the ability for increase in physical health through access to a wide range of health and social services. It also provides for access to recreational, cultural and social activities that could lead to an improvement in mental health.	Affordability and accessibility are most important for low income families, seniors and those with disabilities. Especially for those without reasonable walking distance to subway stations and who do not have access to a vehicle.

7.2.5 Assessment of Safety and Security Related to Subway Use

All forms of commuting and transportation have inherent risk for injury, fatality and personal security. It is important to understand these risks to personal safety and security in the context of subway use.

Commuting by car results in an increased risk of injury and fatality over that of subway use. In 2005, it was estimated that approximately half (47%) of transportation fatalities in the United States were for personal vehicle occupants, while subway ridership accounted for only 0.2% of fatalities (Gershon et al., 2005). They reported that U.S. subway-related mortality rates (0.15) were almost 6 times lower than automobile mortality rates (0.87) for every 100 million passenger miles.

In June 2019, Toronto's Vision Zero 2.0 – Road Safety Plan Update provided Toronto-specific information on passenger vehicle safety (City of Toronto, 2019b). Toronto has one of the lowest traffic fatality rates amongst North American cities at 2.2 fatalities per 100,000 inhabitants. In 2018, there were 66 people killed and 346 seriously injured in Toronto personal vehicle collisions (City of Toronto, 2018). For the same year, the TTC reported that it had 3 non-suicide related subway fatalities; one homicide and two who were decending to track level while alcohol impaired (TTC, 2019 pers. comm.).

For 2018, the TTC estimated ridership injury incidences to be 1.07 per one million boardings (TTC, 2018). This is a system-wide statistic and not specific to subway use and includes incidents such as trips and falls. The TTC reported a downward trend in customer injury rate from 2014 to 2018 that was partly attributed to the reduction in elevator/escalator injury incidences in the subway. It was also attributed to the reduction in slip/trip injury incidences due to installation of slip resistant coating on some station floor areas. Therefore, subway travel is considerably safer than traveling by personal vehicle when it comes to the risk of injury and/or fatality.

With respect to safety and security in 2018, the TTC reported that there were 0.69 offences against customers per one million vehicle boardings, an increase over the previous year (TTC, 2018). Again, these statistics are TTC system-wide and are not subway-specific. Incidences of theft were on the rise, while other crimes such as robbery, assault and sexual assault remained static over 2017. The TTC also reported that there did not appear to be a pattern in reported incidences; such as location or time of the events.

Personal security has been reported as being of particular concern for women when selecting their mode of transportation, especially with respect to the potential to be sexually harassed or assaulted (Hsu, 2009). Loukaitou-Sideris (2014) found that women frequently adjust their behaviour and travel patterns as they have distinct safety/security needs and are often fearful of certain transit environments. Teens in the US reported feeling less safe while traveling on the subway (40%) versus when they travel by car or bus (84%) (Wiebe, 2014).

In July 2016, the Toronto Star reported specific concerns about sexual harassment and assault for Toronto women using the subway (Toronto Star, 2016). They reported that in the first five months of 2016, 35 sexual assaults on the transit system were reported to the commission and that the TTC receives regular complaints about sexual harassment. This led Toronto City Council to request that the TTC review the transit system through a “gender-specific lens” to “address safety concerns of women and women with disabilities”. The TTC has introduced several initiatives to improve customer security in the subway system; including adopting a new safety app, adding designated waiting areas and adding additional TTC Transit Enforcement Special Constables to patrol the system (TTC, 2019). There may be additional populations who are vulnerable to impacts such as assault or harassment (*eg.,* LGBTQ, visible minority) but there is currently no data available to explore this possibility.

Overall, the lower probability of fatality or injury is considered a positive health outcome for those commuting by subway over those in personal vehicles. However, the subway may present unique challenges for personal security and for feeling safe within the system, especially for women and teens (Table 11).

Table 11. Summary of Assessment of Personal Safety and Security

Health Determinant	Potential Health Outcome	Vulnerable Population	Outcome	Equity / Distribution of Impacts
Commuter Safety	Injury or Fatality	Personal vehicle users and those without subway access	Increased risk of injury or fatality for vehicle commuters over subway use.	Those without subway access who must drive may be disproportionately impacted.
Commuter Security	Sexual harassment and assault; Crime or theft	Women Teens	Unique security concerns for those taking the subway instead of personal vehicle for personal security, harassment, assault, and theft.	May disproportionately affect women and teens.

7.2.6 Assessment of Tourism Related to Subway Use

Toronto is Canada's leading tourism destination with over 43 million visitors annually (Tourism Toronto, 2017). Of that, 15.5 million are overnight visitors and 28.2 million are same day visitors. It is estimated that tourists infuse $8.8 billion dollars annually into Toronto's economy (Tourism Toronto, 2017). In 2013 it was estimated that the City of Toronto had over 19,000 tourism-related businesses employing more than 329,000 people (Tourism Toronto, 2017).

The TTC does not collect data on subway use by tourists. Tourism Toronto (2007) acknowledged the importance of public transportation for tourism, especially within the city, and noted that it should be expanded to meet future needs. The report estimates that a 1% improvement to public transportation within Toronto could result in an additional 70,000 visitors yearly.

It is reasonable to assume that the subway system is important in allowing tourists to access the many sites and activities Toronto has to offer. Those tourists that stay in Toronto's downtown core, or along the subway lines, have access to an affordable and easy system to move around the city. This reduces the need for taking taxis or other personal vehicle rideshare trips and reduces the environmental issues associated with these forms of transportation. This was especially true for the Union Pearson Express train that was added to better move people from Union Station to the airport and into the city's core.

It may also lead to an overall increase in enjoyment of the tourist's experience (Table 12).

Table 12. Summary of Assessment of Tourism Related Subway Use

Health Determinant	Potential Health Outcome	Vulnerable Population	Outcome	Equity / Distribution of Impacts
Tourism	Enjoyment of tourist experience	None	Subway access may enhance tourist's experience during their visit to Toronto. It also reduces the number of motor vehicle trips that need to be taken and hence environmental footprint.	Not all tourists will be staying in places with ready access to the subway system.

7.2.7 Summary of Assessment of Social, Economic and Other Determinants of Health

Analysis of the social, economic and other determinants of health indicate that there may be significant positive health outcomes associated with subway access and use, especially when compared with personal vehicle use (Table 13).

Physical activity is higher amongst subway users who walk to the station, which has health benefits such as increasing overall physical health and decrease rate of obesity. Subway commuters typically have a shorter commute time, decrease in self-reported stress levels and an increase in their sense of well-being over personal vehicle commuters.

The subway allows access to employment opportunities across all levels of household income and reduces the need for vehicle ownership. However, subway transportation cost still remains a challenge for low-income families, and the subway may not be accessible to many low income families due to distance. Those living along the subway lines may also have better access to social services and recreation opportunities. This is especially important for low income families, adults with disabilities and seniors. Subway access also provides a means to reduce social isolation in these populations. Although, only half of the subway stations are accessible (i.e., have an elevator) for those with physical disabilities, TTC is making an effort to bring physical access to all of its stations.

It was shown that commuter safety for fatalities and injuries was lower among subway users than personal vehicle commuters. Concerns around personal security for subway use is highest amongst women, who are also the largest users of the system.

Overall, access to the subway system provides a number of positive health benefits to its users (Table 13). The City of Toronto should continue to encourage the use of the subway, especially as an alternative to personal vehicles, and seek to expand the system and continue to improve access to all Torontonians.

Table 13. Summary of the Assessment of Socioeconomic Determinants of Health

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
Physical Activity	Numerous biological and physical adverse health impacts, including obesity and chronic disease.	Those without a reasonable walkability distance to a subway station.	Those who walk to the subway have a greater level of physical activity and lower rates of being overweight and obesity than personal vehicle commuters.	There is an inequitable distribution of impact on those who do not have walkable access to the subway or other means of public transportation.
Mental Health and Well-being	Stress and feeling of personal well-being.	Those without reasonable walkability distance to subway station.	Subway commuters generally have shorter commute times, lower stress levels and an increase in overall sense of well-being over personal vehicle commuters. They are also typically able to enjoy more personal time.	There is an inequitable distribution of impact on those who do not have walkabie access to the subway or other means of public transportation.
Household Income	Overall Health Status	Families and individuals of low income household.	Access to better employment opportunities, education and skills training can lead to higher household incomes that translates to overall positive health outcomes, including mental health.	There is an inequitable distribution of impact in lower household income families that may not have access to the subway or other forms of rapid public transit.
Access to Services	Physical and mental well-being	Low income household Seniors Children Teens	Access to affordable subway use provides the ability for increase in physical health through access to a wide range of health and social services. It also provides for	Affordability and accessibility are most important for low income families, seniors and those

Health Determinant	Potential Health Outcome	Vulnerable Population	Assessment Outcome	Equity / Distribution of Impacts
		Adults with Disabilties or mobility issues	access to recreational, cultural and social activities that could lead to an improvement in mental health.	with disabilities. Especially for those without reasonable walking distance to subway stations and who do not have access to a vehicle.
Commuter Safety	Injury or Fatality	Personal vehicle users and those without subway access	Increased risk of injury or fatality for vehicle commuters over subway use.	Those without subway access who must drive may be disproportionately impacted.
Commuter Security	Sexual harassment and assault; Crime or theft	Women Teens	Unique security concerns for those taking the subway instead of personal vehicle for personal security, harassment, assault, and theft.	May disproportionately affect women and teens.
Tourism	Enjoyment of tourist experience	None	Subway access may enhance tourist's experience during their visit to Toronto. It also reduces the number of motor vehicle trips that need to be taken and hence environmental footprint.	Not all tourists will be staying in places with ready access to the subway system.

8 STUDY LIMITATIONS AND UNCERTAINTIES

Over the past decade, HIA has emerged as an appropriate scientific method to assess and evaluate the potential negative and positive health effects related to projects, programs and policies. Building on previous HIA guidance and best practice standards from around the world, the TPH HIA guidance was used to conduct the TSAQ HIA (TPH, 2019). Similar to quantitative chemical health risk assessment and epidemiological investigations, it is important to document the limitations and uncertainties associated with the TSAQ HIA study.

In the assessment section, the evidence and data used to assess each determinant and the rationale behind the outcomes was clearly documented. In some cases, robust locally-relevant data was not available, and in these cases, literature and evidence from other jurisdictions was used to inform and infer potential impacts. Regardless of the HIA's limitations, a transparent approach to assessment allows for individuals, stakeholders and decision makers to review the available evidence and draw their own conclusions.

The following limitations were noted for the health assessment:

- This HIA was conducted on the existing subway system in isolation. It is challenging to focus singularly on the determinants of health (including environmental and socioeconomic) of the subway system without consideration of the wider integrated TTC and regional network of public transportation.
- Every attempt was made to incorporate available Toronto-specific data where readily available. However, new data to fill Toronto-specific data gaps for some determinants of health were not collected.

- TTC provided data that enables characterization of many aspects of subway rider demographics. However, some data (such as tourism ridership statistics) were not available.
- The consultants, in consultation with TPH and from the scientific literature, developed the list of vulnerable groups associated with the different determinants of health. However, no public consultation was held and it is possible that not all vulnerable populations were identified in the HIA.
- This study analyzes the potential health impacts of subway air quality on the general population, as well as on vulnerable populations in Toronto. Many groups, for example people experiencing homelessness, face unique barriers (e.g., economic, geographical) to accessing public and private transportation. A comprehensive analysis of barriers faced by specific groups, and the impact of these on health equity, was outside of the scope of this assessment and therefore presents an area of uncertainty in relation to potential impacts. As well, vulnerability to negative health impacts is likely not experienced equally across specific groups discussed in this report.
- The analysis was unable to identify any data specific for subway use of Indigenous populations. It is acknowledged that Toronto's Indigenous population may face unique challenges or vulnerabilities that were not captured in this report.
- Numerous assumptions were made throughout the HHRA that help to ensure that the assessment, in light of uncertainties, overestimates (rather than underestimates) potential exposures and health risks. The net effect of these multiple assumptions and input parameters used throughout the HHRA process ensures the protection of human health. Section 7 of the HHRA (Appendix B) provides an account of the assumptions used and the uncertainties that exist throughout the exposure and hazard assessments.
- Additional personal exposure studies for Toronto subway users would help to reduce the uncertainty and better refine the potential risk of exposure to subway air quality.
- It is recognized that sound (noise) can affect health. However, noise is a unique environmental determinant that was outside the scope of the chemical risk assessment.
- Rapid / Intermediate HIAs are by their very nature a preliminary overview of framing the potential positive or negative health outcomes that may occur for each determinant of health. The individual assessments for each determinant are in and of themselves entire areas of research or study. The TSAQ HIA provides an overview of relevant issues to support the Rapid HIA and is not intended as exhaustive review of the literature or science for each determinant.

Overall, the TSAQ HIA attempts to provide a balanced analysis of the potential for the Toronto subway to have both negative and positive effects on the health of the local community and the region.

9 MONITORING

The Monitoring step of an HIA should provide a plan that contains measurable indicators to determine how mitigation or enhancement measures improve anticipated health outcomes.

The overarching recommendation (as outlined in Section 12) of the TSAQ HIA is that improvements to air quality in the system are beneficial for health, particularly for Line 2. The HHRA provided a WHO health-based metric for evaluating the level of $PM_{2.5}$ in the subway system. This metric should be used as a guide for evaluating any improvements made to Toronto's subway air quality.

It was also recommended that $PM_{2.5}$ levels should be used as a surrogate for all metals. The effectiveness of mitigation measures is best assessed with a clear a $PM_{2.5}$ pre-mitigation and post mitigation implementation $PM_{2.5}$ monitoring program. The effectiveness of the mitigation measure in reducing $PM_{2.5}$ in the system should be guided by continuous reduction using the WHO health-based metric used in this assessment.

10 EVALUATION

The evaluation step seeks to review the HIA undertaking and identify lessons learned from the process. It also allows one to identify how the HIA may have influenced final decisions for a policy or project.

It would be valuable for TPH to undertake an internal evaluation of the TSAQ HIA 12 months after the release of this report. It should follow the evaluation protocol set out in the TPH HIA Guidance (2019). It is recommended that the evaluator review the need for the HIA, whether it was scoped appropriately, any lessons learned, whether an appropriate budget was allocated, timelines and timeliness of reporting, the effectiveness of public communication/messaging, and did the recommendations of the HIA change or influence decisions being made about the need for mitigation measures to improve air quality in the subway system. These findings should be used by TPH to inform any future HIA undertakings.

11 CONCLUSIONS

There have been a number of studies that have measured airborne concentrations of chemicals in Toronto's subway system (Van Ryswyk, 2017; TTC, 2019; and Health Canada, 2019). All three studies have found elevated concentrations of $PM_{2.5}$ on subway station platforms and on the trains, as compared to levels found in Toronto's outdoor urban ambient environment. The Toronto subway levels of $PM_{2.5}$, and

associated metals, are consistent with those found in London's Underground system (COMEAP, 2018) and in several cities across Europe (Moreno, 2018).

The TSAQ HHRA addressed the overarching study questions and assessed the potential health risks from exposure to particulate for the ridership of Toronto's subway system. The HIA assessed the overall impact of subway use on the health and well-being of Torontonians. The following are the conclusions based on the three overarching study questions posed.

1. ***What is the potential health risk to current passengers from air pollutants in the subway system?***

The results of the TSAQ HHRA indicate that concentrations of $PM_{2.5}$ are elevated throughout Toronto's subway system. The mean $PM_{2.5}$ concentrations on Toronto subway platforms recorded during weekday peak hours (when ridership is at its greatest) on Line 2 (385 $\mu g/m^3$) are 2.3 times greater than on Line 1 (165 $\mu g/m^3$). In comparison, the annual average ambient $PM_{2.5}$ concentration in Toronto's outdoor environment has been recorded to range from 7.5 $\mu g/m^3$ at the NAPS stations to 10.5 $\mu g/m^3$ from the SAQI monitoring campaign.

Long-term exposure to subway air quality marginally increases an individual's overall annual exposure to $PM_{2.5}$. Short-term exposures to subway air quality, particularly on Line 2, may on occasion, result in transient (i.e., short-lived; passing; not permanent) respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, general asthmatic symptoms) and/or a temporary decline in lung function for children and adults with asthma, adults with COPD, and perhaps even healthy adults.

Given the results of the TSAQ HHRA, the lack of studies assessing the human health effects of subway particulate exposure, and the strong link between adverse health effects and exposure to ambient particulate matter, it is reasonable to conclude that health risks associated with exposure to Toronto's subway air quality are likely elevated. Similar conclusions have been reached for the London Underground (COMEAP, 2019) and the Metro red line (subway) in Los Angeles (Lovett et al., 2017).

Overall, the results of the TSAQ HHRA indicate that the levels of $PM_{2.5}$ are high enough to warrant mitigation, particularly on Line 2. Any reduction in $PM_{2.5}$ concentrations would also lower concentrations of associated metals.

2. ***What are the potential health benefits to mitigation measures that could be implemented to improve air quality in the TTC subway system?***

Fine particulate matter is a non-threshold contaminant. The available research has indicated that although the composition of subway $PM_{2.5}$ is different than that found in an ambient urban environment, its health effects could be similar. The Canadian Council of Ministers of Environment (CCME) set Canadian ambient air quality standards (CAAQS) for $PM_{2.5}$ that seek to lower the concentrations based on a continuous

improvement approach. In other words, any decrease in $PM_{2.5}$ exposure would result in better health outcomes for those exposed.

Similarly, the results of the TSAQ HHRA cannot provide a specific target of $PM_{2.5}$ to achieve negligible health risk. Rather, it is clear that Line 2 $PM_{2.5}$ concentrations are the highest and efforts should be made to lower them. Similarly Line 1 concentrations are also elevated and continuous improvement to lower them should be made. Any decrease in $PM_{2.5}$ concentrations within Toronto's subway, would also improve any potential health risk that the associated metals may pose to subway ridership.

3. What is the overall impact of the TTC's subway system on the health and well-being of Torontonians?

Recognizing the air quality issues, the HIA assessment of the other environmental and social determinants of health concludes that there is a range of health benefits that result from subway use. It provides a safer alternative to driving, reduces outdoor air pollution and greenhouse gases, promotes physical activity and provides better access to employment, education and social/community services.

Each individual reacts differently to air pollution. Children, seniors and those with heart or lung disease are most sensitive to the adverse health effects of air pollution. In addition to system-wide improvements, concerned individuals should self-monitor to determine whether being in the subway is causing them breathing challenges and decide what mode of transportation best meets their needs.

Torontonians should consider all of these factors when they are making their transit choices.

12 RECOMMENDATIONS

Overall, improving access to the subway system provides a number of positive health benefits to its users. The City of Toronto should continue to encourage the use of the subway, especially as an alternative to personal vehicles, and seek to expand public transit and improve access for all Torontonians.

It is important that the TTC commit to implementing a particulate matter reduction strategy that includes both short and long term measures to improve air quality in the subway. To reduce the uncertainty in the HHRA it would be beneficial to determine the form of the chromium in $PM_{2.5}$.

At this time there is a limited amount of research that has been done that suggests these effects may not be clinically significant (does not actually change lung function or result in breathing problems) (Loxham and Niewenhuijsen, 2019). Although these preliminary findings are encouraging, this work is in its infancy and may not have captured concentrations of particulate as high as that found in the Toronto subway systems. Therefore, further personal exposure research is needed to reduce the uncertainties identified in the HHRA and to better understand the potential health

impacts to Toronto subway users. In addition, TPH is encouraged to monitor the scientific literature in this field and continue collaborating with other health authorities, such as COMEAP, to determine how new research findings can be applied to Toronto's subway system.

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Appendix A

Expert Panel Workshop Report

Toronto Subway Air Quality Health Impact Assessment (TSAQ HIA) Expert Panel Workshop Report:

Methods for evaluating subway air quality exposure and non-occupational health risk

Prepared for:

Toronto Public Health
City of Toronto

June 28, 2019

WOLF
Environmental Science

OLLSON
Environmental Health Management

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1 Introduction

The Urban Transportation Exposure Study (UTES) is a Health Canada led study that examined air pollution exposures in major transportation modes (private vehicles, subway systems, and buses) in Canadian cities, including Toronto. In 2017, findings were published from this study on air pollution exposure in subway systems. One of the findings from UTES was that fine particulate matter ($PM_{2.5}$) concentrations in the Toronto subway system were an order of magnitude greater than $PM_{2.5}$ concentrations observed in a typical outdoor urban environment. The study estimated that a typical commute in the Toronto subway each day would contribute 21% to a person's overall daily exposure to $PM_{2.5}$. Another important finding of this work is that the chemical composition of the subway PM is quite different than PM in typical urban areas.

Elevated concentrations of $PM_{2.5}$ and coarse particulate matter ($PM_{2.5-10}$) have been reported in many subway systems around the world. There are many potential sources of $PM_{2.5}$, including, but not limited to, the friction generated between the brakes and the wheels; friction between the wheels and the rail; and dust generated from routine track maintenance. The composition of $PM_{2.5}$ samples taken from within the Toronto subway system was found to be enriched with a variety of metals (e.g., iron, maganese, chromium, copper, and barium). Although there are a significant number of studies that have measured PM concentrations (and associated metals) within different subway systems, globally there are a limited number of studies that have evaluated the potential human health implications of this exposure for passengers who routinely take the subway system.

In 2018, the Toronto Board of Health requested that Toronto Public Health (TPH) work with the Toronto Transit Commission (TTC) to oversee an independent study to understand the potential health impacts that may result for subway users from exposure to air pollution found in the Toronto subway system[1]. As described in a subsequent report to the TTC Board[2], the Toronto Subway Air Quality Health Impact Assessment will use human health risk assessment (HHRA) and health impact assessment (HIA) approaches that are well established and commonly used in the environmental health field. The TTC Board directed the TTC undertake a separate occupational exposure study and, therefore, occupational exposures will not be considered in the current study.

Health Canada (the Subway Air Quality Initiative (SAQI)) and the TTC collected air samples throughout 2017/18 to explore the impacts of potential interventions that the TTC could implement to reduce passenger exposure. The data includes concentrations of $PM_{2.5}$, PM_{10}, and various metals. These data will be available and used to inform the Toronto Subway Air Quality Health Impact Assessment (TSAQ HIA 'The Study') to answer three (3) overarching questions:

1. What is the potential health risk to current passengers from air pollutants in the subway system?
2. What are the potential health benefits to mitigation measures that could be implemented to improve air quality in the TTC subway system?
3. What is the overall impact of the TTC's subway system on the health and wellness of Torontonians?

Dr. Christopher Ollson of Ollson Environmental Health Management (OEHM) and Mr. Christopher Bacigalupo of Wolf Environmental Science Ltd. (the consultants) have been contracted to undertake the Study in collaboration with TPH. Given that this study is the first of its kind, in order to ensure that: the novel aspects are thoughtfully considered, the analytical approach used is defensible, and any limitations are well-understood, it included convening an Expert Panel to provide insight on methodological challenges and approaches that could be considered to overcome them. This report provides an overview of the Expert Panel workshop and the recommendations of the Panel to the consultants and to TPH.

[1] http://app.toronto.ca/tmmis/viewAgendaItemHistory.do?item=2017.HL19.15

[2] https://www.ttc.ca/About_the_TTC/Commission_reports_and_information/Commission_meetings/2017/September_5/Reports/13_Subway_Air_Quality.pdf

2 The Expert Panel

The Expert Panel was selected by TPH, with advice from their consultants, to ensure inclusion of a diversity of professional experience and technical expertise in areas including exposure assessment, toxicology, human health risk assessment, air quality assessment and health impacts, and environmental epidemiology. The vision for panel membership was seven experts, a consultant team expert, and an ad hoc TTC member, chaired by the external consultant. The TTC representative was unable to participate on the day of the workshop.

2.1 Expert Panel Membership

Potential panel members were contacted by phone and email to gauge their interest in participating in the panel in December, 2018. Formal invitations, signed by Gayle Bursey, Director of Health Public Policy at TPH, were sent via email to all invitees in January 2019. The following provides the list of Expert Panel members that accepted the undertaking (in alphabetical order).

Panel Chair

Christopher Ollson, PhD.: is a Senior Environmental Health Scientist with Ollson Environmental Health Management. He has over 20 years of experience in environmental health consulting, with a focus on air quality issues. He is the prime consultant to TPH for this undertaking.

Expert Panel Members

Christopher Bacigalupo, MSc, QEP, QP_{RA}:

Mr. Bacigalupo is the founder of Wolf Environmental Science Ltd. He is an experienced human health risk assessor with expertise in air quality risk assessment.

Donald Cole, MD, MSc, FRCPC:

Dr. Cole is an occupational and public health physician and Professor at the University of Toronto

Greg Evans, PhD, P.Eng. FCAE, FAAAS:

Dr. Evans is a Professor in the Department of Chemical Engineering and Applied Chemistry at University of Toronto. He is also the Director of the Southern Ontario Centre for Atmospheric Aerosol Research (SOCAAR). His research examines the source and composition of airborne particles, a key pollutant contributing to episodes of poor air quality in large cities.

Stephanie Gower, PhD:

Dr. Gower is the Manager (Acting) Healthy Cities and Assessment and Analysis, in the Healthy Public Policy directorate at Toronto Public Health.

Barry Jessiman, MSc:

Mr. Jessiman is the Head of the Air Quality Assessment Section of the Air Health Effects Division of Health Canada.

Lindsay McCallum, PhD:

Dr. McCallum is a Senior Project Manager in the Healthy Public Policy directorate of Toronto Public Health.

Elaina MacIntyre, PhD:

Dr. MacIntyre is an Epidemiologist Specialist on the Environmental and Occupational Health team at Public Health Ontario.

Keith Van Ryswyk, MSc:

Mr. Van Ryswyk is an Air Pollution Exposure Researcher in the Healthy Environments and Consumer Safety Branch of Health Canada.

Dave Stieb, MD, MSc, FRCPC:

Dr. Stieb is a Public Health Physician and Epidemiologist in the Air Health Effects Division of Health Canada

2.2 Charge to the Expert Panel

The Expert Panel was asked to participate in a one-day workshop. A Terms of Reference was provided to the members (Appendix A) and the following was the charge to the Panel:

> *The panel will provide Toronto Public Health advice and guidance on novel, scientifically defensible approaches to evaluating subway air quality exposure and associated non-occupational health risks. It will also identify uncertainties and their associated methodological limitations with reporting the results of such work. The findings of the panel will be incorporated into the human health risk assessment and the health impact assessment.*

While those invited to attend were already experts in their respective fields, a common list of suggested references and reading materials was provided to the Expert Panel prior to the workshop. Topics included: measurements of particulate in subway systems around the world, the limited body of work on risk assessment for such systems, and some information on the toxicology/epidemiology of ambient particulate matter (Appendix B). No additional reference material was suggested by any of the Expert Panel members prior to the workshop.

2.3 Commitment of the Expert Panel

The following were the commitments that were requested of the Expert Panel.

1-day working meeting:

The Expert Panel convened for a one-day workshop. TPH emphasized that this panel was not being convened to do extensive research or undertake the work itself. Rather, each of the members was asked to provide their knowledge and thoughts in response to targeted questions at the one-day workshop. This input will be used to inform the study.

Review of workshop findings:

Each of the panel members was provided with this summary report of the workshop findings. All members were asked to review the report to ensure that it accurately reflected the discussion at the workshop and the Expert Panel's recommendations. The final HHRA/HIA will incorporate the findings of the Expert Panel, but members will not be asked to conduct a review of the HHRA/HIA reports prior to their finalization.

Acknowledgement:

The contribution of the Expert Panel members will be acknowledged in the HIA/HHRA reports. It is anticipated that each member and their affiliation will be listed. However, it will be up to individual members to consent to this approach.

Confidentiality and Conflict of Interest Obligations Form

Each of the Panel members signed a confidentiality and declaration of conflict of interest obligations form prior to the one-day workshop.

3 Expert Panel Workshop

The Expert Panel Workshop was held on March 26, 2019 at Toronto Public Health office at 277 Victoria Street in Toronto. Table 1 provides the agenda for the meeting.

Table 1 Expert Panel Workshop Agenda

Time	Topic	Lead
9:00	Introductions	S. Gower
9:10	Review of Charge to the Panel and Comment by Panel Members	C. Ollson
9:30	Health Canada Review of Data Collection	K.Van Ryswyk
10:15`	TTC Review of Data Collection	C. Bacigalupo
10:45	Break	
11:00	**Hazard Assessment** – Appropriate Toxicity Reference Values (TRV) for Particulate Matter and Metals	C. Ollson
12:30	Lunch	
1:00	**Exposure Assessment Topics** (e.g., time activity patterns, acute/chronic, inclusion of background/ambient exposures, on/off train exposures, etc.)	C. Ollson
2:15	Break	
2:30	**Risk Characterization Topics** – combing exposure data with the appropriate corresponding TRVs (e.g., looking at the form of the PM TRVs, assessment of metals, averaging times, etc.)	C. Bacigalupo
3:30	Discussion of Uncertainties and Study Limitations	C. Ollson
4:00	Parking Lot Issues and Summary of Way Forward	C. Ollson
4:30	Closing	S. Gower

3.1 Summary of Information Presented

The meeting was chaired by Dr. Ollson, with assistance and record keeping by Mr. Bacigalupo and Dr. McCallum. Overall, the meeting was run according to the agenda with the only divergence being towards the additional topics of potential mitigation measures and discussion of the HIA. All members were present during the workshop. Dr. Stieb joined via WEBEX at 11:00 and Dr. Evans left at the lunch break. Dr. Evans was further consulted on the remaining topics he missed on April 12, 2019 at his office at the University of Toronto.

Mr. Van Ryswyk provided an overview of the research that has been conducted by Health Canada over the past decade on the Toronto subway. The UTES data collection began in 2010 and involved the

collection of $PM_{2.5}$ and associated metal speciation on Toronto's subway platforms and trains (researchers using personal monitors). This sampling was system-wide over both above and below grade portions of the system. Elevated concentrations of $PM_{2.5}$ (compared to ambient air levels) on both the platforms and on-trains were documented. The subway $PM_{2.5}$ was comprised largely of metals (>50% iron, aluminum, barium, chromium, copper, manganese, molybdenum, and nickel) and is different than the composition of ambient outdoor $PM_{2.5}$ in Toronto, which is largely comprised of sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water (Van Ryswyk, 2017). In addition, Mr. Van Ryswyk also provided preliminary results of the Subway Air Quality Initiative (SAQI) sampling from 2017 – 2018. This was largely on-platform data focusing on ~30 below-grade sections of the system as well as a small subset of data collected using personal monitors while on the trains. This data has been provided to the consultants and TPH for use in their analysis. The analysis of gravimetric sampling from this study revealed PM2.5 to be comprised on approximately 80% iron, 2-5% barium, silica, calcium and other elements. In all, ~92% of the PM mass has been accounted for by ~30 elements.

The Health Canada SAQI dataset (from 2017-2018) was compared to levels measured in UTES in 2010-11. $PM_{2.5}$ data for peak hours for the 31 stations monitored in SAQI were available for this comparison. Two changes between 2011 and 2018 were noted. First, the $PM_{2.5}$ levels between Line 1 and Line 2 have significantly diverged from one another. Whereas, in UTES they were found to be equal in $PM_{2.5}$, SAQI reveals statistically significant lower concentrations of $PM_{2.5}$ on the Yonge-University-Spadina Line (YUS – Line 1) relative to the Bloor-Danforth Line (BD – Line 2). This may be linked to a change in rolling stock that occurred on Line 1 during the intervening years, from older T1 trains to newer Rocket trains.

Mr. Bacigalupo then presented a brief overview of the TTC occupational subway air quality assessment that was completed in 2018 (TTC data). The purpose of the study was to provide current-day air quality information concerning the underground portions of the TTC subway system and to determine employee (or occupational) exposures to various airborne contaminants during a regular work shift. It was determined that "None of the 40 sample sets collected to date exceeded the Occupational Exposure Limits (OELs) specified in Reg. 833. Based on the interim sampling results, the subway air quality is not expected to affect the health of employees in work positions assessed who do not have pre-existing serious respiratory conditions." Notably, the OEL for particulate matter in Reg. 833 is different than the size fractions and limits typically used for general public exposure.

Although the data collected by the TTC was focused on occupational exposure, a subset of the data could be used in the present human health risk assessment to estimate ridership exposure. For example, Mr. Bacigalupo indicated that it might be possible to use the platform data or the on-train data for those TTC occupations that involved personal monitors in the TTC Study. The data collected by the TTC has been provided to the consultants and TPH for use in their analysis.

The remainder of the workshop then focused on three topics that TPH identified as priorities for input from the Expert Panel: Hazard Assessment, Exposure Assessment and Risk Characterization. The moderated discussion opened with the detailed questions previously posed to the panel in their Terms of Reference (Appendix A). The floor was opened to allow each of the Expert Panel members to raise issues or provide viewpoints for each of the topics. These were captured by the TSAQ HIA study team and at the end of each session Dr. Ollson summarized the key recommendations of the panel (see below).

Upon completion of the discussion of the three priority topics, the panel requested further discussion about how the findings of the human health risk assessment could inform consideration of potential mitigation measures and the HIA. The Expert Panel's recommendations on these topics are also captured in the following sections.

Prior to the close of the meeting, the Chair reviewed a series of slides that were believed to have captured the Expert Panel's recommendations. Through this discussion additional recommendations were added and others were clarified. The Panel was reminded that they would have the opportunity to review and comment on the Expert Panel report prior to its finalization to ensure that all recommendations were accurately captured. The meeting ended at approximately 4:30 pm.

4 Expert Panel Questions and Recommendations

The following section provides the questions that were asked of the Expert Panel and their resulting recommendations. The Chair felt that all recommendations were either reached through consensus, or in some cases individuals on the Panel identified that a particular topic was beyond the scope of their expertise and did not comment on the topic. There was no area where a dissenting or alternative opinion was expressed strongly by a panel member and no need for a dissenting opinion to be presented in this document.

The TSAQ HIA study team has reviewed all of the recommendations and believes that they can be incorporated into the HHRA/HIA.

4.1 Hazard Assessment

Hazard assessment is a process of determining whether exposures to a chemical can cause an increase in the incidence of an adverse health effect (e.g., cancer, birth defects). The hazard (or toxicity) assessment is rooted in a dose-response concept. The dose-response relationship describes '…the *likelihood and severity of adverse health effects (the response) are related to the amount and condition of exposure to an agent (the dose provided)*' (US EPA, 2012). In the case of an inhalation assessment, the same general principles apply for studies where exposure is to a chemical concentration in air, the 'dose-response relationship' is often referred to as a 'concentration-response' relationship (US EPA, 2012).

Question to the Expert Panel

The chemical composition (or speciation) of subway PM is different than that found in ambient air. Specifically, it contains elevated levels of some metals.

a. How are subway related health risks best assessed? By applying existing particulate inhalation reference concentrations (e.g., CAAQS or WHO) that were derived using epidemiological studies that examined the associations between ambient air pollution levels (including particulate matter) and corresponding rates of health effects? Are there other approaches that should be considered?

b. Are there subway-specific inhalation reference concentrations that could be considered to characterize related health risk to PM?

c. How does a potential lack of subway-specific epidemiological or toxicological benchmark concentrations limit the findings of a HHRA / HIA?

Expert Panel Recommendations

1. Health Canada and international health agencies agree that $PM_{2.5}$, regardless of its composition, is a non-threshold health hazard; meaning that exposure to any level of $PM_{2.5}$ poses some potential detriment to health.

2. The composition of Toronto Subway $PM_{2.5}$ in air is markedly different than that typically found in Toronto ambient air. However, there are no Canadian or international subway-specific $PM_{2.5}$ toxicity reference values (TRVs) or exposure guidelines that have been developed. In the absence of sufficient epidemiological or toxicity data, TPH should assume that subway $PM_{2.5}$ has a similar level of toxicity as ambient $PM_{2.5,}$ and should rely on the research underpinning the Canadian and international guidelines for $PM_{2.5}$ in ambient air.

3. The evaluation of the individual airborne subway metal concentrations should be undertaken quantitatively using internationally recognized inhalation reference concentrations (RfC, threshold contaminants) and inhalation unit risk value (IUR values, non-threshold contaminants), where available. TRVs should be sourced from the following agencies: United States Environmental Protection Agency (US EPA), Health Canada, World Health Organization and California EPA. [Subsequent to the Panel discussion TPH identified that a considerable amount of work was completed to identify appropriate inhalation TRVs on another TPH air quality project. Where there are common contaminants between the two studies, the previously approved TPH TRV values will be selected first.]

4.2 Exposure Assessment

The exposure assessment is, at its very basic, a process of measuring or estimating the magnitude, frequency, and duration of human exposures to a chemical present in the surrounding environment, or estimating future human exposures to a chemical that has not yet been released (US, EPA, 2012). This project is focused on the existing scenario of the current subway system.

Question to the Expert Panel

Torontonians have different time activity patterns of subway usage depending on how they use the system. Regardless, only a portion of a subway user's day is spent in the subway while the remaining time is spent above ground.

a. Exposure patterns (i.e., duration and frequency) are unique in that exposure is most likely to occur (at least in the case of a daily transit user) over a series of short-term but repetitive events. Considering this and the availability of established particulate inhalation reference concentrations, how does one best characterize subway related exposures (e.g., acute versus chronic)?

b. Should subway related exposure be evaluated cumulatively with ambient air exposure?

Expert Panel Recommendations

Chemical Data

1. There have been changes made to the subway system since the collection of the UTES data in 2010 that may have improved air quality in some trains and stations. Thus the UTES data better describes past exposure while the SAQI 2017-18 data and the TTC 2017-2018 on-train occupational data better describe current exposure. Preference should be given to use of the SAQI 2017-18 data and the TTC 2017-2018 on-train occupational data to assess current exposure. This will require appropriate statistical analysis to ensure that like datasets will be used in the HHRA. It may be possible to use the limited personal exposure monitoring data collected under the SAQI program, if it is found that the TTC data cannot be used. If the existing results are found to be insufficient to assess exposure to the desired level of confidence, then additional supporting measurements may be suggested.
2. A distribution, or range, of $PM_{2.5}$ and metal concentrations that reflect chemical exposure estimates should be used in the HHRA. This would incorporate the platform, on-train and even the time of day that a person is using the subway.

Human Exposure Characteristics

3. Three ridership exposure scenarios should be evaluated: Line 1, Line 2 and the Overall System. The study should include a distribution of ridership times from those who spend only a short period of time (e.g., one to two stops) to those riding the full length of each Line.
4. The ridership of the subway includes all age groups, and thus consideration should be given to all segments of the ridership population (e.g., children, seniors).
5. Given that the response to $PM_{2.5}$ exposure can be heightened for those with certain pre-existing health conditions (e.g., asthmatic children) consideration should be afforded to these vulnerable populations.
6. Although daily rail commuter data suggests an average one-way trip takes approximately 34 minutes for the typical Canadian (Canadian Human Activity Pattern Survey), it would be preferable to use a distribution of actual ridership times for each of the two subway lines, if the information is available from the TTC. Toronto commuter data from the 2016 Canadian Census should be used in the absence of TTC-specific data. In addition, the use of time weighting to apportion the time spent in each microenvironment (on platform and on-train) and ambient air

exposure should be included in an effort to capture the overall daily exposures of the range of subway users.

7. Ideally, discussions should occur with the TTC to understand planned operational alterations, or capital investments, to the system that could influence future pollution levels in the subway.
8. Exposure estimates should reflect both daily acute exposure (exposure per ride) and chronic exposures (exposure over lifetime of commuting).

4.3 Risk Characterization

Risk characterization pulls together the results of exposure and hazard assessments to provide estimation as to the nature and presence or absence of risks, while also providing the necessary information as to how risk was assessed (US EPA, 2012).

Question to the Expert Panel

Appropriately matching exposure and toxicity data is critical to characterizing potential health impacts. In order to examine potential human health impacts, exposure point concentrations (EPCs) for PM and associated metals of interest will need to be characterized, such that EPCs can be compared against established inhalation reference concentrations of the same averaging time (e.g., 24-hour versus annual average) and statistical form.

> In the case of particulate matter, there are inhalation toxicity reference values, such as the Canadian Ambient Air Quality Standards (CAAQS) published by the Canadian Council of Ministries of the Environment (CCME) and the National Ambient Air Quality Standards (NAAQS) published by the United States Environmental Protection Agency (US EPA) that were designed to be used in conjunction with ambient air quality data collected over a series of several years. For example, a metric of the CCME (2012) 24-hour CAAQS value for $PM_{2.5}$ (of 27 µg/m^3 by 2020) is a 3-year average of the annual 98th percentile of the daily 24-your average concentrations. Is it valid to apply inhalation toxicity reference values (of the nature described above) to air quality data collected from the subway system over the course of several weeks or months?

Expert Panel Recommendations

1. Given the unique nature of the subway $PM_{2.5}$ composition and that Canadian air quality objectives are airshed management objectives, it is inappropriate to attempt to quantify potential health impacts using a single benchmark or ambient air quality guideline. Therefore, the use of specific ambient air $PM_{2.5}$ guidelines would provide a false sense of accuracy or confidence in the risk assessment. A qualitative discussion of ranges of $PM_{2.5}$ effect levels, especially on vulnerable populations with pre-existing conditions, should be provided. This should also include relative ranges found in the subway system, apportionment to total exposure (including ambient), and other similar levels.
2. Where metals elicit the same critical health effect or have a similar toxicological mode of action, the resulting risks should be considered additive.
3. A range of potential health risk estimates for both the carcinogens and non-carcinogens should be presented if the exposure data is readily available.

4.4 Mitigation Measures

Throughout the course of the workshop, Panel members raised considerations surrounding potential mitigation measures to reduce the concentrations of PM in the subway and how they should be considered in the HHRA/HIA. While these issues were not the focus of the charge to the Expert Panel they are recorded below for consideration. The following considerations were discussed and stated by one or more of the Expert Panel members:

1. As $PM_{2.5}$ is a non-threshold pollutant, any reduction in $PM_{2.5}$ levels in the subway would be beneficial to the health of the ridership.

TPH would benefit from working closely with the TTC to identify how potential mitigation measures could result in measurable changes to $PM_{2.5}$ in the subway.

2. The sources and removal mechanisms for PM in the subway need to be better understood in order for the potential benefits of candidate mitigation strategies to be assessed, for both current operations, and as the subway system and operations change over time.
3. Feasibility is an important factor when considering mitigation measures and it is possible that an outcome of the study could be to recommend that a prospective cost-benefit analysis be conducted to evaluate various reduction strategies.

4.5 Health Impact Assessment

Although not a specific focus of the workshop, there was discussion of the HIA. The following considerations were discussed and stated by one or more of the Expert Panel members:

1. Risk communication and presentation of the findings within an appropriate context will be critical for this undertaking.
2. Consideration should be given to comparing and contrasting relative health benefits and concerns to that of other forms of transportation.
3. Methodology could be identified for estimating the potential health benefits achievable through candidate mitigation measures to support any cost-benefit analyses.
4. The HIA should focus on population (and sub-population) level health, specifically identifying potentially vulnerable groups that may be directly or indirectly affected, both positively and negatively, through the use of the subway system.
5. Throughout the report the proper acknowledgement of the uncertainties and limitations of the TSAQ HIA study should be well documented

.

5 Closure

We believe that the recommendations made the by Expert Panel can be incorporated into the upcoming HHRA/HIA. We appreciate all of the valuable input and expertise provided by each of the Expert Panel members.

Sincerely,

OLLSON ENVIRONMENTAL HEALTH MANAGEMENT **WOLF ENVIRONMENTAL SCIENCE LTD.**

Christopher Ollson, Ph.D.
Senior Environmental Health Scientist

Christopher Bacigalupo, M.Sc., QEP
Principal

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Appendix A
Expert Panel Terms of Reference

Terms of Reference

Toronto Subway Air Quality Health Impact Assessment - Expert Panel

Background

The Urban Transportation Exposure Study (UTES) is a Health Canada led study that examined air pollution exposures in major transportation modes (private vehicles, subway systems, and buses) in Canadian cities. In 2017, findings were published from this study on air pollution exposure in subway systems. One of the findings from UTES was that particulate matter (PM) concentrations in the Toronto subway system were several times greater than PM concentrations observed in a typical outdoor urban environment.

Elevated concentrations of fine particulate matter (PM2.5) and coarse particulate matter (PM2.5-10) have been reported in many subway systems around the world. There are many potential sources of PM2.5, including, but not limited to, the friction generated between the brakes and the wheels; friction between the wheels and the rail; and dust generated from routine track maintenance. The composition of PM2.5 samples taken from within the Toronto subway system was found to be enriched with a variety of metals, including but not limited to, iron, maganese, chromium, copper, and barium. Although there are a significant number of studies that have measured PM concentrations (and associated elements) from within different subway systems, globally there is a limited number of studies that have evaluated the potential human health implications for passengers who routinely take the subway system.

The Toronto Board of Health requested that Toronto Public Health (TPH) work with the Toronto Transit Commission (TTC) to understand the potential health impacts that may result for transit users from exposure to air pollution found in the subway system. As described in a subsequent report to the TTC Board, the Toronto Subway Air Quality Health Impact Assessment will use human health risk assessment (HHRA) and health impact assessment (HIA) approaches, which are well established and commonly used in the environmental health field. The TTC is undertaking a separate occupational exposure study and, therefore, occupational exposures will not be considered in the current study.

Since UTES sampling was completed, the TTC has introduced new trains and improved onboard ventilation and filtration. These actions may have led to improved air quality inside the trains and on the subway platforms. To that end, Health Canada and the TTC have continued to collect air samples throughout 2017/18 to explore potential interventions that the TTC could implement to reduce passenger exposure. The data will include concentrations of PM2.5, PM10, various metals, black carbon, carbon monoxide and nitrogen oxides. These data will be available and used to inform the Toronto Subway Air Quality Health Impact Assessment in 2019.

Using these data, the study objective is to answer three (3) overarching questions:

1. What is the potential health risk to passengers from air pollutants in the subway system?
2. Is there a potential health benefit to mitigation measures that could be implemented to improve air quality in the TTC subway system?

3. What is the overall impact of the TTC's subway system on the health and wellness of Torontonians?

Dr. Christopher Ollson of Ollson Environmental Health Management (OEHM) and Mr. Christopher Bacigalupo of Wolf Environmental Science Ltd. have been contracted to undertake this project in collaboration with TPH.

Expert Panel

This study is the first of its kind. In order to ensure that the novel aspects are thoughtfully considered, the analytical approach used is defensible, and any limitations are well-understood, the study will include convening an Expert Panel to provide insight on three (3) main aspects of the methodology, including:

1. The chemical composition (or speciation) of subway PM is different than that found in ambient air. In particular, it contains elevated levels of some metals.
    a. How are subway related health risks best assessed? By applying existing particulate inhalation reference concentrations (e.g., CAAQS or WHO) that were derived using epidemiological studies that examined the associations between ambient air pollution levels (including particulate matter) and corresponding rates of health effects? Are there other approaches that should be considered?
    b. Are there subway-specific inhalation reference concentrations that could be considered to characterize related health risk to PM?
    c. How does a potential lack of subway-specific epidemiological or toxicological benchmark concentrations limit the findings of a HHRA / HIA?
2. Torontonians have different time activity patterns of subway usage depending on how they use the system. Regardless, only a portion of a transit user's day is spent in the subway while the remaining time spent above ground.
    a. The exposure patterns (i.e., duration and frequency) are unique in that exposure is most likely to occur (at least in the case of a daily transit user) over a series of short-term but repetitive events. Considering this and the availability of established particulate inhalation reference concentrations, how does one best characterize subway related exposures (e.g., acute versus chronic)?
    b. Should subway related exposure be evaluated cumulatively with ambient air exposure?
3. Appropriately matching exposure and toxicity data is critical to characterizing potential health impacts. In order to examine potential human health impacts, exposure point concentrations (EPCs) for PM and associated metals of interest will need to be characterized. Representative EPCs of PM, and associated metals, experienced by passengers on any given day will need to be characterized such that EPCs can be compared against established inhalation reference concentrations of the same averaging time (e.g., 24-hour versus annual average) and statistical form.
    a. In the case of particulate matter, there are inhalation toxicity reference values, such as the Canadian Ambient Air Quality Standards (CAAQS) published by the

Canadian Council of Ministries of the Environment (CCME) and the National Ambient Air Quality Standards (NAAQS) published by the United States Environmental Protection Agency (US EPA) that were designed to be used in conjunction with ambient air quality data collected over a series of several years. For example, metric of the CCME (2012) 24-hour CAAQS value for $PM_{2.5}$ (of 27 $\mu g/m^3$ by 2020) is a 3-year average of the annual 98^{th} percentile of the daily 24-your average concentrations. Is it valid to apply inhalation toxicity reference values (of the nature described above) to air quality data collected from the subway system over the course of several weeks or months?

The charge to the Expert Panel:

The panel will provide Toronto Public Health advice and guidance on novel, scientifically defensible approaches to evaluating subway air quality exposure and associated non-occupational health risks. It will also identify uncertainties and their associated methodological limitations with reporting the results of such work. The findings of the panel will be incorporated into the human health risk assessment and the health impact assessment.

Membership

There were a number of considerations in determining invitation to the Expert Panel, including diversity of professional experience, technical expertise, and financial constraints. The vision for panel membership was seven internal and external experts, a consultant team expert, an ad hoc TTC member, and a consultant chairperson. The following are the roles of panel members:

Chair: Dr. Christopher Ollson (consultant) will chair the Expert Panel. His role will be to provide neutral arbitration and guidance to the panel deliberations. He will not provide professional opinion on matters being discussed but will seek to achieve consensus on topics. He will author the panel report and capture any dissenting opinion where needed.

Expert Panel: Will be comprised of approximately 7 professionals in the fields of air quality, risk assessment, toxicology, air monitoring, epidemiology, public health and related fields. Panelist will have advance degrees and training in their respective fields and will be selected from Canadian academics, public servants or consultants. Although formal voting on issues is not anticipated, a majority consensus will be sought on topics of primary interest.

Consultant on Expert Panel: Mr. Chris Bacigalupo will be afforded full membership to the Expert Panel. He will contribute and have the same standing as the other Expert Panel members.

Ad hoc TTC Member: The TTC will elect one ad hoc member to the Expert Panel. The Member will be requested to provide technical and policy insight into panel discussions. Although their views will be heard they will not be afforded the same consensus seeking rights as Expert Panel members.

Commitment

1-day working meeting:

The Expert Panel will convene in late January (28 and 30) or early February 2019 (4, 11, 12) for a one-day working session. A package of relevant material will be provided in advance. One week prior to the session Dr. Ollson will contact each panel member with a brief phone call to focus the agenda. TPH wishes to emphasize that this panel is not being convened to do extensive research or undertake the work itself. Members are being asked to provide their knowledge and thoughts on a specific focus area at the one-day workshop that will be used to inform the study.

Review of workshop findings:

A summary of the workshop findings will be provided in a draft report to each of the members. It is anticipated that a two-hour follow-up conference call will be convened to review the report and discuss any outstanding items. The final HHRA/HIA will incorporate the findings of the Expert Panel, but members are not being asked to conduct a review of these reports prior to their release.

Acknowledgement:

The contribution of the Expert Panel members will be acknowledged in the Forward of the report. It is anticipated that each member and their affiliation will be listed. However, it will be up to individual members as to the acceptability of this approach.

Confidentiality and Conflict of Interest Obligations Form

Each of the Panel members will be asked to review and sign the attached confidentiality and declaration of conflict of interest obligations form.

Appendix B
Reference Material Provided to the Expert Panel

Papers Suggested for Review by All Panel Members

Xu, B., Hao, J. 2017. *Air quality inside subway metro indoor environment worldwide: A review* Environment International 107 (2017) 33–46

Van Ryswyk, K., Anastasopolos, A.T., Evans, G., Sun, L., Sabaliauskas, K., Kulka, R., Wallace, L., Weichenthal, S. 2017. *Metro Commuter Exposures to Particulate Air Pollution and PM2.5-Associated Elements in Three Canadian Cities: The Urban Transportation Exposure Study* Environ. Sci. Technol. 2017, 51, 5713−5720

Matz, C., Stieb, D.M., Davis, K., Egyed, M., Rose, A., Chou, B., Brion, O. 2014. *Effects of Age, Season, Gender and Urban-Rural Status on Time-Activity: Canadian Human Activity Pattern Survey 2 (CHAPS 2)* Int. J. Environ. Res. Public Health 2014, *11*, 2108-2124;

Additional Selected References

Chillrud, S.N., Epstein, D., Ross, J.M., Sax, S.N., Pederson, D., Spengler, J.D., Kinney, P.L. 2004. *Elevated Airborne Exposures of Teenagers to Manganese, Chromium, and Iron from Steel Dust and New York City's Subway System.* Environ Sci Technol . 2004 February 1; 38(3): 732–737.

Gerber, A., Bohn, J., Groneberg, D.A., Schulze, J. and Bundschuh, M. 2014 *Airborne particulate matter in public transport: a field study at major intersection points in Frankfurt am Main (Germany)* Journal of Occupational Medicine and Toxicology 2014, 9:13

Moreno, T., Reche, C., Rivas, I., Cruz Minguillón, M., Martins, V., Vargas, C., Buonanno, G., Parga, J., Pandolfi, M., Brines, M., Ealo, M., Fonseca, A., Amato, F., Sosa, G., Capdevila, M., deMiguel, E., Querol, X., Gibbons, W. 2015. *Urban air quality comparison for bus, tram, subway and pedestrian commutes in Barcelona.* Environmental Research142(2015)495–510

Strasser, G., Hiebaum, S., Neuberger, M. 2018. *Commuter exposure to fine and ultrafine particulate matter.* Vienna Wien Klin Wochenschr (2018) 130:62–69

World Health Organization. 2013. Health effects of particulate matter Policy implications for countries in eastern Europe, Caucasus and central Asia

Appendix B

Human Health Risk Assessment of Toronto Subway Air Quality

FINAL

Toronto Subway Air Quality Human Health Risk Assessment

Prepared for:

Toronto Public Health
City of Toronto

October 31, 2019

WOLF
Environmental Science

OLLSON
Environmental Health Management

Executive Summary

It is widely acknowledged that there are considerable positive health benefits to using public transit (James et al., 2014). However, the past decade has seen an increase in research focused on measuring airborne concentrations of particulate and associated contaminants in subway systems around the world (Xu and Hao, 2017). Collectively, these findings indicate that subway systems world-wide (i.e., North America, Europe, and Asia) have concentrations of fine particulate matter ($PM_{2.5}$) greater than outdoor urban air (Lovett et al., 2017, Moreno et al., 2017; Xu and Hao, 2017; Van Ryswk et al., 2017).

Although there are a significant nuber of studies that have measured $PM_{2.5}$ concentrations (and associated metals) within different subway systems around the world, there are a limited number of studies that have evaluated the potential human health implications of this exposure for passengers who routinely take the subway system (Loxham and Nieuwenhuijsen (2019); Xu and Hao, 2017).

In 2018, the Toronto Board of Health requested that Toronto Public Health (TPH) work with the Toronto Transit Commission (TTC) to oversee an independent study to understand the potential health impacts that may result for subway users from exposure to air pollution found in the Toronto subway system. The Toronto Subway Air Quality Health Impact Assessment (TSAQ HIA) used human health risk assessment (HHRA) and health impact assessment (HIA) approaches that are well established and commonly used in the environmental health field.

Health Canada and the United States Environmental Protection Agency (US EPA) define an HHRA as a process used to approximate the nature and likelihood (or probability) of adverse human health effects occurring among individuals who may be exposed to chemicals in the surrounding environment either now or in the future (US EPA, 2012; HC, 2010a). The TSAQ HHRA was conducted in accordance with accepted HHRA methods and guidance documents published by various regulatory agencies including Health Canada (2010a; 2010b; 2012), the Ontario Ministry of the Environment, Conservation and Parks (previously referred to as Ontario Ministry of the Environment and Climate Change (MOE, 2005a, 2011), the California Office of Environmental Health Hazard Assessment (Cal OEHHA), the Texas Commission on Environmental Quality (TCEQ), and guidance provided by the United States Environmental Protection Agency (US EPA, 2011, 2012).

Air quality data, including concentrations of $PM_{2.5}$ and associated metals collected from the Toronto subway system in 2018 by Health Canada (through a project called the Subway Air Quality Initiative (SAQI)) were used in by the TSAQ

HHRA to help characterize potential health risks of passengers from air pollutants in the Toronto subway system.

The results of the TSAQ HHRA indicate that concentrations of $PM_{2.5}$ are elevated throughout Toronto's subway system. The average $PM_{2.5}$ concentrations on Toronto subway platforms recorded during weekday peak hours (when ridership is at its greatest) on Line 2 (of 385 µg/m^3) are 2.3 times greater than on Line 1 (165 µg/m^3). In comparison, the ambient concentration of $PM_{2.5}$ in Toronto's outdoor environment is 7.5 µg/m^3.

Similar to other subway systems around the world that employ the use of a steel-wheel steel rail arrangement known to generate steel 'rail dust' through friction (Bukowiecki, et al., 2007), the airborne $PM_{2.5}$ is largely comprised of metals (e.g., iron, barium, chromium, cobalt, manganese, nickel, etc.). As such, the metal enriched $PM_{2.5}$ found in Toronto's subway differs greatly in composition from the $PM_{2.5}$ found in a typical ambient urban environment.

Loxham and Nieuwenhuijsen (2019) concluded that although the toxicological effects of subway particulate matter exposure may be different from the effects associated ambient $PM_{2.5}$ (likely due to the unique characteristics of subway $PM_{2.5}$), it is not the case that subway $PM_{2.5}$ related effects are greater than the effects associated with ambient $PM_{2.5}$. Canadian and international guidelines for ambient $PM_{2.5}$ are predicated on the fact that particulate matter is a non-threshold contaminant, meaning there is no level below which adverse health effects are not expected to occur (WHO, 2006a; HC, 2013). Therefore, the HHRA assumed that the subway $PM_{2.5}$ was similar in toxicity as ambient particulate matter and as such, used the WHO (2006a) annual (chronic) and daily (acute) health-based benchmarks to place subway particulate matter concentrations into context.

Overall, the results of the TSAQ HHRA indicate that the levels of $PM_{2.5}$ (and by association, a number of metals) are high enough to warrant remedial action, particularly on Line 2. Any reduction in $PM_{2.5}$ platform concentrations would also lower concentrations of associated metals. Long-term (or chronic) exposure to subway air quality increases an individual's overall annual exposure to $PM_{2.5}$ by approximately 13 to 45% on Line2 and 3 to 21% on Line 1.

Incremental lifetime cancer risk (ILCR) estimates as a result of long-term (or chronic) exposure to arsenic, cadmium, and hexavalent chromium in subway $PM_{2.5}$ exceeded an ILCR level of 1-in-1,000,000, considered by Toronto Public Health (TPH) and the Ontario Ministry of the Environment, Conservation, and Parks (MECP) as an 'acceptable' or de minimis level of incremental lifetime risk. With the exception of hexavalent chromium, which is associated with a high

degree of uncertainty due to the lack of speciation data, all ILCR estimates for individual metals were either below or within the range of risks considered by Health Canada, as essentially negligible (i.e., 1-in-1,000,000 to 1-in-100,000).

Short-term (or acute) exposure to subway air quality, particularly on Line 2, may on occasion, result in transient (i.e., short-lived; passing; not permanent) respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, general asthmatic symptoms) and/or a reversible decline in lung function for children and adults with asthma, adults with COPD, and perhaps even healthy adults.

Given the results of the TSAQ HHRA, the lack of studies evaluating the human health effects of subway particulate exposure, and the causal relationship between many adverse health outcomes and exposure to fine particulate matter under ambient conditions, it is reasonable to conclude, despite the uncertainty that exists, that health risk estimates associated with exposure to Toronto's subway air quality, particularly on Line 2, are elevated. Similar conclusions have been reached for the London Underground (COMEAP, 2018) and the Metro red line (subway) in Los Angeles (Lovett et al., 2017)

Although the limited research in the field suggests these effects may not be clinically significant, further research should be undertaken to reduce the uncertainties identified in the HHRA and to better understand the potential health impacts of Toronto subway users.

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Abbreviations and Acronyms

Acronym	Explanation
AAQC	Ambient Air Quality Criteria
ACGIH	American Conference of Governmental Industrial Hygienists
ACS	American Cancer Study
AR	Abundance Ratio
ATSDR	The Agency for Toxic Substances and Disease Registry
CAAQS	Canadian Ambient Air Quality Standard
CCME	Canadian Council of Ministers of the Environment
COPC	Chemical of Potential Concern
Cr(VI)	Hexavalent Chromium
DSD	Decision Support Document
ESL	Effects Screening Level
HC	Health Canada
HIA	Health Impact Assessment
HHRA	Human Health Risk Assessment
HQ	Hazard Quotient
ILCR	Incremental Lifetime Cancer Risk
IRIS	Integrated Risk Information System
Line 1	Toronto Subway System Line 1 – Yonge-University Line
Line 2	Toronto Subway System Line 2 – Bloor-Danforth Line
LOAEL	Lowest Observed Adverse Effect Level
MECP	Ontario Ministry of the Environment, Conservation and Parks
NOAEL	No Observed Adverse Effect Level
OEHHA	California Office of Environmental Health Hazard Assessment
$PM_{2.5}$	Fine Particulate Matter
REL	Recommended Exposure Limit
ReV	Reference Value
RfC	Reference Concentration
RSL	Regional Screening Level
SAQI	Subway Air Quality Initiative
TC/TC_{05}	Tolerable Concentration / Tumorigenic Concentration
TCEQ	Texas Commission of Environmental Quality
TLV	Threshold Limit Value
TSAQ	Toronto Subway Air Quality
TTC	Toronto Transit Commission
URF	Unit Risk Factor
US EPA	United States Environmental Protection Agency
UTES	Urban Transport Exposure Study
WHO	World Health Organization
µg	Microgram
95% UCLM	95% upper confidence limit on arithmetic mean

1.0 Introduction

It is widely acknowledged that there are considerable positive health benefits to using public transit (James et al., 2014). However, the past decade has seen an increase in research focused on measuring airborne concentrations of particulate and associated contaminants in subway systems around the world (Xu and Hao, 2017). Collectively, these findings indicate that subway systems world-wide (i.e., North America, Europe, and Asia) have concentrations of fine particulate matter ($PM_{2.5}$) greater than outdoor urban air (Lovett et al., 2017, Moreno et al., 2017; Xu and Hao, 2017; Van Ryswk et al., 2017).

Although there are a significant number of studies that have measured $PM_{2.5}$ concentrations (and associated metals) within different subway systems around the world, there are a limited number of studies that have evaluated the potential human health implications of this exposure for passengers who routinely take the subway system (Loxham and Nieuwenhuijsen (2019); Xu and Hao, 2017). Therefore, there is a need to investigate if exposure to these elevated concentrations of $PM_{2.5}$ and associated metals in Toronto's subway system may impact the health of riders. As such, the Toronto Board of Health requested that Toronto Public Health (TPH) work with the Toronto Transit Commission (TTC) to oversee an independent study to understand the potential health impacts that may result for subway users from exposure to air pollution found in the Toronto subway system.

The Urban Transportation Exposure Study (UTES) was a Health Canada led investigation that measured air pollution exposures across major transportation modes (private vehicles, subway systems, and buses) in Vancouver, Montreal and Toronto. In 2017, they reported the levels of air pollution exposure in the Toronto subway system (Van Ryswyk et al., 2017). Similar to other large city subway systems, UTES reported that fine particulate matter ($PM_{2.5}$) concentrations in the Toronto subway system were an order of magnitude greater than $PM_{2.5}$ concentrations observed in the City's ambient outdoor air environment. In addition, the composition of $PM_{2.5}$ samples taken from within the Toronto subway system was found to be different from outdoor $PM_{2.5}$ in that it is enriched with a variety of metals (Van Ryswyk et al., 2017).

Personal exposure to elevated concentrations of ambient $PM_{2.5}$ is a known health risk and may be associated with an increased rate of morbidity and mortality (HC, 2013; US EPA, 2009, 2010; WHO, 2006a). $PM_{2.5}$ has been classified by the World Health Organization (WHO, 2006a) and Health Canada (HC, 2013) as a non-threshold contaminant. This means that there is not a clear level of exposure to $PM_{2.5}$ below which there would be no impact on public health.

1.1.1 Scope and Objectives

In 2018, the Toronto Board of Health requested that Toronto Public Health (TPH) work with the Toronto Transit Commission (TTC) to oversee an independent study to understand the potential health impacts that may result for subway users from exposure to air pollution found in the Toronto subway system. As described in a subsequent report to the TTC Board, the Toronto Subway Air Quality Health Impact Assessment (TSAQ HIA) will use human health risk assessment (HHRA) and health impact assessment (HIA) approaches that are well established and commonly used in the environmental health field. The TTC Board directed the TTC to undertake a separate occupational exposure study (TTC, 2019). Therefore, occupational exposure was not considered in the TSAQ HIA.

Health Canada (through a project called the Subway Air Quality Initiative (SAQI)) and the TTC collected air samples throughout 2017/18 to gather data about current air quality in the Toronto subway system, and to explore the impacts of potential interventions that the TTC could implement to reduce passenger exposure to air pollution. The data includes concentrations of $PM_{2.5}$, PM_{10}, and various metals. These data were used in the HHRA to characterize the potential health risks to current passengers from air pollutants in the Toronto subway system.

2.0 General Human Health Risk Assessment Methodology

Human Health Risk Assessment (HHRA) is not an exact science. Health Canada and the United States Environmental Protection Agency (US EPA) define an HHRA as a process used to approximate the nature and likelihood (or probability) of adverse human health effects occurring among individuals who may be exposed to chemicals in the surrounding environment either now or in the future (US EPA, 2012; HC, 2010a).

More specifically, an HHRA evaluates the frequency and extent to which humans may be exposed to chemicals present in various environmental media (e.g., air, soil, water, food, etc.) through one or more exposure pathways (e.g., inhalation of air, direct dermal contact, ingestion of food or water, etc.). An estimate of human exposure to a specific chemical is then compared to information concerning its inherent toxicity. Toxicity information is typically expressed in the form of a chemical-specific toxicological reference value (TRV), published by regulatory agencies. By combining the results of the exposure evaluation with chemical-specific toxicity information, an HHRA can provide an approximation of the nature, magnitude, and probability of adverse human health effect(s) that may occur (US EPA, 2012).

In an ideal world, an HHRA would rely entirely on strong, complete, and reproducible data concerning the extent and nature of contamination, the environmental fate and transport processes, the frequency and extent of human exposure, and the toxicity of each chemical of interest. In practice, this type of information is often limited in at least one of these areas, resulting in the need for approximations, professional judgement, and assumptions during the development of an HHRA. As such, a certain level of uncertainty is inherently introduced into all human health risk estimates (US EPA, 2012). Presenting these uncertainties in a clear and transparent manner is an important component of any HHRA (US EPA, 2012; HC, 2010a).

Regulatory guidance concerning the methods, data, and assumptions used to conduct an HHRA can vary among provincial, national, and international regulatory agencies (HC, 2010a). The current HHRA was conducted in accordance with accepted HHRA methods and guidance documents published by various regulatory agencies including Health Canada (2010a; 2010b; 2012), the Ontario Ministry of the Environment, Conservation and Parks (previously referred to as Ontario Ministry of the Environment and Climate Change (MOE, 2005a, 2011), the California Office of Environmental Health Hazard Assessment (Cal OEHHA), the Texas Commission on Environmental Quality (TCEQ), and guidance provided by the United States Environmental Protection Agency (US EPA, 2011, 2012).

Although HHRA guidance can vary among different regulatory agencies, it is widely accepted that the HHRA framework typically consists of four (4) key components or steps — Problem Formulation, Exposure Assessment, Hazard (Toxicity) Assessment, and Risk Characterization (Figure 2-1). The HHRA framework is a well-established and accepted approach to examining the potential health risks from exposure to contaminants.

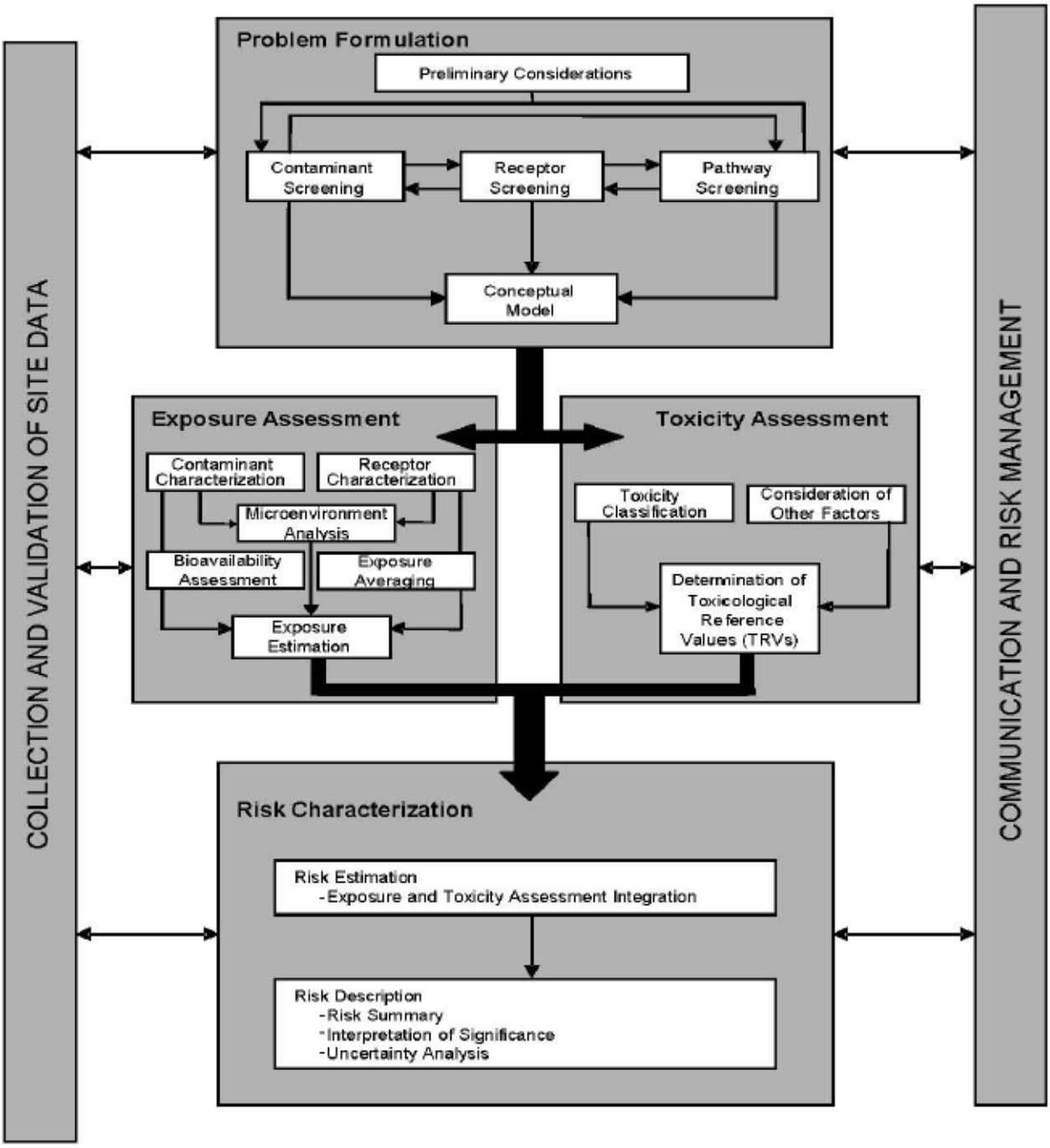


Figure 2-1 Risk Assessment Framework (HC, 2010a)

2.1 Risk Assessment Framework – Methodological Overview

2.1.1 Problem Formulation

The problem formulation (or planning/scoping step) is the first stage of an HHRA and involves the screening and identification of chemicals, exposure pathways, and receptors of interest (HC, 2010a). The objective of the problem formulation stage is to develop a conceptual model that clearly outlines the precise scope of the assessment by identifying the chemicals of potential concern (COPC), the human receptors of interest, and the identification of relevant exposure pathways (Figure 2-2). The goal of the problem formulation is to focus the HHRA on the contaminants, pathways, and receptors that have the greatest potential to contribute to human health risks (HC, 2010a).

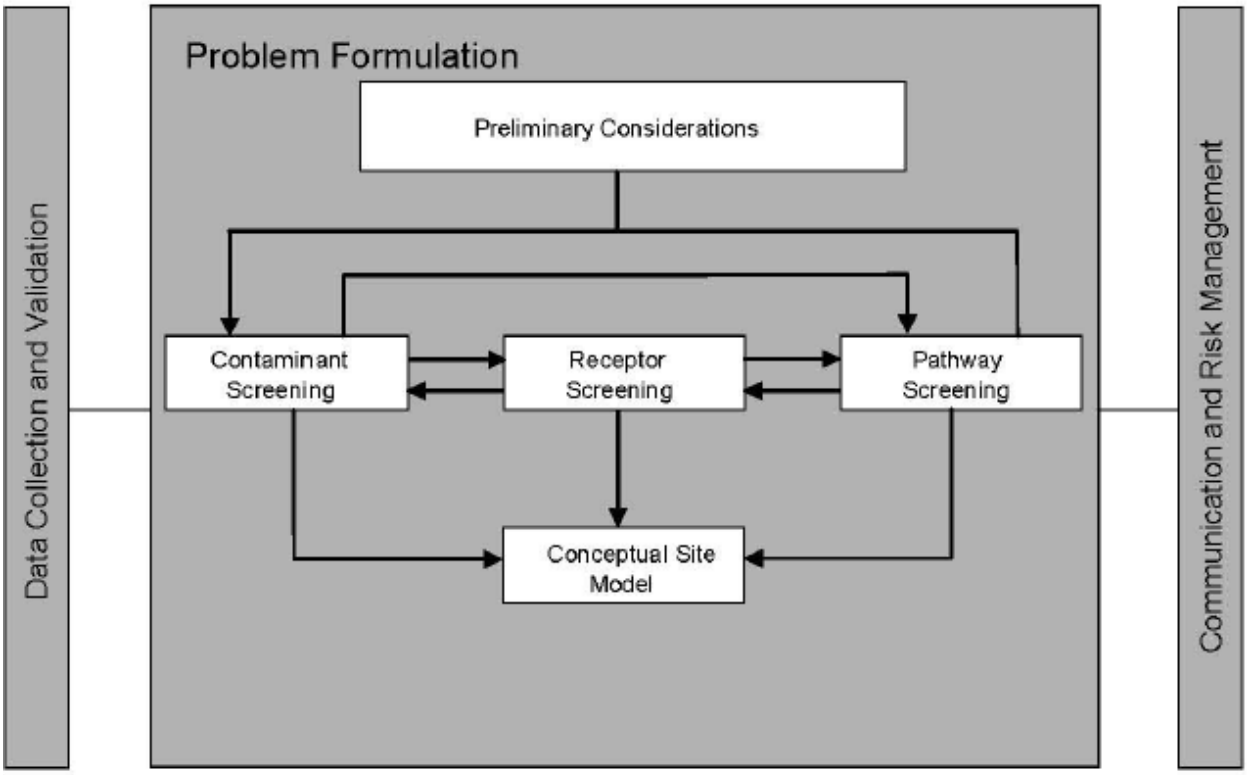


Figure 2-2 Problem Formulation (HC, 2010a)

Contaminant Screening

In situations where multiple chemicals exposure could occur, it is standard and accepted practice to identify and assess those chemicals that present the greatest potential for adverse human health effects. The identification of chemicals of potential concern (COPCs) is facilitated using a chemical screening and selection process, which involves the use of media-specific concentrations (e.g., chemical concentrations in air, soil, and/or water) and associated effects-based screening-level values and/or toxicity reference values (TRVs) published by regulatory agencies. A chemical's ability to impact human health is, in part, due to its environmental concentrations, its inherent toxicity, and the human receptors being exposed.

Receptor Screening

A receptor is a term that represents an individual who may come into contact, either directly or indirectly, with COPCs. It is important that the HHRA employ conservative, yet realistic, assumptions throughout the assessment to help ensure that exposure estimates (and the associated health risks) err on the side of caution (i.e., that they strive to over-predict potential risk, rather than under-predict). However, it is not practical to evaluate all receptors under all possible conditions and, therefore, it is important for the HHRA to identify those receptor groups with greatest susceptibility and likelihood of exposure. Receptor groups may include members of the general public, on-site residents, members of specific sub-populations such as Indigenous communities or other subpopulations with specific time/activity patterns and/or behavioural patterns relevant to the exposure scenarios of interest (HC, 2010a).

Exposure Pathway Screening and Identification

The objective of the exposure pathway identification process is to screen and identify those exposure pathways that involve the COPCs and receptors of interest previously identified (HC, 2010a). One or more of three exposure routes is often evaluated in an HHRA, including: inhalation; ingestion; and direct dermal contact. How an individual comes into contact with a COPC in their surrounding environment is often referred to as an exposure pathway, including the contaminant source, release mechanism, environmental transport, exposure point concentration, and the route of exposure (HC, 2010a).

Conceptual Model

The conceptual model summarizes the problem formulation, laying the foundation for the subsequent HHRA by summarizing the COPCs, receptors of

interest, and operable pathways and conditions under which exposure may occur. The conceptual model is often summarized using a descriptive diagram.

2.1.2 Exposure Assessment

The US EPA (2012) defines exposure as '…*contact between an agent and the visible exterior of a person (e.g., skin and opening into the body)*'. The exposure assessment is simply a process of measuring or estimating the magnitude, frequency, and duration of human exposure to COPCs present in the surrounding environment (HC, 2010a; US EPA, 2012).

It is often not practical to directly measure the exposure of humans to a COPC and, as such, exposure is often estimated indirectly using measurements of COPCs in various environmental media (e.g., air, soil, water, food, consumer products, etc.), the properties of COPCs that can influence their fate and transport in the environment, and estimates of human intake and time/activity patterns. When predicting exposures of humans to COPCs via the inhalation route, it is common practice to use either the measured or predicted air concentration of a COPC as a surrogate to represent exposure via direct inhalation.

There are two main components that make up an exposure assessment — chemical characterization (i.e., the development of an exposure point concentration) and receptor characterization.

Chemical Characterization

The first, and one of the most critical, requirements in quantifying human exposure is to develop chemical- and media-specific exposure point concentrations (EPCs). An EPC is a chemical concentration in a specific environmental medium (e.g., air, soil, water, etc.) that a receptor may come into contact with over a prolonged (or chronic) period of time (e.g., several months to years). The EPC can also represent the chemical concentration in a specific medium that a receptor may be subjected to over a short (or acute) time frame (e.g., an hour to several weeks). EPCs may be measured directly for the environmental media of interest (e.g., air, soil, water, food, etc.) or they may be predicted using mathematical models (HC, 2010a). The US EPA Risk Assessment Guidance for Superfund (US EPA, 1989) has recommended that the reasonable maximum EPC should be characterized using the 95% upper confidence interval on the arithmetic mean concentration (i.e., the 95% UCI). Health Canada (HC, 2010a) also prefers the use of the mean or 95% UCI, assuming adequate data exist, when conducting a detailed point-estimate exposure assessment.

Some individuals may experience greater exposures than others due, in part, where they live to their daily time/activity patterns, intake rates, etc. It is US EPA policy that exposure assessments consider a range of potential exposures. Typically, two common exposure scenarios are evaluated, including a 'Central Tendency' and a 'High End' scenario (US EPA, 2012). The 'Central Tendency' scenario represents the average exposure expected to occur by the affected population, using environmental media EPCs and the frequency and duration of exposure. The 'High End' exposure estimate is defined by the US EPA (2012) as the highest exposure estimated to occur among some individuals and approximates the 90th percentile exposure estimate.

Receptor Characterization

The second critical component in quantifying human exposure is characterizing a receptor's physical (e.g., body weight, breathing rate, water intake rate, food ingestion rate, etc.) and/or behavioural characteristics (e.g., time/activity patterns). The physical and behavioural characteristics of a receptor vary by age (i.e., infant, toddler, adolescent, adult) and can greatly influence the extent of exposure to COPCs (HC, 2010a). The exposure assessment should capture those receptor types that are most susceptible to COPCs due to having the greatest probability and extent of exposure to the COPCs (as identified in the problem formulation). There are some individuals within the general population that are more sensitive to COPCs than others. This type of susceptibility to developing adverse effects (i.e., heightened sensitivity to a COPC) is often addressed in the hazard or toxicity assessment (HC, 2010a). As such, in deterministic exposure assessments (i.e., assessments that use single point estimate values to characterize exposure parameters), the receptors identified as having the greatest probability of exposure are assigned slightly over-stated characteristics, ideally resulting in overestimating, rather than underestimating, exposure.

Health Canada (HC, 2010a) identifies five different age groups of receptors, all having different physical/behavioural characteristics that can, depending on the exposure pathway evaluated, influence the extent of exposure, including:

- Infant (0 to 6 months of age, inclusive);
- Toddler (7 months to 4 years of age, inclusive);
- Child (5 to 11 years of age, inclusive);
- Teen (12 to 19 years of age, inclusive); and
- Adult (20 to 80 years of age, inclusive.

In the case of inhalation exposure assessments that are strictly focused on exposure via direct air inhalation, it is common practice to use the measured or predicted air concentration as a surrogate for exposure. As discussed further in the risk characterization stage (Section 6.0), the requirement for inhalation rates and body weights of different receptor types is not needed when appropriate health-based inhalation reference concentrations (RfCs) and/or tolerable concentrations (TC) are available to characterize health risks.

2.1.3 Toxicity Assessment

The overall purpose of the toxicity assessment (sometimes referred to as a hazard assessment) is two-fold:

1. Identify the potential toxicological effects (e.g., birth defects, reproductive effects, cancer, etc.) associated with each COPC identified in the problem formulation stage; and,

2. Select, or if needed develop, a toxicity reference value (TRV) specific to each COPC that can be used with the exposure data to facilitate the risk characterization. TRVs may take the form of oral slope factors, oral reference doses (RfDs), RfCs, or inhalation unit risk (IUR) values (HC, 2010a).

Dose-Response Classification

The first step of the toxicity assessment involves classifying a COPC based on its mode of toxicological action. This step is founded in the dose-response relationship, which describes how '…*the likelihood and severity of adverse health effects (the response) are related to the amount and condition of exposure to an agent (the dose provided)*' (US EPA, 2012). The same general principles apply for an inhalation assessment, where exposure occurs via a chemical's concentration in air. The 'dose-response relationship' can often be referred to as a 'concentration-response' relationship (US EPA, 2012).

There are a number of ways in which COPCs can be classified (e.g., by their effect, the target organ, the mechanism of action, etc.), all of which are very informative. However, the type of dose-response relationship exhibited by a COPC (i.e., threshold versus non-threshold) is central to the toxicity assessment (HC, 2010a).

Threshold Dose-Response

A substance that has a non-linear dose-response relationship (Figure 2-3), whereby a maximum dose (or concentration) is identified to which a receptor can

be exposed without appreciable risk of adverse health effects, is often described as having a threshold dose-response relationship. For these substances, a specific dose (or concentration) can be established, below which adverse health effects are not expected to occur. This dose (or concentration) is often referred to as a No-Observed-Adverse-Effect-Level (NOAEL).

In deriving TRVs for substances with a threshold dose-response relationship, regulatory authorities routinely apply uncertainty factors (UF) (in the range of 10 to 1,000) to an established NOAEL in an effort to account for uncertainties in one or more of the following areas: a) the uncertainties associated with extrapolating toxicity test results from test species to humans (e.g., mice to humans); b) the uncertainties in responses within the general population (e.g., some individuals may be more susceptible than others); and c) the quality of the toxicological study or studies upon which the NOAEL was derived.

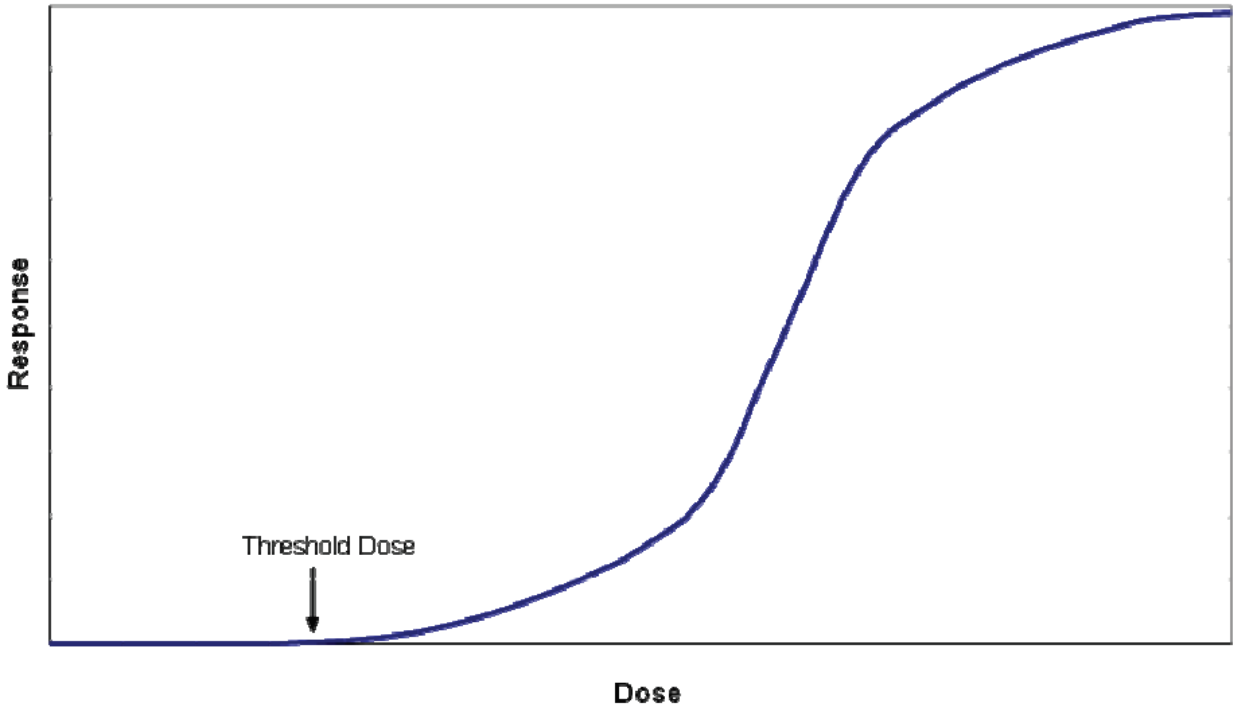


Figure 2-3 Threshold Dose-Response Relationship (HC, 2010a)

Non-Threshold Dose-Response

If the mode of toxicological action of a substance indicates that toxicity does not have a threshold, then a linear dose-response relationship is typically assumed (Figure 2-4). A linear dose-response relationship implies that, in theory, no level of exposure exists that does not result in the probability of generating a response (US EPA, 2012). Non-threshold chemicals are often associated with substances deemed to be genotoxic carcinogens. However, it is noted that non-threshold dose response relationships may exist for non-cancer health outcomes. This type of linear extrapolation does not employ uncertainty factors; rather, a straight line is taken from the point of departure (identified in the toxicological study) to the origin of the dose-response relationship (i.e., zero dose and zero response). The slope of the line (Figure 2-4) is often referred to as a cancer slope factor and is used to approximate the risk of exposure at various points along the slope of the line. In reality, there are many instances where toxicological data for non-threshold chemicals have identified a threshold (i.e., a NOAEL); however, toxicological bioassays and human epidemiological studies rarely, if ever, have the statistical power to detect or observe adverse responses (e.g., cancer, etc.) at environmentally relevant concentrations (HC, 2010a). As such, a linear extrapolation from a point of departure (often identified in a toxicological study) to lower environmental doses (or concentrations) is often used.

Figure 2-4 Non-Threshold Dose-Response Relationship (HC, 2010a)

TRV Identification and Selection

Inhalation TRVs published by regulatory agencies (e.g., Health Canada, US EPA, the World Health Organization (WHO), the Agency for Toxic Substances and Disease Registry (ATSDR), the Texas Commission on Environmental Quality (TCEQ), etc.) for threshold substances are often referred to as a RfC or, in the case of Health Canada, as Tolerable Concentrations (TC). The US EPA defines a RfC as *"…an estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. It can be derived from a NOAEL, LOAEL, or benchmark concentration, with uncertainty factors generally applied to reflect limitations of the data used.*" The RfC is often expressed as a concentration of the chemical in air (e.g., µg of chemical/m^3, etc.) and applies only to chemicals acting through a threshold mode of toxicological action.

Regulatory-published TRVs for non-threshold substances are often expressed as a slope factor relating the oral dose (or exposure) to the expected probability of developing cancer, for example. For the inhalation route of exposure, the TRVs for non-threshold substances are typically expressed as an inhalation unit risk (IUR) value, representing the amount of risk-per unit-concentration to which a receptor can be continually exposed (HC, 2010a). An IUR is typically expressed as the inverse of an air concentration (i.e., $(\mu g/m^3)^{-1}$). The US EPA defines an IUR factor or estimate as the "*…upper-bound excess lifetime cancer risk estimated to result from continuous exposure to an agent over a lifetime at a concentration of 1 µg/m^3 in air."* An IUR factor, or estimate, of 2.0 x 10^{-5} per µg/m^3 would mean that, under an upper worst-case estimate, two (2) excess or additional cancer cases (above and beyond the background cancer rate of approximately 0.4 or 40%) would be expected to develop per one hundred thousand (100,000) people, if all 100,000 people were exposed every day (for a lifetime) to 1 µg of the chemical per m^3 of air.

As particulate matter (PM) is also a non-threshold contaminant associated with a variety of serious adverse health effects, including premature death, PM guidelines that achieve complete protection against adverse health effects resulting from PM exposure cannot be implemented or developed (WHO, 2006a). As such, the objective of many PM guidelines and standards (e.g., WHO, 2006a, HC, 2013) is to continuously reduce $PM_{2.5}$ exposure to the extent technically and/or feasibly possible (Section 5.2).

*2.1.4 **Risk Characterization***

The risk characterization is the final step (of the four main stages of risk assessment) and pulls together the results of the exposure and toxicity assessments. The purpose of risk characterization is to provide a descriptive estimate of the potential human health risks associated with predicted exposures of receptors to the COPC identified in the problem formulation. It is important that the risk characterization be transparent in its presentation and that health risk estimates be placed into context with background exposures (i.e., exposures independent of the site or source of contamination being evaluated) (HC, 2010a). It is also critical that the risk characterization clearly identifies and discusses areas of uncertainty that have the potential to influence health risk estimates.

Inhalation hazard quotient (HQ) values are typically derived when characterizing health risks associated with non-carcinogenic COPCs via the inhalation route of exposure, according to the following example:

$$Hazard\ Quotient\ (HQ) = \frac{Air\ Concentration\ \left(\frac{\mu g}{m^3}\right) X\ Fraction\ of\ Time\ Exposed}{Reference\ Concentration\ \left(\frac{\mu g}{m^3}\right)}$$

Where both on-site and background exposures are combined (i.e., total exposure is assessed), a HQ value of less than one (HQ <1.0) is considered, by Health Canada, to represent a negligible risk (HC, 2010a).

For COPCs determined to be carcinogenic, only site- or source-related exposures are typically considered. The estimated lifetime average daily exposure, or EPC (in the case of an inhalation assessment), is multiplied by an inhalation unit risk (IUR) value, resulting in an incremental lifetime cancer risk (ILCR) estimate, according to the following example:

$$ILCR = Air\ Concentration\ \left(\frac{\mu g}{m^3}\right)\ X\ Fraction\ of\ Time\ Exposed\ X\ Unit\ Risk\ \left(\frac{\mu g}{m^3}\right)^{-1}$$

Because a linear dose-response assessment implies that, in theory, no level of exposure exists that does not result in the probability of generating a carcinogenic response, ILCR estimates are typically evaluated by comparing estimates to levels that are deemed ‘acceptable, tolerable, or essentially negligible’. The ‘acceptable level’ of ILCR is an issue of regulatory policy, rather than science, and is set by various regulatory agencies such as the U.S. Environmental Protection Agency (US EPA), Health Canada, the Canadian

Council of Ministers of the Environment (CCME), and the Ontario Ministry of Environment, Conservation, and Parks (MECP).

Although 'acceptable' ILCR levels are generally considered to range from 1 in 10,000 to 1 in 1,000,000 (1.0E-04 to 1.0E-06), regulatory agencies have typically employed 'acceptable' ILCR levels (i.e., excess cancer risks over and above existing background rates) between 1 in 100,000 (1.0E-05) and 1 in 1,000,000 (1.0E-06) (HC, 2010a). British Columbia, Alberta, and the Atlantic provinces have an 'acceptable' ILCR level of 1 in 100,000 (1.0E-05), while Ontario and Québec target 1 in 1,000,000 (1.0E-06). Health Canada (2010a) and the Canadian Council of Ministries of the Environment (CCME, 2006) deemed ILCRs of less than, or equal to, 1 in 100,000 (1.0E-05) and 1 in 1,000,000 (1.0E-06), respectively, to be 'essentially negligible'. In setting drinking water standards, the US EPA employs a 1 in 10,000 (1.0E-04) excess (or incremental) lifetime cancer risk when setting Maximum Concentration Levels (MCLs). The MCL represents the highest level of a contaminant allowed in drinking water (US EPA, 2018). Toronto Public Health (TPH) has used 1 in 1,000,000 (1.0E-06) as a tolerable risk level.

Analogous to the ILCR estimate (discussed above), the Lifetime Cancer Risk (LCR) estimate can also be used to assess cancer risks from multiple sources. Unlike ILCR estimates, LCR estimates include cancer risks estimates from all sources (i.e., both background and/or baseline conditions plus assessment-specific sources). Regulatory agencies (e.g., Health Canada, MECP, US EPA, etc.) do not recommend 'acceptable' ranges of LCR estimates that are inclusive of background/baseline conditions and assessment specific sources. As such LCR are often used for reference purposes of comparing LCR associated background/baseline conditions against assessment-specific sources.

3.0 Problem Formulation – A Planning/Scoping Step

Elevated concentrations of $PM_{2.5}$ and coarse particulate matter ($PM_{2.5-10}$) have been reported in many subway systems around the world (e.g. Lovett et al., 2017, Moreno et al., 2017, Van Ryswk et al., 2017, etc.). There are many potential sources of $PM_{2.5}$ within a typical subway system, including, but not limited to: the friction generated between the brakes and the wheels; friction between the wheels and the rail; and dust generated from routine track maintenance. The composition of $PM_{2.5}$ samples taken from within the Toronto subway system was found to contain a variety of metals (e.g., iron, manganese, chromium, copper, barium, etc.).

The objective of the Toronto Subway Air Quality HHRA was to evaluate the potential human health risks for subway users from exposure to $PM_{2.5}$ and

associated metals of interest (e.g., iron, manganese, chromium, copper, barium, etc.) measured in $PM_{2.5}$. The objective of the problem formulation stage is the ultimate development of a conceptual model that clearly outlines the scope of the assessment for each COPC (e.g., $PM_{2.5}$ and metals), the human receptors of interest, and the relevant exposure pathways.

3.1 Overview of Subway Air Quality Data

Several different sources of subway air quality data were considered for use in the HHRA, including:

- The Urban Transportation Exposure Study (UTES) — a Health Canada-led study that examined air pollution exposures in major transportation modes (private vehicles, subway systems, and buses) in Canadian cities, including Toronto. Air quality sampling from the Toronto subway system was conducted in the summer of 2010 and winter of 2011. The findings from this study were published by Van Ryswyk et al. (2017);

- The Toronto Transit Commission (TTC) Subway Air Quality Study — a TTC-directed occupational exposure study, conducted in 2017 and 2018; and,

- The Subway Air Quality Initiative (SAQI) — a Health Canada-led investigation, designed to explore the impacts of potential interventions that could reduce passenger exposure to airborne contaminants. Air samples were collected from within the Toronto subway system throughout 2017 and 2018.

3.1.1 Health Canada Urban Transport Exposure Study (UTES)

The UTES examined air pollution exposures in major transportation modes (private vehicles, subway systems, and buses) in Canadian cities, including Toronto. One of the findings from the UTES (Van Ryswyk et al., 2017) was that fine particulate matter ($PM_{2.5}$) concentrations in the Toronto subway system were an order of magnitude greater than ambient $PM_{2.5}$.

The UTES sampling was conducted for three (3) consecutive weeks in both the summer of 2010 and winter of 2011. Three (3) technicians carried their own personal sampling backpacks. Each technician was assigned a specific route, representing approximately one-third of the subway system. Each technician took samples on weekday mornings (between 7 am and 10 am) and weekday evenings (between 3 pm and 6 pm) and followed a pattern of boarding and disembarking at each station on their route (Van Ryswyk et al., 2017, HC, 2019b).

Two methods were used to sample $PM_{2.5}$, including continuous DustTrak sampling and a filter-based gravimetric (or integrated) method. The continuous DustTrak monitoring was conducted for $PM_{2.5}$, ultrafine particulate, and black carbon. The continuous monitoring for $PM_{2.5}$ (using DustTrak) was mobile in nature (i.e., attached to each of the 3 individuals navigating the subway system) and was used in conjunction with integrated digital voice recordings to determine $PM_{2.5}$ concentrations while riding on the train and waiting on a subway platform. (Van Ryswyk et al., 2017, HC, 2019b).

The UTES integrated sampling was conducted using personal exposure monitors (PEMs) that generated 18 individual concentrations of $PM_{2.5,}$ PM_{10}, and associated metals and represented a 1-week sampling period (i.e., 30 hours of sampling — 3 hrs/session x 2 sessions/day x 5 days/week). The UTES integrated 30-hour samples were collected on Teflon filters and analyzed for elemental composition using ICP-MS for 36 elements (Van Ryswyk et al., 2017; HC, 2019b).

As previously indicated, UTES sampling of the Toronto subway system occurred in 2010/2011. Since this time, a number of changes and upgrades to the Toronto subway system have occurred, including, but not limited to, ventilation improvements and the introduction of new trains. As such, the data collected in 2010 and 2011 many not, in some circumstances, reflect current-day conditions in the Toronto subway system; therefore, the UTES data was not directly used in the quantification of human health risk estimates.

*3.1.2 **TTC Subway Air Quality Study***

The purpose of the TTC Subway Air Quality Study (TTC, 2018) was to provide current-day air quality information concerning the underground portions of the Toronto subway system and to characterize occupational exposures to various airborne contaminants (e.g., asbestos, respirable dust, respirable metals, total metals, $PM_{2.5}$, carbon dioxide, etc.) during a typical work shift. The scope of the study focused specifically on characterizing occupational exposures to airborne contaminants and to verify compliance with occupational exposure limits as set by Ontario Regulation 833 – Control of Exposure to Biological or Chemical Agents (O. Reg. 833). As stated previously, this HHRA does not consider occupational exposures, rather the occupational study was reviewed for the purpose of identifying information and/or data that could be used to inform the HHRA.

Inhalable and respirable dust in the workplace is regulated under O. Reg. 833. The metal concentrations presented in the Subway Air Quality Study (TTC, 2018) are not associated with the $PM_{2.5}$ particle size fraction but, rather, with the

'respirable' and 'inhalable' size fractions, as defined by O. Reg. 833. As such, metal concentrations reported in the Subway Air Quality Study (TTC, 2018) are not directly comparable to air quality data presented by the UTES and the Health Canada Subway Air Quality Initiative (SAQI) (Section 3.1.3).

Although $PM_{2.5}$ is not regulated under Ontario Regulation 833, the TTC (2018) collected $PM_{2.5}$ samples for future reference. $PM_{2.5}$ levels were expressed as 8-hour time-weighted-averages (TWAs) for specific occupational titles and job descriptions. These data (i.e., 8-hour personal TWAs by job description) were not immediately and/or directly comparable with the continuous $PM_{2.5}$ collected under SAQI. Although the TTC (2018) study is informative, many of the contaminants reported are not directly comparable with air quality information presented by the UTES and the SAQI, in part, due to differences in particulate size and/or the methods use to collect particulate samples (i.e., stationary platform monitoring versus personal exposure monitoring over an 8-hour duration). As such, the HHRA did not directly rely on air quality data from the TTC (2018) to quantify human health risk estimates.

3.1.3 Health Canada Subway Air Quality Initiative (SAQI) Dataset

The Subway Air Quality Initiative (SAQI) is a Health Canada-led investigation that involved two air monitoring campaigns occurring in parallel. The air monitoring campaign began in December of 2017 and was completed by the end of August 2018. The primary sampling initiative was conducted in the Toronto subway system (Figure 3-1). Subway platforms were sampled three to five at a time for periods ranging from several days to weeks. The second sampling campaign involved the collection and analysis of ambient air at two different urban locations (i.e., 200 College Street and 4905 Dufferin) (HC, 2019a).

Gravimetric samples were collected at subway and ambient air locations using the Harvard School of Public Health's Cascade Impactor (CI). The CI collected $PM_{2.5}$ and $PM_{2.5\text{-}10}$ onto Teflon filters and polyurethane foam (PUF) samples, respectively. The Teflon filters were analyzed for elemental concentrations using X-Ray fluorescence (XRF). In the subway system, the CI samples were collected over 12-hour time periods (6 am -6 pm), daily. Under ambient conditions, the CI ran for 7-day periods, in parallel with $PM_{2.5}$ ambient samples collected using a high volume URG 3000N sampler, allowing for substantial collection of particulate mass over the 7-day sampling periods. For quality control measures, 10% duplicates and 10% blanks were collected for CI and URG samples throughout the investigation (HC, 2019a).

In addition to gravimetric samples, continuous $PM_{2.5}$ data, among other parameters, were also collected at subway platforms. Continuous

measurements (at 5-second intervals) of $PM_{2.5}$ were made using the TSI DustTrak II (TSI, Shoreview, MN, USA). Daily visits were made to platforms to replenish batteries for all units as needed, download data, conduct DustTrak zero checks, and clean DustTrak impaction plates. DustTrak sample flows were calibrated on a weekly basis.

Continuous air quality data were collected from 31 stations for $PM_{2.5}$ and from 22 stations for gravimetric coarse and fine particulate matter. Fine particulate matter was analyzed for metallic elements using XRF. At each subway platform, data were collected for anywhere from 2 to 39 days. Continuous $PM_{2.5}$ data, collected by the TSI DustTrak II, compared well with gravimetric sampling (i.e., a 1.59 factor bias relative to gravimetric). As such, all DustTrak data were corrected for this bias. 21 ambient air samples were collected from two monitoring stations (i.e., 200 College Street and 4905 Dufferin) between May and August of 2018 (HC, 2019a).

In addition to the data described above, HC (2019a) also provided a PEM dataset containing continuous $PM_{2.5}$ data collected using the same approach as the UTES (Section 3.1.1). The PEM dataset, collected in 2018, allows for the determination of $PM_{2.5}$ concentrations while riding on the subway trains and while waiting on platforms. Further details concerning how these data were used are provided in the Exposure Assessment (Section 4.0).

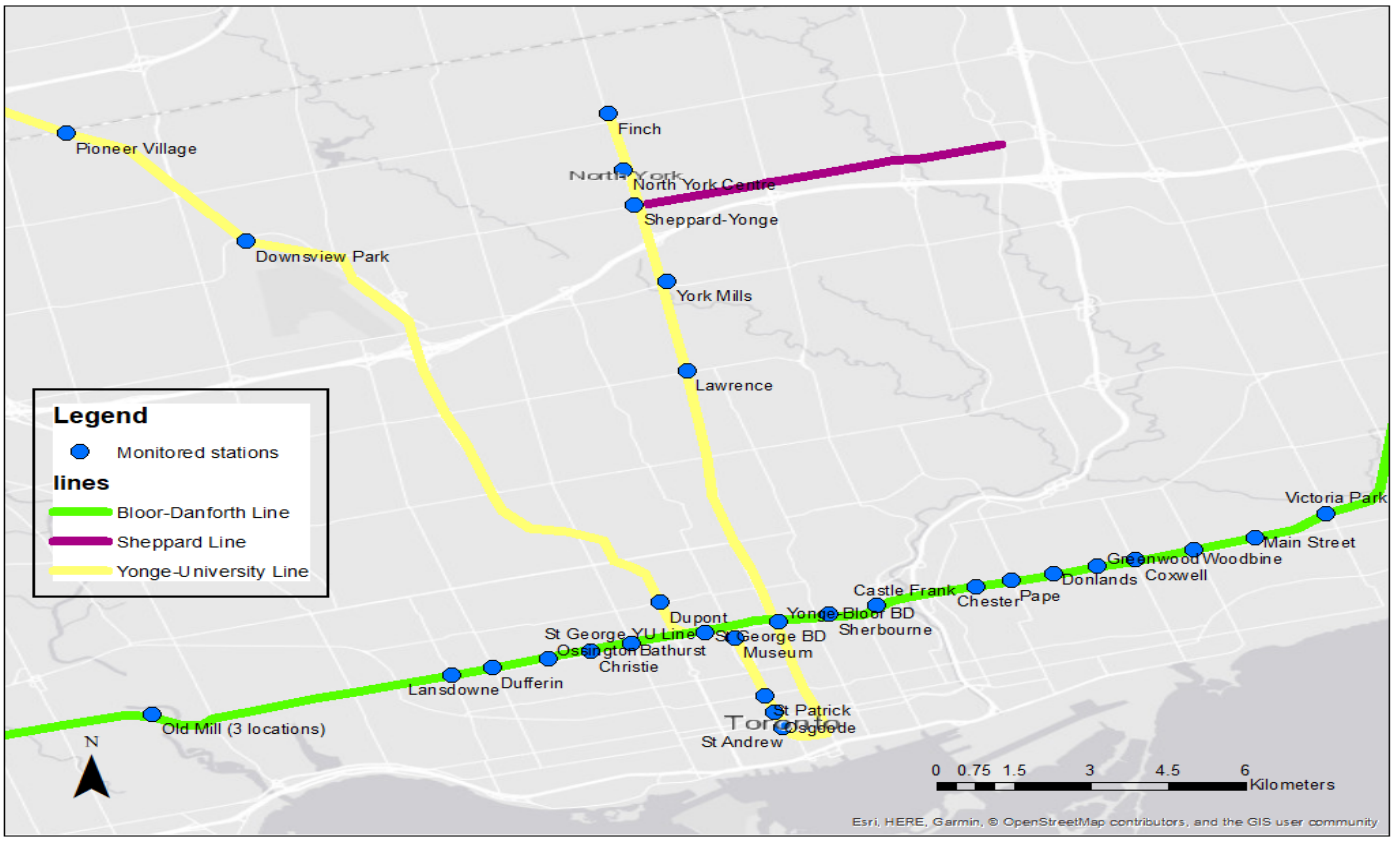


Figure 3-1 Location of Subway Platform Monitoring in SAQI (HC, 2019b)

3.2 Identification and Selection of Chemicals of Potential Concern

In addition to evaluating the potential human health risks associated with exposure to $PM_{2.5}$ in the Toronto subway system, the potential health risks associated with exposure to a number of key metals of interest (identified as constituents of the subway $PM_{2.5}$) were also evaluated. As previously indicated (Section 3.1), the SAQI dataset included, among other data, an analysis of 33 different elements in subway $PM_{2.5}$. A relative toxic potency screening was completed to focus the HHRA on those metallic elements (identified in subway $PM_{2.5}$) that have the greatest potential to impact human health.

The screening process considered potential exposures and the inhalation toxicity of each metallic element in $PM_{2.5}$. The relative exposure to each metallic element in subway $PM_{2.5}$ was determined by each element's abundance ratio (refer to the discussion below regarding the development of abundance ratios). For the purposes of an initial chemical screening and selection, the chronic inhalation toxicity of each metallic element was represented by a regulatory inhalation TRV or inhalation screening-level value.

As part of the SAQI dataset, HC (2019a) analyzed 189 individual 12-hour gravimetric particulate matter samples (obtained from various subway platforms on both Lines 1 and 2), for 33 different elements, using an X-ray fluorescence (XRF) analyzer. Of the 33 elements analyzed by XRF, six elements (bromine, cerium, chlorine, phosphorous, sulfur, and titanium) were removed from further consideration in the relative toxic potency screening exercise because:

- titanium and cerium were never detected above their respective reported method of detection limits (MDLs);
- bromine is a non-metallic gaseous element (at room temperature);
- chlorine is a non-metallic gaseous element (at room temperature); and
- phosphorus (which is extremely reactive in air) and sulfur are non-metallic elements.

Abundance ratio (AR) values, defined as the concentration of a specific element in $PM_{2.5}$ (expressed as $\mu g/m^3$), divided by the concentration of $PM_{2.5}$ (expressed as $\mu g/m^3$), were calculated for each of the remaining 27 elements, resulting in approximately 6,000 individual AR values. Each element-specific AR dataset (for Line 1, Line 2, and the entire subway system) was entered into ProUCL (Version 5.1), a software package provided by the US EPA, to determine a 95 percent upper confidence limit on the arithmetic mean (95% UCLM) of each element-specific AR, for each subway Line, and for the system as a whole. Refer to Table 4-7 for a summary of AR statistics.

For the purpose of chemical screening and selection, chronic inhalation TRVs in the form of a RfC, a risk-specific dose (RsD - with a target risk level of one-in-one million), ambient air quality criteria (AAQC), regional screening levels (RSLs), or environmental screening levels (ESLs) were assigned to each of the remaining 27 elements using the following regulatory hierarchy:

- TRVs identified and selected for use by TPH as part of a recently completed air quality human health risk assessment;
- United States Environment Protection Agency's Integrated Risk Information System (US EPA IRIS);
- Health Canada;
- The World Health Organization (WHO);
- Ontario Ministry of Environment, Conservation and Parks (MECP) chronic ambient air quality criteria (AAQCs);
- US EPA Regional Screening Levels (RSLs); and

- The Texas Commission of Environmental Quality (TCEQ) chronic Environmental Screening Levels (ESLs).

It is noted that for the purpose of chemical screening and selection (Table 3-1), inhalation TRVs were selected as per the hierarchy stated above and may not reflect the TRV ultimately selected to characterize health risk estimates in the HHRA. Further details are provided concerning the inhalation TRVs selected for use in the risk characterization stage of the HHRA (Section 5).

The relative toxic potency of each element in $PM_{2.5}$ was calculated by dividing the 95% UCLM element-specific AR by its regulatory chronic TRV or screening-level value. To determine the relative contribution of each element to the total toxic potential (i.e., the sum of individual toxic potencies), each individual toxic potency was divided by the total toxic potential. When combined, those elements that contribute 99.9% to the total toxic potential were included as COPCs to be evaluated in the HHRA. The relative toxic potency screening exercise was conducted using AR data from Line 1, Line 2, and the combined subway system (i.e., data from both Lines combined). Table 3-1 presents the relative toxic potency screening for the combined subway system.

Table 3- 1 Relative Toxic Potency Screening – Combined Subway System (Lines 1 and 2 combined)

Element	95 UCL AR Values both lines (Unitless)	Chronic Inhalation Screening-Level Value (µg/m^3)	Reference and Comments	Individual Toxic Potency	Contribution to Total Toxic Potential (%)	Cumulative Potency (%)
Chromium	3.4E-03	9.1E-05	Previously selected by TPH (HC, 2010); [1.0E-06/1.1E-02]	3.8E+01	94.4	94.4
Cadmium	1.4E-04	1.0E-04	Previously selected by TPH (HC, 2010); [1.0E-06/9.8E-03]	1.4E+00	3.5	97.9
Arsenic	7.7E-05	1.6E-04	Previously selected by TPH (HC, 2010); [1.0E-06/6.4E-03]	5.0E-01	1.25	99.1
Iron	5.3E-01	5.0E+00	TCEQ long-term ESL - personal communications with TCEQ	1.1E-01	0.27	99.4
Manganese	4.6E-03	5.0E-02	Previously selected by TPH (US EPA,1993)	9.2E-02	0.23	99.6
Nickel	2.8E-04	3.8E-03	Previously selected by TPH (Cal EPA, 2011)	7.3E-02	0.18	99.8
Barium	2.6E-02	1.0E+00	Previously selected by TPH (RIVM, 2001)	2.6E-02	0.06	99.9
Cobalt	1.5E-03	1.0E-01	Previously selected by TPH (WHO, 2006)	1.5E-02	0.04	99.9
Silver	1.4E-04	1.0E-02	TCEQ Long-term ESL -accessed 2019	1.4E-02	0.035	100
Silicon	8.7E-03	1.0E+00	MECP Reg 419 24-hr AAQC for silica of 5 ug/m3 (health)	8.7E-03	0.022	100
Copper	1.7E-03	1.0E+00	Previously selected by TPH	1.7E-03	0.004	100
Antimony	3.4E-04	2.0E-01	HCTP Assessment (US EPA, 1995) - Antimony trioxide	1.7E-03	0.004	100
Aluminum	6.5E-03	5.2E+00	US EPA Regional Screening Levels (RSLs) - May, 2019	1.3E-03	0.003	100
Cesium	2.1E-03	2.0E+00	TCEQ Long-term ESL for cesium hydroxide-accessed 2019	1.1E-03	0.003	100
Zinc	2.0E-03	2.0E+00	Previously selected by TPH - TCEQ accessed 2019	1.0E-03	0.003	100
Calcium	6.8E-03	7.0E+00	MECP Reg 419 24-hr AAQC calcium stearate of 35 ug/m3 (health)	9.7E-04	0.002	100

Element	95 UCL AR Values both lines (Unitless)	Chronic Inhalation Screening-Level Value (µg/m^3)	Reference and Comments	Individual Toxic Potency	Contribution to Total Toxic Potential (%)	Cumulative Potency (%)
Vanadium	9.4E-05	1.0E-01	US EPA Regional Screening Levels (RSLs) - May, 2019	9.4E-04	0.002	100
Potassium	7.7E-04	2.0E+00	TCEQ Long-term ESL -accessed 2019	3.9E-04	0.001	100
strontium	6.1E-04	2.0E+00	Previously selected by TPH – TCEQ – accessed 2019	3.1E-04	0.001	100
Lead	4.4E-05	1.5E-01	Previously selected by TPH (US EPA, 2008)	2.9E-04	0.001	100
Magnesium	7.4E-04	4.0E+00	TCEQ Long-term ESL - accessed 2019	1.8E-04	0.000	100
Tin	3.0E-04	2.0E+00	TCEQ Long-term ESL - accessed 2019	1.5E-04	0.000	100
Sodium	3.4E-03	2.4E+01	MECP Reg 419 24-hr AAQC for sodium bisulphite of 120 ug/m3 (health/particulate)	1.4E-04	0.000	100
Selenium	9.9E-06	2.0E-01	Previously selected by TPH – TCEQ – accessed 2019	5.0E-05	0.000	100
Zirconium	1.2E-04	5.0E+00	TCEQ Long-term ESL -accessed 2019	2.4E-05	0.000	100
Lanthanum	8.7E-05	5.0E+00	TCEQ Long-term ESL lanthanum oxide –– TCEQ – accessed 2019	1.7E-05	0.000	100
Rubidium	3.4E-05	2.5E+00	TCEQ Long-term ESL -accessed 2019	1.3E-05	0.000	100
			TOTAL	**4.0E+01**		

Highlighting represents all contaminants that contribute up to 99.9% of the total toxic potential.

The relative toxic potency screening conducted on data from the entire subway system (Table 1) indicated that the following eight (8) metallic elements comprised 99.9% of the total toxic potential:

- Chromium (95.8%)
- Cadmium (2.5%)
- Arsenic (1.1%)
- Manganese (0.2%)
- Nickel (0.2%)
- Iron (0.1%)
- Barium (0.06%)
- Cobalt (0.04%)

The relative toxic potency screening conducted on Line 2 data alone produced the same list of metallic elements of interest, while screening of Line 1 data alone resulted in the addition of silver. As such, silver was added to the list of metallic elements for further evaluation in the HHRA. Therefore, $PM_{2.5}$, in addition to the following nine (9) metallic elements in subway $PM_{2.5}$, were identified for further evaluation in the HHRA:

Arsenic	Barium	Cadmium
Chromium	Cobalt	Iron
Manganese	Nickel	Silver

3.3 Identification and Selection of Receptors of Interest

A receptor is simply an individual who may come into contact, either directly or indirectly, with subway $PM_{2.5}$ and the associated metals of interest. As such those subway users that are most susceptible to subway particulate matter ($PM_{2.5}$) and associated metals, due to having the greatest probability of exposure, should be identified and selected for assessment in the HHRA.

Given that the objective of the HHRA is to evaluate the potential human health risks of subway users, individuals who consistently use the subway system as part of their daily routine — particularly during morning and afternoon peak weekday hours where $PM_{2.5}$ and associated metal concentrations have been observed to be higher as compared with other times of the day (Section 4) — were considered to be most susceptible, from an exposure standpoint, to subway $PM_{2.5}$. The Toronto Transit Commission (TTC) has

defined the 'Morning Peak' as being from 6 am to 9 am (Monday to Friday) and the 'Afternoon Peak' as being from 3 pm to 7 pm (Monday to Friday) (TTC, 2019a).

There are some individuals (e.g., children, pregnant women, the elderly, individuals with pre-existing respiratory conditions, etc.) within the ridership population who may be more sensitive to $PM_{2.5}$ and/or metals of interest than others. This type of susceptibility (i.e., a heightened sensitivity to specific types of substances) is often addressed in the toxicity assessment (HC, 2010). For example, non-cancer inhalation TRVs for arsenic have been developed for both children and adults by the California Office of Environmental Health Hazard Assessment (OEHHA) (Section 5.0).

For the purposes of the inhalation assessment, the HHRA has selected the subway user who is consistently in the subway system as part of his/her daily routine during morning and afternoon peak hours. The subway user may represent all individuals (including adults and children) who may rely on the subway for their daily commute to and from work or school.

The selection of this highest user group of subway users acts as a surrogate for occasional users of the subway system. There was no indication during the development of the problem formulation that there would be a group of Toronto subway users that would use the system with greater frequency than commuters.

3.4 Identification of Exposure Pathways and Scenarios

The primary objective of the HHRA was to evaluate the potential human health risks to subway users from exposure to levels of $PM_{2.5}$ (and associated metals of interest) measured in the Toronto subway system. As such, the HHRA has focused on the inhalation exposure pathway (i.e., direct exposure resulting from the inhalation of $PM_{2.5}$ and associated metals measured from within the subway system). Unlike larger particulate (e.g., total suspended particulate) that may settle or deposit onto surfaces and subsequently available for direct contact with skin and/or be ingested (via the typical hand-to-mouth activities, direct inhalation of fine particulate (i.e., particulate matter with an aerodynamic diameter less than 2.5 microns or about 3% of the diameter of a human hair) was considered the only relevant exposure pathway.

3.4.1 Subway Air Quality Scenarios

As described in detail in the Exposure Assessment (Section 4.0), the concept of microenvironments was used in the development of both acute and chronic subway air quality scenarios. Depending on the scenario being evaluated, individuals were assigned different exposure durations under each microenvironment based on ridership data provided by the TTC (2019). The three key microenvironments included: the subway platform environment; the on-train environment; and ambient air (i.e., the typical outdoor urban airshed environment).

Three long-term (or chronic) subway air quality scenarios were evaluated, including:

1. Daily use of the Young-University-Sheppard Line (Line1) during weekday morning and afternoon peak hours of operation or transit use (defined by the TTC (2019) as 6 am to 9 am, Monday to Friday, and 3 pm to 7 pm, Monday to Friday, respectively.
2. Daily use of the Bloor-Danforth (Line 2) during weekday morning and afternoon peak hours of operation of transit use; and
3. Daily use of the entire subway system (using a combination of both lines) during weekday morning and afternoon peak hours of operation or transit use. As described in the Exposure Assessment (Section 4.0), air quality data from both Line 1 and Line 2 were used to approximate platform and on-train concentrations of $PM_{2.5}$ and associated metals.

For each of the chronic inhalation exposure scenarios mentioned above, a range of potential exposures, expressed as EPCs, were developed and were bound by the central tendency and upper percentile estimates. As discussed in more detail in the Exposure Assessment (Section 4.0), chronic EPCs were intended to represent the average daily exposure among individuals who routinely take the subway during peak hours of operation or transit use, representing a series of regular short-term events/exposures that occur daily and that contribute to an individual's overall average daily exposure.

In addition to characterizing chronic exposures among individuals who regularly use the subway, the HHRA also evaluated, as a point of reference, chronic exposures among individuals who do not use the subway system (i.e., exposure under ambient conditions alone).

Three short-term or acute scenarios were also evaluated for each subway line, and the system as a whole, during morning and afternoon peak hours of operation or transit use. Unlike the chronic scenarios, whereby the resulting EPCs represent a series of routine, daily, short-term events that contribute to an individual's overall total average daily exposure (inclusive of ambient conditions), the acute scenarios were designed to evaluate one-off exposure events, assumed to last anywhere from approximately ½-hour to one hour in duration, during peak hours of operation or transit use.

3.5 Conceptual Human Health Risk Assessment Model

The conceptual model (Figure 3-2) summarizes the problem formulation, laying the foundation for the subsequent HHRA by summarizing the COPCs, receptors of interest, possible exposure pathways, and conditions under which exposure may occur.

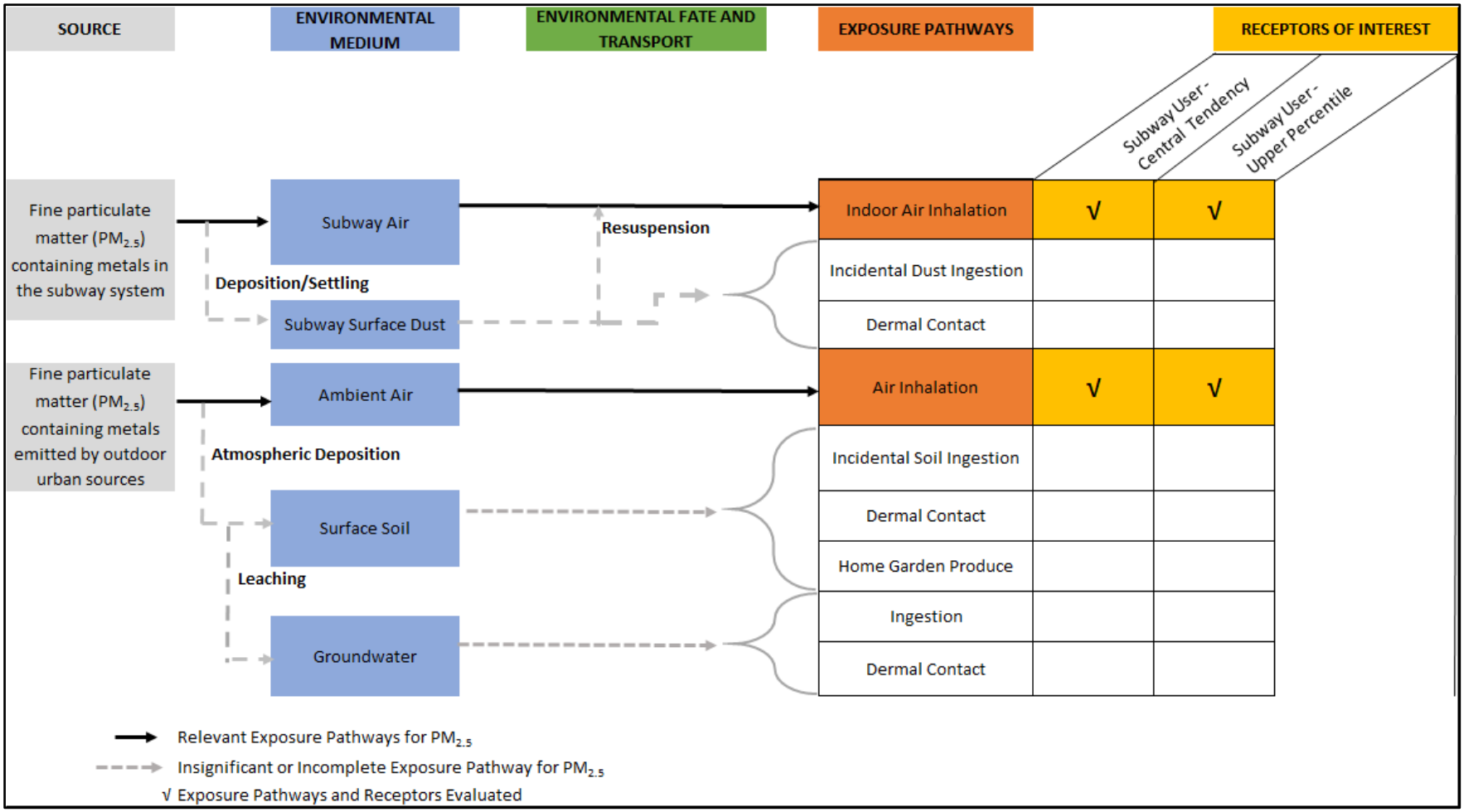


Figure 3-2 Human Health Risk Assessment Conceptual Mode

4.0 Exposure Assessment

The two main components that make up an exposure assessment are chemical characterization (the development of exposure point concentrations) and receptor characterization (defining an individual's physical and/or behaviour activity patterns). The following sections describe the information used to develop quantitative estimates of acute and chronic exposure, expressed as exposure point concentrations (EPCs).

4.1 Human Receptor Characterization

To develop quantitative estimates of human exposure, an individual's physical characteristics (e.g., body weight, breathing rate, water intake rate, food ingestion rate, etc.) and/or behavioural characteristics (e.g., time/activity patterns) may need to be quantitatively characterized. The physical and behavioural characteristics of a receptor can vary by age (i.e., infant, toddler, adolescent, adult) and can greatly influence the extent of exposure to COPCs (HC, 2010a).

In the case of an inhalation exposure assessment, where the only exposure pathway of interest is direct inhalation, it is standard practice to directly use the measured or predicted air concentration as a surrogate for systemic exposure. In other words, the requirement for age-specific inhalation rates and body weights is not required (in an inhalation assessment), as health-based TRVs published by regulatory agencies — used to characterize health risks (Section 5.0) — are expressed as $\mu g/m^3$ (e.g., RfC) or a $(\mu g/m^3)^{-1}$ (e.g., inhalation unit risk value).

As such, the receptor characterization has focused on defining the time-activity patterns of those subway users that have the greatest probability of chronic expose to subway $PM_{2.5}$ and associated metals. Subway users who consistently use the subway system as part of their daily routine — particularly during morning and afternoon peak weekday hours where $PM_{2.5}$ and associated metal concentrations have been observed to be higher as compared with other times of the day (Section 4.2.1) — were considered to be most susceptible, from an exposure standpoint, to subway $PM_{2.5}$. As indicated previously, there are some subway users (e.g., children, pregnant women, the elderly, individuals with pre-existing respiratory conditions, etc.) who may be more sensitive to the effects of $PM_{2.5}$ and/or metals of interest than others. This type of susceptibility (i.e., a heightened sensitivity to specific types of substances) is often addressed in the toxicity assessment (HC, 2010a).

4.1.1 TTC Subway Ridership Information – Platform Wait Times and In-Train Trip Duration

The Toronto Transit Commission (TTC) provided service interval data (i.e., data describing the frequency with which subway trains arrive at a given station during

specific times of the day and on specific days of the week) for both Line 1 and Line 2. In addition to the service interval data, the TTC (2019) also provided summary statistics describing in-train travel time for both Line 1 and Line 2 (i.e., the amount of time a subway user spends on the subway train during a typical trip). As described below, the TTC (2019) data were used to characterize the time-activity patterns of a subway user within each micro-environment of interest (i.e., time spent waiting on the platform, time spent within a subway train, and the remaining time spent outside of the subway system under ambient conditions).

The TTC (2019) defined the 'Morning Peak' weekday hours as being from 6:00AM to 9:00AM (Monday to Friday) and the 'Afternoon Peak' weekday hours as being from 3:00PM to 7:00PM (Monday to Friday) (TTC, 2019). It is within these peak hours where ridership, train frequency, and, consequently, subway $PM_{2.5}$ are at their greatest. The TTC does not track individual customer wait times on subway platforms; however, in their modelling exercises, the TTC assumes platform wait times are random, given that, in theory, subway users could wait (on the platform) anywhere from zero (0) minutes to a full headway between trains (e.g., 2 minutes and 21 seconds during the morning peak hours on Line 1). The median (or middle) wait time would occur at the halfway point of a full headway (e.g., 1 minute and 10 seconds).

To approximate the total amount of time spent waiting on the platform per day, it was assumed that a regular subway user would always experience a return trip (e.g., to work and back home). As such, reported weekday wait times (both median and maximum) during morning and afternoon peak hours for each Line were added together to approximate a daily return trip (Table 1). Median and maximum wait times were used to support the development of central tendency and upper percentile EPCs (Section 4.3), respectively. Furthermore, there are subway users who use both Lines 1 and 2 on a daily basis and, therefore, platform wait times for the entire system (both Lines combined), were calculated using the Line with the longest wait times (albeit only marginally, Line 1 has slightly greater afternoon peak wait times).

The TTC (2019) provided summary statistics for on-train travel times for Line 1 and Line 2. Median and 90th percentile on-train travel times for each subway line were selected to support the development of the central tendency and upper percentile EPCs (Section 4.3), respectively (Table 4-1).

Table 4-1 Subway-Specific Time-Activity Patterns

Line	Platform Wait Times Morning Trip		In-Train Travel Time Morning Trip	
	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Line 1	1.2	2.4	8.9	29.3
Line 2	1.2	2.4	13.1	26.5
Line	**Platform Wait Times Afternoon Trip**		**In-Train Travel Time Afternoon Trip**	
	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Line 1	1.3	2.6	8.9	29.3
Line 2	1.3	2.5	13.1	26.5
Line	**Platform Wait Times Return Trip**		**In-Train Travel Time Return Trip**	
	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Line 1	2.5	5.0	17.8	58.6
Line 2	2.5	4.9	26.2	53.0
Entire System[2]	2.5	5.0	17.8	58.6

[1]All times cited are during weekday travel
[2]Ridership data from Line 1 was used to characterize the entire subway system as Line 1 data had the highest platform wait and in-train travel times.

From the information provided in Table 4-1, the amount of time spent in the subway system (both on the platform and riding in the subway) on a daily basis could range anywhere from approximately 20 minutes per day (2.5 + 17.8) to 64 minutes per day (5.0 + 58.6).

For the purpose of estimating a total daily EPC (Section 4.3), subway users were assumed to spend the remainder of the day subjected to outdoor ambient concentrations. For example, if a subway user spends 64 minutes on a given day within the subway system, the remainder of the day — or 1,376 minutes (1440 – 64 = 1,376) — was assumed to be spent under ambient conditions.

Although the TTC (2019) has provided detailed time-activity data concerning daily platform wait times and in-train travel times (used to approximate an average daily EPC over a prolonged period of time), data concerning how often (e.g., number of days per week, etc.) a user might take the subway are not available. To our knowledge, the TTC does not collect individual ridership data (e.g., the number of trips per week, or per month, that an individual might take, etc.). As such, several assumptions were made concerning the frequency with which individual subway users might use the subway (Table 4-2). Two ridership frequency scenarios were assumed — three days per week and five days per week — furthermore, each time an individual used the subway system, it was assumed to be a return trip (e.g., to work or school and back). These assumptions form the basis for the return trip time-activity patterns (presented in Table 4-1) used in the HHRA.

Table 4- 2 Assumed Frequency of Subway Use

Central Tendency Days per Week	Central Tendency Weeks per Year	Upper Percentile Days per Week	Upper Percentile Weeks per Year
3	48	5	50

4.2 Characterizing Exposure Pont Concentrations by Microenvironment

One of the most critical steps to quantifying human exposure is to develop chemical- and media-specific EPCs. An EPC is a chemical concentration in a specific environmental medium (e.g., air, soil, water, food, etc.) that a receptor may encounter over either a chronic (e.g., several months to years) or acute (e.g., ½-hour, 1-hour, or 24-hour) period of time. EPCs may be measured directly for the environmental media of interest (e.g., air, soil, water, food, etc.) or they may be predicted using mathematical models (HC, 2010a). The US EPA Risk Assessment Guidance for Superfund (US EPA, 1989) recommends that the reasonable maximum EPC should be characterized using the 95% upper confidence limit on the arithmetic mean concentration (i.e., the 95% UCLM). Health Canada (HC, 2010a) also prefers the use of the mean or 95% UCLM assuming adequate data exist, when conducting a detailed point-estimate exposure assessment.

4.2.1 $PM_{2.5}$ Subway Platform Concentrations

As part of the SAQI study, continuous air quality samples were collected from thirty-one (31) subway stations. Samples were analyzed for $PM_{2.5}$ using a TSI Dust Trak II sampling device. At each subway station platform, data were collected on a minute-by-minute basis over durations varying between 2 and 39 days. A total of 876,762 individual one-minute $PM_{2.5}$ readings were collected and analyzed when considering all subway station platforms and time periods.

As previously indicated, the TTC (2019) identified ‘Morning Peak’ weekday hours as being from 6 am to 9 am (Monday to Friday) and ‘Afternoon Peak’ weekday hours as being from 3 pm to 7 pm (Monday to Friday) (TTC, 2019). The morning and afternoon peak hours represent times with the greatest ridership numbers, train frequencies, and, as illustrated below (Table 4-3 and Figure 4-1), peak subway $PM_{2.5}$ concentrations relative to other time periods (i.e., weekday evenings and overnight).

Table 4-3 $PM_{2.5}$ Concentrations (µg/m^3) — Subway Platform Monitoring — SAQI dataset PM

Statistic	All Data			Peak Weekday Hours (6am–9am and 3pm–7pm)			Late Evening and Overnight Hours (10pm–1am and 1:30am–5:30am)		
	Line1	Line 2	Combined	Line1	Line 2	Combined	Line1	Line 2	Combined
Number of Samples	266,076	610,686	876,762	80,352	135,599	215,951	59,928	135,481	195,409
Arithmetic Mean $PM_{2.5}$ Platform Concentration (µg/m^3)	138	291	244	164	385	301	89	178	151
Standard Deviation	67.3	173	165	67.3	170	176	49.7	144	129
95% UCLM[1]	139	291	245	**165**	**385**	**303**	89.5	179	151

[1]Represents the 95% upper confidence limit on the arithmetic mean. 95% confidence intervals on the arithmetic mean were calculated using Mircosoft Excel® as the size of the dataset exceeded the limit of the US EPA software package ProUCL (Version 5.1).
Shaded and bolded values represent the $PM_{2.5}$ concentrations used to facilitate the exposure assessment and risk characterization.

Continuous (minute-by-minute) sampling of subway platforms during peak weekday hours (6am– 9am and 3pm–7pm) resulted in 95% UCLM $PM_{2.5}$ concentrations of 165, 385, and 303 µg/m^3 on Line 1, Line 2, and the entire system, respectively. As illustrated in Table 4-3 and Figure 4-1 (below), the 95% UCLM $PM_{2.5}$ platform concentrations measured over peak weekday hours were observed to be approximately two (2) times greater than platform concentrations measured during late evening (10pm–1am) and overnight periods (1:30am–5:30am) combined (i.e., combined E/O).

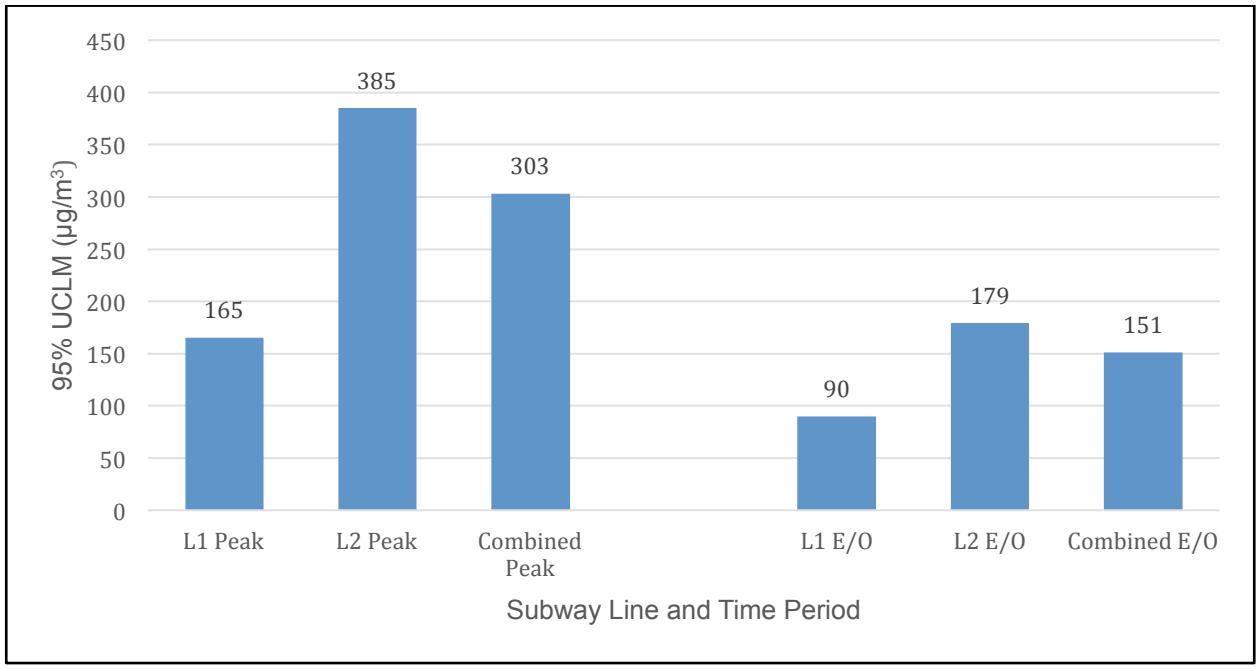


Figure 4-1 $PM_{2.5}$ Subway Platform Concentrations During Peak and Evening/Overnight (E/O) Hours on Line 1, Line 2, and the Combined System

As such, the 95% upper confidence limit on the arithmetic mean of continuous (minute-by-minute) $PM_{2.5}$ monitoring data from all subway platforms during weekday peak hours (6am–9am and 3pm–7pm) was used to facilitate the derivation of EPCs for $PM_{2.5}$ and associated metals on Line 1, Line 2, and the entire subway system.

The mean $PM_{2.5}$ concentrations on Toronto subway platforms over all operational hours on Line 1 (138 µg/m^3) and Line 2 (291 µg/m^3) fall within the range of $PM_{2.5}$ concentrations found in other subway systems around the world, as observed by Moreno (2017). However, it is noted that the mean $PM_{2.5}$ subway platform concentration on Line 2 (of 291 µg/m^3) is at or near the upper limit of the range presented by Moreno (2017) (Figure 4-2).

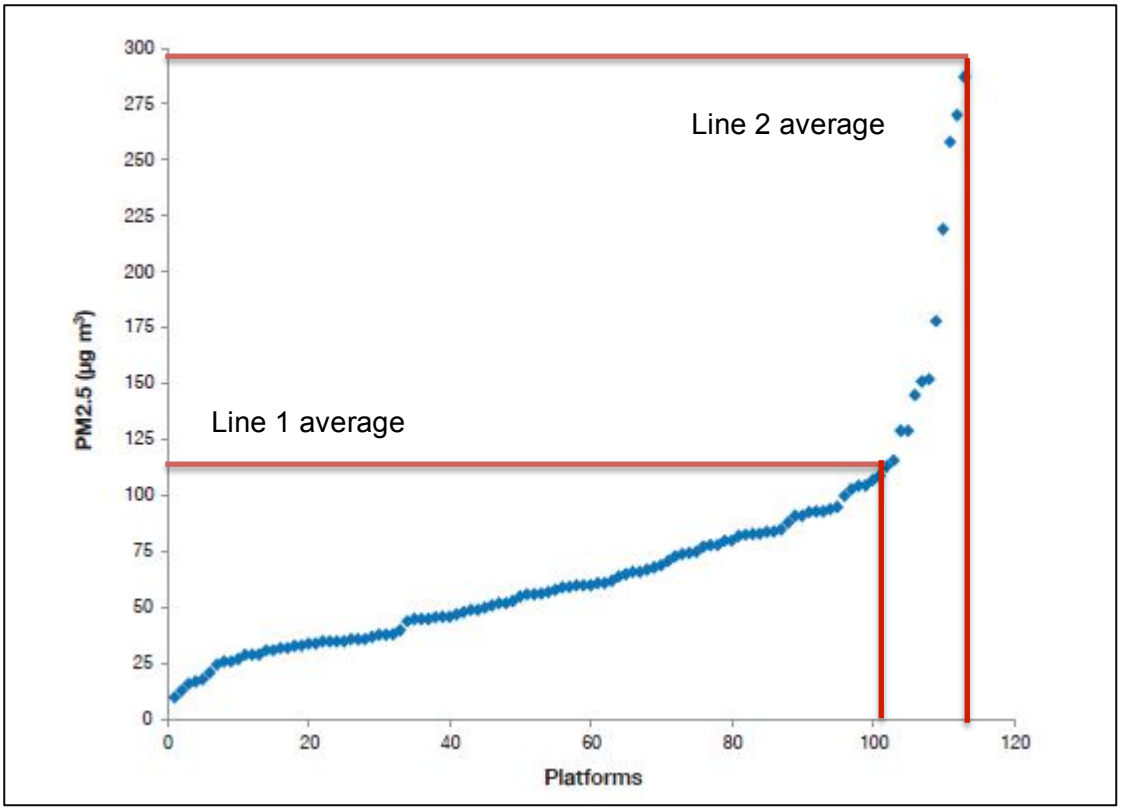


Figure 4- 2 $PM_{2.5}$ Concentrations measured on platforms of subway systems around the world – adapted from Moreno et al. (2017)

4.2.2 $PM_{2.5}$ In-Train Concentrations

The TTC (2019) data indicated that a significant proportion of an individual's time in the subway system is spent riding within the subway train (Table 4-1). As such, the concentrations of $PM_{2.5}$ and associated metals found within the subway train cars (as opposed to on the platform) are critical to approximating EPCs. HC (2019a) provided a personal exposure monitoring dataset, containing continuous $PM_{2.5}$ data collected in a similar manner as the UTES (Van Ryswyk et al., 2017). Technicians, equipped with Personal Exposure Monitors (PEMs), continuously monitored $PM_{2.5}$ concentrations while travelling throughout the subway system. More specifically, technicians circumnavigated the subway system (Lines 1 and 2), during September and October of 2018 while spending time on both subway platforms and riding trains. The SAQI personal exposure monitoring dataset provided by HC (2019a) contained over 11,000 individual $PM_{2.5}$ measurements taken while waiting on subway platforms and riding in trains on both Lines 1 and 2 (Table 4-4).

Table 4-4 Summary of Continuous $PM_{2.5}$ Personal Exposure Monitoring Data ($\mu g/m^3$)

Parameter	On-Train			Platform		
	Line1	Line 2	Combined	Line1	Line 2	Combined
Number of Samples	4,528	2,158	6,686	2,562	2,498	5,060
Arithmetic Mean ($\mu g/m^3$)	65.5	155	94.3	139	344	241
Median ($\mu g/m^3$)	57.0	154	82.0	121	361	217
Standard Deviation	37.0	51.4	59.4	67.2	118	140

The SAQI personal exposure monitoring dataset (summarized in Table 4-4) allowed for the development of on-train-to-platform concentration ratios (Table 4-5). As illustrated in Table 4-5 and Figure 4-3, median on-train concentrations of $PM_{2.5}$ were observed to be 39% to 47% lower than $PM_{2.5}$ concentrations measured on platforms. Median on-train-to-platform concentration ratios calculated using the SAQI personal exposure monitoring dataset (Table 4-5) are similar to the results found in the Barcelona subway system where mean on-train $PM_{2.5}$ concentrations were observed to be 30% to 50% lower than those measured on the platforms from the same subway line and time period (Moreno, et al., 2017).

Table 4-5 Summary of $PM_{2.5}$ on-train-to-platform Concentration (unitless)

Parameter	Line 1	Line 2	Combined[1]
Arithmetic Mean	0.47	0.45	0.39
Median	0.47	0.43	0.38

[1]Represents a $PM_{2.5}$ on-train-to-platform concentration ratio calculated using data (as presented in Table 4-4) from both Line 1 and Line 2.

The personal exposure monitoring results from the Toronto subway system published in the UTES (Van Ryswyk et al., 2017) reported median on-train (riding) and on-platform (waiting) $PM_{2.5}$ concentrations of 80 and 140 $\mu g/m^3$, respectively. The resulting median on-train-to-platform ratio was reported to be approximately 0.57 (i.e., on-train $PM_{2.5}$ concentrations were found to be approximately 57% lower than on-platform concentrations).

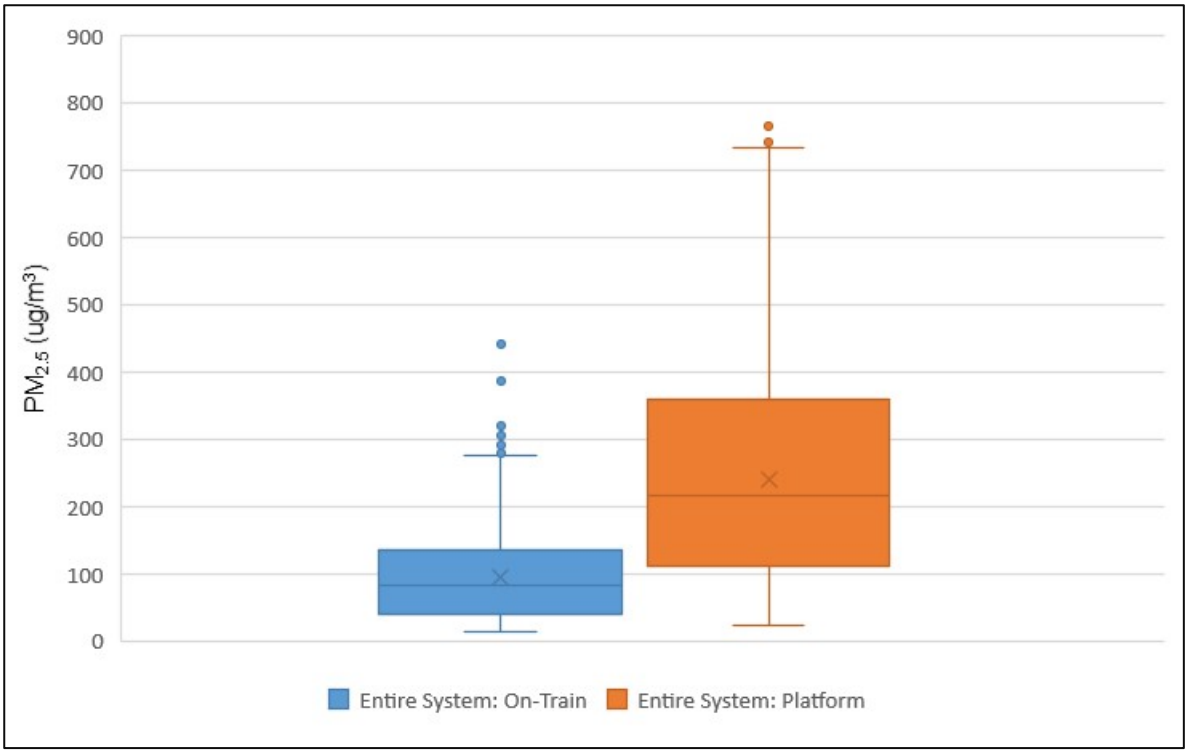


Figure 4-3 Box Whisker Plot of On-Train and Platform $PM_{2.5}$ Concentrations ($\mu g/m^3$) – Lines 1 and 2 Combined

Median $PM_{2.5}$ on-train-to-platform ratios specific to each line and the combined subway system (Table 4-5) were multiplied by the 95% UCLM on-platform $PM_{2.5}$ concentrations during weekday peak times (summarized in Table 4-3) to predict on-train $PM_{2.5}$ concentrations for each line and the subway system as a whole (Table 4-6).

Table 4-6 Summary of Platform and Predicted On-Train $PM_{2.5}$ Concentrations

Subway Line	Median On-Train-to-Platform $PM_{2.5}$ Ratio	95% UCLM $PM_{2.5}$ Platform Concentration ($\mu g/m^3$)[1]	Predicted On-Train $PM_{2.5}$ Concentration ($\mu g/m^3$)
Line 1	0.47	165	78
Line 2	0.43	385	165
Combined System[2]	0.38	303	115

[1]the 95% upper confidence limit on the arithmetic mean $PM_{2.5}$ subway platform concentration during weekday peak hours (6 am–9 am and 3 pm–7 pm).
[2]Combined System refers to data from both Line 1 and Line 2.

4.2.3 Metal-Specific Abundance Ratios and Concentrations

As described in Section 3.2, the SAQI dataset included an analysis of 189 individual, 12-hour gravimetric particulate matter (PM) samples collected from various subway platforms for thirty-three (33) different elements, using an X-ray fluorescence (XRF) analyzer. Summary statistics of abundance ratio (AR) values, defined as the concentration of a specific element in $PM_{2.5}$ (expressed as $\mu g/m^3$) divided by the

concentration of $PM_{2.5}$ (expressed as µg/m^3), are presented below (in Table 4-7) for each metal of interest and per subway line. Each element-specific AR dataset (for Line 1, Line 2, and the entire subway system) was run through ProUCL (Version 5.1), a software package provided by the US EPA, to determine an appropriate 95 percent upper confidence limit on the arithmetic mean (95% UCLM).

Metal-specific platform concentrations (on Line 1, Line 2, and the entire subway system) were approximated by multiplying the 95% UCLM $PM_{2.5}$ concentrations measured during peak hours (Table 4-3) by metal-specific 95% UCLM AR values (Table 4-7), as described in Equation 1. Metal-specific on-train concentrations were approximated by multiplying platform concentrations by the median on-train-to-platform ratios, as described in Equation 2.

$$PC_{metal} = PC_{PM2.5} \times AR_{metal} \qquad \textit{Equation 1}$$

Where:
PC_{metal} = concentration of a specific metal in platform $PM_{2.5}$ (µg/m^3)
$PC_{PM2.5}$ = 95% UCLM $PM_{2.5}$ platform concentrations measured during peak hours (µg/m^3)
AR_{metal} = metal-specific 95% UCLM AR value (unitless)

$$TC_{metal} = PC_{metal} \times Ratio \qquad \textit{Equation 2}$$

Where:
TC_{metal} = concentration of a specific metal in train $PM_{2.5}$ (µg/m^3)
PC_{metal} = concentration of a specific metal in platform $PM_{2.5}$ (µg/m^3)
Ratio = line-specific median on-train-to-platform ratio (unitless)

Table 4- 7 Summary Statistics of Abundance Ratios[1]

Subway	Silver	Arsenic	Barium	Cadmium	Cobalt	Chromium	Iron	Manganese	Nickel
Combined (Lines 1 and 2)									
N	194	194	194	194	194	194	194	194	194
Min	2.8E-06	2.7E-06	5.2E-03	2.9E-06	7.8E-04	1.3E-03	3.5E-01	3.1E-03	1.8E-04
Max	7.3E-04	5.3E-04	4.6E-02	4.3E-04	2.1E-03	6.2E-03	7.3E-01	6.3E-03	3.9E-04
Mean	1.3E-04	6.2E-05	2.2E-02	1.3E-04	1.5E-03	3.3E-03	5.2E-01	4.5E-03	2.8E-04
Median	9.5E-05	4.9E-05	2.4E-02	1.0E-04	1.5E-03	3.5E-03	5.2E-01	4.5E-03	2.7E-04
Std Dev	1.0E-04	5.1E-05	9.9E-03	9.9E-05	2.9E-04	1.1E-03	4.4E-02	3.7E-04	3.0E-05
95% UCLM[2]	1.4E-04	7.7E-05	2.6E-02	1.4E-04	1.5E-03	3.4E-03	5.3E-01	4.6E-03	2.8E-04
Line 1									
N	82	82	82	82	82	82	82	82	82
Min	2.6E-05	1.2E-05	5.2E-03	1.6E-05	1.0E-03	1.3E-03	4.3E-01	3.6E-03	2.2E-04
Max	7.3E-04	1.6E-04	2.9E-02	4.3E-04	2.1E-03	4.1E-03	7.3E-01	6.1E-03	3.9E-04
Mean	2.0E-04	8.1E-05	1.3E-02	2.1E-04	1.4E-03	2.2E-03	5.3E-01	4.5E-03	2.8E-04
Median	1.9E-04	7.8E-05	1.1E-02	2.0E-04	1.4E-03	2.0E-03	5.2E-01	4.5E-03	2.8E-04
Std Dev	1.1E-04	3.1E-05	5.6E-03	9.8E-05	1.9E-04	6.7E-04	5.2E-02	4.3E-04	3.1E-05
95% UCLM	2.3E-04	8.6E-05	1.4E-02	2.3E-04	1.4E-03	2.3E-03	5.4E-01	4.6E-03	2.9E-04
Line 2									
N	112	112	112	112	112	112	112	112	112
Min	2.8E-06	2.7E-06	1.6E-02	2.9E-06	7.8E-04	2.8E-03	3.5E-01	3.1E-03	1.8E-04
Max	2.9E-04	5.3E-04	4.6E-02	1.9E-04	2.1E-03	6.2E-03	7.1E-01	6.3E-03	3.9E-04
Mean	7.1E-05	4.8E-05	2.9E-02	6.9E-05	1.6E-03	4.1E-03	5.2E-01	4.6E-03	2.7E-04
Median	6.2E-05	3.9E-05	3.1E-02	6.8E-05	1.6E-03	4.2E-03	5.1E-01	4.6E-03	2.7E-04
Std Dev	4.5E-05	5.8E-05	5.8E-03	4.2E-05	3.2E-04	5.4E-04	3.6E-02	3.3E-04	3.0E-05
95% UCLM	8.9E-05	7.1E-05	3.0E-02	7.6E-05	1.6E-03	4.2E-03	5.2E-01	4.6E-03	2.8E-04

[1] Defined as the concentration of an element in $PM_{2.5}$ (expressed as $\mu g/m^3$) divided by the concentration of $PM_{2.5}$ (expressed as $\mu g/m^3$)
[2] Upper 95% confidence limit on the arithmetic mean as calculated by ProUCL (Version 5.1)

4.2.4 $PM_{2.5}$ Ambient Concentrations

As part of the SAQI, a second sampling campaign was completed that involved the collection and analysis of $PM_{2.5}$ in ambient air (HC, 2019a). Ambient air samplers were situated at two different monitoring locations (i.e., 200 College Street and 4905 Dufferin Rd.) between May and August of 2018. $PM_{2.5}$ in ambient air was collected using a high-volume sampler that ran continuously for over a 7-day sampling period. A total of 23 seven-day samples comprised the SAQI ambient dataset. $PM_{2.5}$ samples were analyzed for 33 different elements using X-Ray fluorescence (XRF) (HC, 2019b).

The ambient air quality dataset collected as part of the SAQI was considered the most appropriate dataset to use in the approximation of EPCs under ambient conditions. As summarized by Moreno et al. (2017), ambient urban air quality can influence subway air quality and, therefore, using ambient air quality data collected in tandem with subway air quality data allows for a more direct comparison between subway and ambient conditions. In addition to the subway and ambient data having been collected in parallel with one another, there was consistency in the methods used (within the SAQI) to collect $PM_{2.5}$ samples in subway and ambient air as well as consistency in the methods used to analyze the elemental composition (i.e., the use of XRF for both subway and ambient samples).

Ambient air quality data from SAQI (i.e., $PM_{2.5}$ and metal concentrations of interest, as analyzed by XRF) were reviewed and, where metal concentrations were reported to be below the method of detection limit (MDL), the metal was assumed to exist at the reported MDL. HC (2019b) provided MDLs for all metals of interest. The ambient air quality data was then analyzed by the US EPA Software Package ProUCL (Version 5.1) to derive an appropriate 95% UCL on the arithmetic mean (or 95% UCLM) (Table 4-8).

Table 4-8 Ambient Air Concentrations (µg/m^3) – SAQI Dataset

Parameter	Sample Size	Min	Max	Mean	Median	Std Dev	95% UCLM
$PM_{2.5}$	23	5.8E+00	1.4E+01	9.6E+00	8.7E+00	2.3E+00	1.1E+01
Arsenic		1.0E-04	1.4E-03	6.0E-04	5.0E-04	3.0E-04	1.0E-03
Barium		7.9E-03	2.0E-02	1.3E-02	1.3E-02	3.2E-03	1.4E-02
Cadmium		1.0E-04	2.1E-03	1.8E-03	2.1E-03	6.0E-04	2.0E-03
Chromium (total)		4.0E-04	1.2E-03	8.0E-04	7.0E-04	2.0E-04	1.0E-03
Cobalt		2.0E-04	8.0E-04	5.0E-04	5.0E-04	2.0E-04	1.0E-03
Iron		6.8E-02	1.9E-01	1.2E-01	1.2E-01	3.2E-02	1.4E-01
Manganese		1.8E-03	5.7E-03	3.2E-03	3.0E-03	9.0E-04	4.0E-03
Nickel		1.0E-04	5.0E-04	3.0E-04	3.0E-04	1.0E-04	3.0E-04
Silver		7.0E-04	1.6E-03	1.6E-03	1.60-3	1.9E-04	1.6E-03

As discussed further in Section 4.2.5, due to the lack of chromium speciation data in subway $PM_{2.5}$ samples, it was assumed that all chromium present in subway particulate exists as Cr (VI). As such, the HHRA has assessed chromium separately as Cr (VI) and Cr (III). Similarly, the SAQI ambient sampling program did not include chromium speciation in ambient $PM_{2.5}$ samples. Bell and Hipfner (1997) indicate that approximately 20% of routinely-monitored ambient airborne chromium is present as Cr (VI). As such, the derivation of an EPC for Cr (VI) (Section 4.3) assumed that 20% of the ambient total chromium concentration (Table 4-8) exists as Cr (VI).

The SAQI ambient data (Table 4-8) resulted in a mean ambient $PM_{2.5}$ concentration of 9.6 µg/m^3 (with the 95% UCLM estimated at 10.5 µg/m^3). Data collected by the National Ambient Pollution Surveillance (NAPS) program in 2017 (at both the Downsview and Resources Road Stations) were analyzed resulted in an annual average $PM_{2.5}$ concentration of 7.1µg/m^3 (N=202) and a 95% UCLM of 7.5 µg/m^3 (as calculated by ProUCL Version 5.1). It is noted that the SAQI ambient air quality sampling was conducted in the summer months and was from sampling locations closer to the downtown core. The proximity of stations to the downtown core and sampling events during the summer months only maybe contributing factors as to why the ambient $PM_{2.5}$ concentrations (as reported by the SAQI) are greater than those reported by the NAPS in 2017.

4.2.5 Summary of Exposure Point Concentrations by Microenvironment

Using the 95% UCLM $PM_{2.5}$ platform concentrations (Table 4-3), median on-train-to-platform ratios (Table 4-6), and AR values (Table 4-7), concentrations of $PM_{2.5}$ and associated metals of interest were derived for three different microenvironments (Table 4-9).

Currently, chromium in subway $PM_{2.5}$, analyzed by XRF, represents total chromium. To-date, chromium in $PM_{2.5}$ has not been speciated and, therefore, the proportion of total chromium in subway $PM_{2.5}$ that exists as hexavalent chromium (Cr (VI)) is unknown. Lovett et al. (2017) and Chillrud et al. (2004) make the argument that any chromium found in a subway system should be assumed to exist as Cr (VI) due, at least in part, to the high temperatures involved in the braking process. It is noted that neither study speciated chromium in subway particulate matter — both authors make the assumption of 100% Cr (VI) based on data from other sources (e.g., observations in welding and other high-temperature industrial activities, etc.). Considering these two studies, in addition to the current lack of site-specific chromium speciation data, the HHRA assessed both Cr (VI) and Cr (III) individually to ensure risks were not under-estimated.

It is noted that the TTC (2018) speciated chromium in the respirable particulate size fraction (as defined under Ontario Regulation 833) and was unable to detect Cr(VI) above the limit of quantification (approximately 0.03 µg/m^3). Given that the source of Cr(VI) may influence where within the particle size distribution Cr(VI) is found, the absence of Cr(VI) (above the level of quantification) in respirable particulate size fraction cannot be used to rule out the presence of Cr(VI) in $PM_{2.5}$.

The assumption that all chromium measured in subway $PM_{2.5}$ is present as Cr (VI) may be highly conservative; however, in the absence of data to suggest otherwise, it was considered appropriate.

Table 4-9 $PM_{2.5}$ and Metal Concentrations in Different Microenvironments (µg/m^3)

Chemical Parameter	Platform Concentration (95% UCLM)	On-Train Concentration	Ambient Concentration (95% UCLM)
Combined (Lines 1 and Lines 2)			
$PM_{2.5}$	3.0E+02	1.2E+02	1.1E+01
Arsenic	2.3E-02	8.9E-03	6.9E-04
Barium	7.9E+00	3.0E+00	1.4E-02
Cadmium	4.2E-02	1.6E-02	2.3E-03
Chromium (VI)	1.0E+00	3.9E-01	1.7E-04[1]
Chromium (III)	1.0E+00	3.9E-01	8.7E-04
Cobalt	4.5E-01	1.7E-01	5.2E-04
Iron	1.6E+02	6.1E+01	1.4E-01
Manganese	1.4E+00	5.3E-01	3.6E-03
Nickel	8.5E-02	3.2E-02	3.3E-04
Silver	4.2E-02	1.6E-02	1.6E-03
Line 1			
$PM_{2.5}$	1.6E+02	7.8E+01	1.1E+01
Arsenic	1.4E-02	6.7E-03	6.9E-04
Barium	2.3E+00	1.1E+00	1.4E-02
Cadmium	3.8E-02	1.8E-02	2.3E-03
Chromium (VI)	3.8E-01	1.8E-01	1.7E-04[1]
Chromium (III)	3.8E-01	1.8E-01	8.7E-04
Cobalt	2.3E-01	1.1E-01	5.2E-04
Iron	8.9E+01	4.2E+01	1.4E-01
Manganese	7.6E-01	3.6E-01	3.6E-03
Nickel	4.8E-02	2.3E-02	3.3E-04
Silver	3.8E-02	1.8E-02	1.6E-03
Line 2			
$PM_{2.5}$	3.0E+02	1.2E+02	1.1E+01
Arsenic	2.3E-02	8.9E-03	6.9E-04
Barium	7.9E+00	3.0E+00	1.4E-02
Cadmium	4.2E-02	1.6E-02	2.3E-03
Chromium (VI)	1.0E+00	3.9E-01	1.7E-04[1]
Chromium (III)	1.0E+00	3.9E-01	8.7E-04
Cobalt	4.5E-01	1.7E-01	5.2E-04
Iron	1.6E+02	6.1E+01	1.4E-01
Manganese	1.4E+00	5.3E-01	3.6E-03
Nickel	8.5E-02	3.2E-02	3.3E-04
Silver	4.2E-02	1.6E-02	1.6E-03

[1] represents 20% of the 95% ULCM total chromium ambient air concentration as per Bell and Hipfner (1997).

4.3 Characterizing of Acute and Chronic Exposure Point Concentrations

An EPC represents an approximation of an individual's daily exposure to a COPC. To approximate a subway user's exposure to $PM_{2.5}$ and associated metals, the concentration and time spent within each microenvironment (i.e., on the platform, riding the subway train, and time spent under ambient conditions) must be considered. As such, a series of time-weighted average EPCs were developed to facilitate the approximation of acute and chronic daily EPC values (Tables 4-10 and 4-11).

4.3.1 Chronic Exposure Point Concentrations

Time-activity patterns (Table 4-1) were used in conjunction with microenvironment-specific concentrations (Table 4-9) to develop a series of time-weighted EPCs and average daily EPCs. Daily subway and ambient time-weighted EPCs were calculated (Equations 3 and 4) to develop a total daily EPC (Equation 5) and average daily EPCs (Table 4-10).

$$EPC_{subway} = (PC \times TP/1440) + (TC \times TT/1440) \qquad \textit{Equation 3}$$

$$EPC_{ambient} = AC \times (1440 - (TP+TT))/1440 \qquad \textit{Equation 4}$$

$$EPC_{TD} = \text{Daily } EPC_{subway} + \text{Daily } EPC_{ambient} \qquad \textit{Equation 5}$$

Where:

EPC_{subway} = Time-weighted daily subway EPC ($\mu g/m^3$)
$EPC_{ambient}$ = Time-weighted daily ambient EPC ($\mu g/m^3$)
EPC_{TD} = Total Daily EPC($\mu g/m^3$)
PC = Concentration of $PM_{2.5}$ and specific metals on subway platforms during peak hours ($\mu g/m^3$)
TC = Concentration of $PM_{2.5}$ and specific metals in subway trains during peak hours ($\mu g/m^3$)
AC = Ambient air concentration as per Table 4-9 ($\mu g/m^3$)
TP = Time spent on subway platforms per day (minutes)
TT = Time spent riding in subway trains per day (minutes)
1440 = Number of minutes per 24-hour period (minutes)

As previously detailed (Section 4.1.1 and Table 4-2), several assumptions were made concerning the frequency with which individuals use the subway. To approximate chronic (or long-term) average daily EPCs (Table 4-10), the assumptions concerning frequency of subway use were applied to the total daily EPC estimates as per the Equation below.

$EPC_{ATD} = [(EPC_{TD} \times DPW_{subway}) + (AC \times DPW_{ambient})] \times WPY_{subway} + (AC \times WPY_{ambient})$ *Equation 6*

Where:

EPC_{ATD} = Average total daily EPC ($\mu g/m^3$)
EPC_{TD} = Total Daily EPC ($\mu g/m^3$)
AC = Ambient air concentration ($\mu g/m^3$)
DPW_{subway} = Days per 7-day period (or week) that an individual uses the subway (unitless)
$DPW_{ambient}$ = Days per 7-day period (or week) spent only under ambient conditions (unitless)
WPY_{subway} = Weeks per 52-week period (or year) that an individual uses the subway (unitless)
$WPY_{ambient}$ = Weeks per 52-week period (or year) spent only under ambient conditions (unitless)

As previously discussed, to provide ILCR estimates, the incremental lifetime average daily exposure (or EPC_{ILAD}) must be approximated. EPC_{ILAD} estimates are not inclusive of background or ambient exposures and were approximated in the following manner:

$$EPC_{ILAD} = EPC_{subway} \times DPW_{subway} \times WPY_{subway} \times AF \qquad \textit{Equation 7}$$

Where:

EPC_{ILAD} = Incremental Lifetime Average Daily EPC ($\mu g/m^3$)
EPC_{subway} = Time-weighted daily subway EPC ($\mu g/m^3$)
DPW_{subway} = Days per 7-day period (or week) that an individual uses the subway (unitless)
WPY_{subway} = Weeks per 52-week period (or year) that an individual uses the subway (unitless)
AF = Lifetime amortization factor (years of exposure / 80-year lifespan) (unitless)

For the purposes of developing EPC_{ILAD} estimates, the lifetime amortization factor (AF) was assumed to be equal to a value of one (1). In other words, it was assumed that an individual uses the subway as per the activity patterns established above (Table 4-1) for 80 years of an 80-year lifespan.

Table 4-10 Chronic Subway Exposure Point Concentration (EPC) Estimates (µg/m^3)

Metal of Interest	Time-Weighted Subway EPC		Time-Weighted Ambient EPC		Time-Weighted Total Daily EPC		Average Time-weighted Daily EPC		Incremental Lifetime Average Daily EPC	
	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Combined (Line 1 and Line 2)										
$PM_{2.5}$	2.0E+00	5.7E+00	1.0E+01	1.0E+01	1.2E+01	1.6E+01	1.1E+01	1.4E+01	7.7E-01	3.9E+00
Arsenic	1.5E-04	4.4E-04	6.8E-04	6.6E-04	8.3E-04	1.1E-03	7.5E-04	9.7E-04	5.9E-05	3.0E-04
Barium	5.1E-02	1.5E-01	1.4E-02	1.4E-02	6.5E-02	1.6E-01	3.4E-02	1.2E-01	2.0E-02	1.0E-01
Cadmium	2.7E-04	8.0E-04	2.3E-03	2.2E-03	2.6E-03	3.0E-03	2.4E-03	2.8E-03	1.1E-04	5.5E-04
Chromium (VI)	6.6E-03	2.0E-02	1.7E-04	1.7E-04	6.8E-03	2.0E-02	2.8E-03	1.4E-02	2.6E-03	1.3E-02
Chromium (III)	6.6E-03	2.0E-02	8.5E-04	8.3E-04	7.5E-03	2.0E-02	3.5E-03	1.4E-02	2.6E-03	1.3E-02
Cobalt	2.9E-03	8.6E-03	5.1E-04	5.0E-04	3.4E-03	9.1E-03	1.7E-03	6.4E-03	1.2E-03	5.9E-03
Iron	1.0E+00	3.0E+00	1.3E-01	1.3E-01	1.2E+00	3.2E+00	5.4E-01	2.2E+00	4.1E-01	2.1E+00
Manganese	9.0E-03	2.6E-02	3.5E-03	3.4E-03	1.3E-02	3.0E-02	7.1E-03	2.2E-02	3.5E-03	1.8E-02
Nickel	5.5E-04	1.6E-03	3.3E-04	3.2E-04	8.8E-04	1.9E-03	5.5E-04	1.4E-03	2.2E-04	1.1E-03
Silver	2.7E-04	8.0E-04	1.6E-03	1.6E-03	1.9E-03	2.4E-03	1.7E-03	2.1E-03	1.1E-04	5.5E-04
Line 1										
$PM_{2.5}$	1.2E+00	3.7E+00	1.0E+01	1.0E+01	1.2E+01	1.4E+01	1.1E+01	1.3E+01	4.9E-01	2.6E+00
Arsenic	1.1E-04	3.2E-04	6.8E-04	6.6E-04	7.9E-04	9.8E-04	7.3E-04	8.9E-04	4.2E-05	2.2E-04
Barium	1.7E-02	5.2E-02	1.4E-02	1.4E-02	3.2E-02	6.6E-02	2.1E-02	5.0E-02	6.9E-03	3.6E-02
Cadmium	2.9E-04	8.6E-04	2.3E-03	2.2E-03	2.6E-03	3.1E-03	2.4E-03	2.8E-03	1.1E-04	5.9E-04
Chromium (VI)	2.9E-03	8.6E-03	1.7E-04	1.7E-04	3.0E-03	8.7E-03	1.3E-03	6.1E-03	1.1E-03	5.9E-03
Chromium (III)	2.9E-03	8.6E-03	8.5E-04	8.3E-04	3.7E-03	9.4E-03	2.0E-03	6.7E-03	1.1E-03	5.9E-03
Cobalt	1.7E-03	5.2E-03	5.1E-04	5.0E-04	2.3E-03	5.7E-03	1.2E-03	4.1E-03	6.9E-04	3.6E-03
Iron	6.7E-01	2.0E+00	1.3E-01	1.3E-01	8.1E-01	2.1E+00	4.0E-01	1.5E+00	2.7E-01	1.4E+00
Manganese	5.7E-03	1.7E-02	3.5E-03	3.4E-03	9.3E-03	2.1E-02	5.8E-03	1.5E-02	2.3E-03	1.2E-02
Nickel	3.6E-04	1.1E-03	3.3E-04	3.2E-04	6.9E-04	1.4E-03	4.8E-04	1.1E-03	1.4E-04	7.4E-04
Silver	2.9E-04	8.6E-04	1.6E-03	1.6E-03	1.9E-03	2.4E-03	1.7E-03	2.2E-03	1.1E-04	5.9E-04
Line 2										

Metal of Interest	Time-Weighted Subway EPC		Time-Weighted Ambient EPC		Time-Weighted Total Daily EPC		Average Time-weighted Daily EPC		Incremental Lifetime Average Daily EPC	
	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
$PM_{2.5}$	3.7E+00	7.4E+00	1.0E+01	1.0E+01	1.4E+01	1.7E+01	1.2E+01	1.5E+01	1.5E+00	5.1E+00
Arsenic	2.6E-04	5.3E-04	6.8E-04	6.6E-04	9.4E-04	1.2E-03	7.9E-04	1.0E-03	1.0E-04	3.6E-04
Barium	1.1E-01	2.2E-01	1.4E-02	1.4E-02	1.2E-01	2.4E-01	5.8E-02	1.7E-01	4.4E-02	1.5E-01
Cadmium	2.8E-04	5.6E-04	2.3E-03	2.2E-03	2.6E-03	2.8E-03	2.4E-03	2.6E-03	1.1E-04	3.9E-04
Chromium (VI)	1.5E-02	3.1E-02	1.7E-04	1.7E-04	1.6E-02	3.1E-02	6.3E-03	2.2E-02	6.1E-03	2.1E-02
Chromium (III)	1.5E-02	3.1E-02	8.5E-04	8.3E-04	1.6E-02	3.2E-02	7.0E-03	2.2E-02	6.1E-03	2.1E-02
Cobalt	5.9E-03	1.2E-02	5.1E-04	5.0E-04	6.4E-03	1.2E-02	2.8E-03	8.7E-03	2.3E-03	8.1E-03
Iron	1.9E+00	3.9E+00	1.3E-01	1.3E-01	2.0E+00	4.0E+00	8.9E-01	2.8E+00	7.6E-01	2.6E+00
Manganese	1.7E-02	3.4E-02	3.5E-03	3.4E-03	2.0E-02	3.8E-02	1.0E-02	2.7E-02	6.7E-03	2.3E-02
Nickel	1.5E-03	3.1E-03	3.3E-04	3.2E-04	1.9E-03	3.4E-03	9.4E-04	2.4E-03	6.1E-04	2.1E-03
Silver	3.3E-04	6.6E-04	1.6E-03	1.6E-03	1.9E-03	2.2E-03	1.7E-03	2.0E-03	1.3E-04	4.5E-04

4.3.2 Acute Exposure Point Concentrations

The TTC (2019) data indicated that most subway users spend approximately one (1) hour in the subway system on any given travel day (i.e., approximately a ½-hour each way). Most of this time is spent on the subway train, with up to five minutes a day (in total for both directions) spent waiting on the platform. As such, exposure to subway $PM_{2.5}$ and associated metals of interest over a ½-hour to 1-hour averaging time would be considered relevant to characterizing acute human health risks. Acute EPCs were derived in a similar fashion to the chronic daily EPCs, with the exception that time-weighted subway exposures were averaged over the time spent only within the subway system (Equation 8), not over an entire 24-hour period. As such, it is the difference between platform wait and train riding times that influence acute EPC estimates. Table 4-11 presents the short-term (or acute) subway EPCs for $PM_{2.5}$ and associated metals of interest.

$$EPC_{Acute} = [PC \times TP / (TP+TT)] + [TC \times TT / (TP+TT)] \qquad \textit{Equation 8}$$

Where:

EPC_{Acute} = Acute EPC while in the subway system ($\mu g/m^3$)
PC = Concentration of $PM_{2.5}$ and specific metals on subway platforms during peak hours ($\mu g/m^3$)
TC = Concentration of $PM_{2.5}$ and specific metals in subway trains during peak hours ($\mu g/m^3$)
TP = Time spent on subway platforms per trip (minutes)
TT = Time spent riding in subway trains per trip (minutes)

Table 4-11 Acute Subway Exposure Point Concentration (EPC_{Acute}) Estimates

Chemical Parameter	Time-Weighted Subway EPC_{Acute} ($\mu g/m^3$)		
	Line 1	Line 2	Combined (Lines 1 and 2)
$PM_{2.5}$	8.5E+01	1.8E+02	1.3E+02
Arsenic	7.3E-03	1.3E-02	1.0E-02
Barium	1.2E+00	5.5E+00	3.4E+00
Cadmium	1.9E-02	1.4E-02	1.8E-02
Chromium (VI)	1.9E-01	7.7E-01	4.4E-01
Chromium (III)	1.9E-01	7.7E-01	4.4E-01
Cobalt	1.2E-01	2.9E-01	1.9E-01
Iron	4.6E+01	9.5E+01	6.9E+01
Manganese	3.9E-01	8.4E-01	6.0E-01
Nickel	2.5E-02	5.1E-02	3.6E-02
Silver	1.9E-02	1.6E-02	1.8E-02

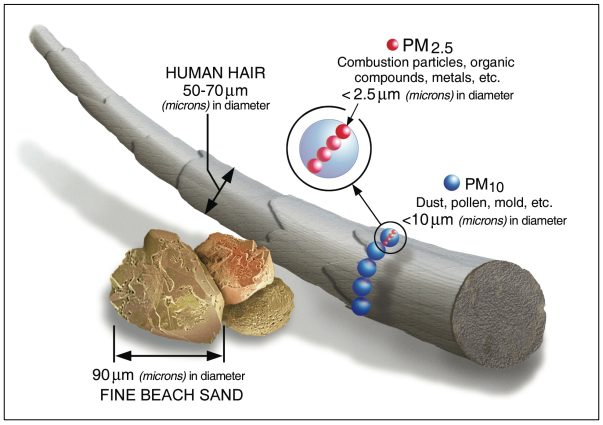
5.0 Toxicity Assessment

There are two steps of the Toxicity Assessment, including: a) the classification of COPC based on their dose-response relationship (i.e., threshold versus non-threshold), recognizing that some COPC may have both threshold and non-threshold effects and, b) the identification of appropriate toxicity reference values (TRVs). Most HHRAs identify and select TRVs (e.g., inhalation RfCs, IUR values, oral RfDs, etc.) published and recommended for use by recognized regulatory agencies (e.g., Health Canada, MECP, US EPA, WHO, ATSDR, Cal EPA, etc.). The following Sections present the acute and chronic inhalation TRVs selected for use to assist in the characterization of health risks from exposure to subway $PM_{2.5}$ and associated metals of interest.

5.1 Fine Particulate Matter ($PM_{2.5}$)

Particulate matter (or PM) is a term used to represent a mixture of very small solid particles and liquid droplets in air. PM is a concern, as it is associated with a variety of serious health effects and premature death (US EPA, 2019a). The composition of PM is complex, with some particles (e.g., dust, soot, smoke, etc.) being large and/or dark enough to be visible with the naked eye, while other particles can only be detected using an electron microscope (US EPA, 2019b). Two common particle sizes are often referenced when discussing PM pollution:

- PM_{10}: representing particles with a nominal mean aerodynamic diameter of less than 10 micrometres or microns (µm); and,
- $PM_{2.5}$: representing particles with a nominal mean aerodynamic diameter of less than, or equal to, 2.5 µm (US EPA, 2009).



Source: US EPA (2019b)

$PM_{2.5}$, often referred to as fine PM, is approximately 35 times smaller than the diameter of fine beach sand or about 30 times smaller than the diameter of the average human hair (US EPA, 2009; 2019b). $PM_{2.5}$ represents the greatest risk to human health (relative to larger PM size fractions), as $PM_{2.5}$ can be deposited deep within the lungs and can, in some instances, enter the bloodstream (US EPA 2019a).

5.1.1 Human Health Effects

The US EPA Integrated Science Assessment (ISA) for Particulate Matter (US EPA, 2009) represents the scientific foundation for the review of the health-based primary and welfare-based secondary National Ambient Air Quality Standard (NAAQS) for PM. It is

noted that a draft 2018 ISA for PM is available for public review and comment; however, the US EPA has not yet finalized the 2018 ISA. The US EPA (2009) presents a weight of evidence approach to classify causality, breaking down causal effects into the following five (5) possible determinations:

- *Causal Relationship* – It has been demonstrated in scientific studies that exposure to the pollutant of interest has resulted in health effects in which chance, bias, and confounding factors could be ruled out with reasonable confidence;
- *Likely to be a Causal Relationship* – It has been demonstrated in scientific studies that exposure to the pollutant of interest has resulted in health effects in which chance, bias, and confounding factors could be ruled out with reasonable confidence; however, potential issues remain;
- *Suggestive of a Causal Relationship* – The scientific evidence is suggestive of a causal relationship between relevant exposures to the pollutant and the health effect; however, causality is limited because chance, bias, and/or confounding factors could not be ruled out;
- *Inadequate to Infer a Causal Relationship* – Scientific studies are not sufficient in terms of quantity, quality, consistency, or statistical power to allow for the determination of an effect (or no effect) resulting from exposure; and
- *Not Likely to be a Causal Relationship* – Requires several studies, of adequate quality, that collectively cover a range of exposures that humans (including sensitive sub-populations) may potentially encounter, which consistently show no effects at any level of exposure.

A review of the scientific literature by the US EPA (2009) led to the conclusion that strong and consistent evidence exists that long-term (or chronic) exposure to $PM_{2.5}$ is associated with an increased risk of human mortality. The strongest evidence of this relationship comes from studies that investigated mortality due to cardiovascular disease (CVD). More specifically, many large-scale cohort studies conducted in the Unites States reported strong and consistent associations between chronic PM2.5 exposure and cardiovascular mortality. Additional evidence comes from an epidemiological study (Miller et al., 2007) that demonstrated consistent associations between chronic PM2.5 exposure and cardiovascular disease morbidity among post-menopausal women (US EPA, 2009). The evidence produced from epidemiological and toxicological studies was sufficient for the US EPA (2009) to conclude that *a causal relationship* exists between chronic $PM_{2.5}$ exposure and cardiovascular effects.

The most convincing evidence that supports a likely relationship between chronic PM2.5 exposure and respiratory morbidity comes from epidemiological studies that have investigated associations between fine particulate exposure and changes in lung

function growth among children, in addition to disease incidence in adults. Toxicological studies have provided evidence of biological plausibility by demonstrating altered pulmonary function, mild inflammation, oxidative responses, histopathological changes, and enhanced allergic responses (US EPA, 2009). The US EPA (2009) stated that the evidence from both epidemiological and toxicological studies was sufficient to conclude that a *likely causal relationship* exists between chronic $PM_{2.5}$ exposure and respiratory effects.

Numerous studies conducted throughout various part of the world have found that long-term exposure to ambient $PM_{2.5}$ is associated with lung cancer mortality among nonsmokers. The Harvard Six Cities Study demonstrated that statistically significant association exists between long-term ambient $PM_{2.5}$ exposure and lung cancer mortality rates. A linear concentration-response relationship, with no evidence of a threshold to a concentration of 8 $\mu g/m^3$, was observed by Lepeule et al., 2012 (IARC, 2013). Although $PM_{2.5}$ is considered carcinogenic, no regulatory published inhalation unit risk factors specific to $PM_{2.5}$ and lung cancer incidence have been identified.

In summary, a review of the epidemiological, controlled human exposure, and toxicological studies led the US EPA (2009) to conclude that a *causal relationship* exists between both acute and chronic $PM_{2.5}$ exposures and cardiovascular effects and mortality. Similarly, the US EPA (2009) concluded that *a likely causal relationship* exists between both acute and chronic $PM_{2.5}$ exposures and respiratory effects. In addition, the US EPA (2009) concluded that a *suggestive causal relationship* exists between chronic $PM_{2.5}$ exposure and reproductive and developmental effects, in addition to cancer, mutagenicity, and genotoxicity.

Acute exposure studies involving individuals participating in normal activities under ambient conditions have shown that short-term exposures to $PM_{2.5}$ are associated with a multiple effects, including increased respiratory symptoms (*e.g.,* cough, chest tightness, shortness of breath general asthma symptoms, *etc.*) , decrements in lung function (as measured by decreased forced exploratory volume, for example), and pulmonary inflammation. Asthmatic children and adults with COPC appear to be most susceptible to these effects; however, limited evidence indicates that healthy children and adults may be at an increased risk (HC, 2013). Evidence from controlled human exposure studies, albeit limited, lend support for the identification of asthmatic individuals as a sensitive group to acute PM exposure. Individuals with pneumonia and those with existing respiratory infections may also be at greater risk of effects from acute PM exposure (HC, 2013).

5.1.2 Concentration-Response Relationship

The US EPA (2009) reviewed epidemiological studies that attempted to characterize the shape of the PM-cardiovascular hospital admission and emergency department visit

concentration-response relationship. Most of the studies reviewed by the US EPA (2009) support the use of a no-threshold log-linear concentration-response model; however, several issues, including the effect of seasonal and regional differences in PM on the concentration-response relationship, warrant further examination.

The US EPA (2009) also identified and reviewed a study by Schwartz et al. (2008) that analyzed the shape of the concentration-response relationship associated with long-term exposure to PM. The US EPA (2009) indicated that Schwartz et al. (2008) found a linear concentration-response curve was linear which extended below the US EPA air quality standard (at that time) of 15 $\mu g/m^3$, suggesting that a threshold does not exist between chronic $PM_{2.5}$ exposure and the risk of death. The Toronto Subway Air Quality Health Impact Assessment (TSAQ HIA) Expert Panel Workshop Report (Appendix A) also concluded that both Health Canada and international health agencies agree that $PM_{2.5}$, regardless of its composition, is a non-threshold health hazard, meaning that exposure to any level of $PM_{2.5}$ poses some potential detriment to health.

5.1.3 Composition of Subway PM

The composition of atmospheric PM is a complex mixture of both primary (i.e., directly emitted by sources) and secondary components (often produced by the oxidation of precursor gases) such as SO_2 and NOx (US EPA, 2009). The UTES (Van Ryswyk et al., 2017) clearly illustrated the difference in elemental composition between $PM_{2.5}$ samples collected from within the Toronto subway system and ambient air samples. Van Ryswyk et al. (2017) compared the abundance of fourteen (14) different elements in $PM_{2.5}$ from subway and ambient air samples and found that subway $PM_{2.5}$ was highly enriched in several elements, including iron, chromium, cobalt, nickel, and barium. The most abundant element identified in $PM_{2.5}$ samples collected from the Toronto subway system was iron, with a median abundance of 54% — approximately two orders of magnitude greater than the amount of iron found in ambient $PM_{2.5}$ samples. Similarly, the SAQI data (as discussed in Section 4.2.3), also indicated that iron was the most abundant element found in Toronto Subway $PM_{2.5}$, at a median abundance of 52% compared with a median iron abundance of approximately 1.4% from Toronto ambient air $PM_{2.5}$ samples.

The results from Van Ryswyk et al. (2017) and the SAQI dataset are consistent with the latest findings from Loxham and Nieuwenhuijsen (2019) who conducted a systematic review of the evidence concerning the health effects of PM air pollution in underground railway systems. Among other conclusions, Loxham and Nieuwenhuijsen (2019) found that underground PM is often associated with an increased PM mass concentration and enriched in transition metals, with iron being predominant. However, levels of metals associated with train brake wear, electrical components, and lubricants (e.g., copper, barium, antimony, etc.) were also elevated relative to ambient PM.

Loxham and Nieuwenhuijsen (2019) also noted that the proportion of transition metals found in underground PM that are water-soluble (and, therefore, bioavailable) was observed to be lower than the proportion of water-soluble metals found in ambient PM collected from urban sources. This observation may, as indicated by Loxham and Nieuwenhuijsen (2019), potentially be due to the low levels of secondary anions (i.e., NO_3^- and SO_4^{2-}) often associated with underground PM. As such, without considering the water-soluble fraction, the concentration of bioavailable metal present in underground PM may be overestimated (relative to ambient PM) if only total metal in PM is considered in isolation (Loxham and Nieuwenhuijsen (2019)).

Although the Loxham and Nieuwenhuijsen (2019) review concluded that there was little direct evidence that exposure to subway PM is more harmful than exposure to ambient PM, the conclusion may, in part, have been a result of inconsistencies identified between the results of in person exposure studies and *in vitro* toxicity tests. The authors indicated that while a variety of effects were measured following in vivo (or in person) exposure, no evidence was found that these measured effects were of any clinical significance (Loxham and Nieuwenhuijsen, 2019). The authors also highlighted the need for future research to understand the mechanisms of toxicity, possible biomarkers of exposure, and the outcome of long-term, in person (or *in vivo*) exposures to underground railway PM.

The TSAQ HIA Expert Panel Workshop Report (Appendix A) concluded that the composition of Toronto Subway $PM_{2.5}$ in air is markedly different than that typically found in Toronto ambient air. However, there are no Canadian or international subway-specific $PM_{2.5}$ TRVs or exposure guidelines that have been developed. In the absence of sufficient epidemiological or toxicity data, it should be assumed that subway $PM_{2.5}$ has a similar level of toxicity as ambient $PM_{2.5}$, and should rely on the research underpinning the Canadian and international guidelines for $PM_{2.5}$ in ambient air.

5.2 Inhalation Air Quality Standards for $PM_{2.5}$

5.2.1 Canadian Ambient Air Quality Standards

The Canadian Ambient Air Quality Standards (CAAQS) for fine PM, published by the Canadian Council of Ministries of the Environment (CCME, 2012), were developed through a collaborative process involving federal, provincial, and territorial governments as directed by the CCME. Under the Air Quality Management System (AQMS), stakeholders and provincial and territorial governments are to work together to maintain air quality, achieve the CAAQS, and drive continuous improvements in air quality.

As summarized below (Table 5-1), the CCME (2012) developed annual average CAAQS for $PM_{2.5}$ of 10 µg/m^3 and 8.8 µg/m^3 for compliance by 2015 and 2020, respectively. The long-term CAAQS were designed to be used in conjunction with ambient air quality data collected over a series of several years. More specifically, the

intended metric is the 3-year average of the annual average $PM_{2.5}$ concentrations. The CCME (2012) also developed 24-hour average CAAQS for $PM_{2.5}$ of 28 µg/m^3 and 27 µg/m^3 for compliance by 2015 and 2020, respectively. The 24-hour average CAAQS were designed to be compared with the 3-year average of the annual 98th percentile of the daily 24-hour average concentrations.

Table 5-1 Canadian Ambient Air Quality Standards - Fine Particulate Matter ($PM_{2.5}$)

Averaging Time	2015	2020	Metric
Annual $PM_{2.5}$ CAAQS (µg/m^3)	10.0	8.8	The 3-year average of the annual average concentrations
24-hour $PM_{2.5}$ CAAQS (µg/m^3)	28	27	The 3-year average of the annual 98th percentile of the daily 24-hour average concentrations.

The objective or intent of an air quality standard will influence the methods used to develop the standard. Unlike many contaminants, where air standards are designed to protect the most sensitive members of a population from a specific adverse health effect that may (or may not) have a clearly defined effects threshold, $PM_{2.5}$ exposures (as outlined above) are associated with a variety of serious adverse health effects, including premature death, where no discernable effects threshold has been identified. The CAAQS were developed to 'better protect human health and the environment', but they are also aspirational in nature in that they were designed, in part, to drive continuous improvements in air quality. Although supporting documentation is available (CCME, 2012), the rationale and specific methods used by the CCME to derive the final CAAQS for $PM_{2.5}$ are not published.

Personal communication with Health Canada (HC, 2019b) confirmed that, due to the pseudo-linear relationship between health and ambient $PM_{2.5}$ concentrations and the lack of an effects threshold, a specific attainable target concerning the reduction in population exposure relative to current levels was developed, within which an ambient $PM_{2.5}$ concentration standard could be generated and recognizing that all improvements in $PM_{2.5}$ will benefit health . As such, the CAAQS for $PM_{2.5}$ represents ambient air concentrations associated with a specific percent improvement in population exposure over existing conditions. It is not intended to be used as a threshold to identify health impacts.

5.2.2 United States Environmental Protection Agency – National Ambient Air Quality Standard

The US EPA developed a primary annual National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$, to protect the health of 'sensitive' populations, of 12 µg/m^3. The primary NAAQS was based largely on evidence obtained from epidemiological studies relating ambient $PM_{2.5}$ concentrations to various adverse health endpoints (e.g., respiratory morbidity, cardiovascular-related effects, increased risk of mortality, etc.)

(US EPA, 2010). The primary annual NAAQS is to be used in conjunction with the annual average ambient air concentration, averaged over a 3-year period.

The US EPA also developed a 24-hour average (NAAQS) for $PM_{2.5}$ of 35 µg/m^3 based on epidemiological data relating ambient $PM_{2.5}$ concentrations with mortality and morbidity rates. The 24-hour average NAAQS is to be compared to the 3-year average value (98th percentile) of 24-hour average concentrations (US EPA 2010). Although the US EPA staff concluded that the protection of human health resulting from both short- and long-term exposures to $PM_{2.5}$ can effectively be provided through the use of the annual standard, the 24-hour standard was thought to provide added protection on days of with elevated peak concentrations (US EPA, 2010).

5.2.3 World Health Organization

The World Health Organization (WHO, 2006a) developed an annual air quality guideline (AQG) for $PM_{2.5}$ of 10 µg/m^3. The annual AQG (of 10 µg/m^3) was based on data obtained from two significant long-term exposure studies, including the American Cancer Society (ACS) study (Pope et al., 2002) and the Harvard Six Cities study (Krewski et al., 2000), both of which reported strong associations between long-term $PM_{2.5}$ exposure and mortality.

The WHO (2006a) annual AQG represents the lowest $PM_{2.5}$ concentration over which cardiopulmonary and cancer mortality rates were shown to increase (at ≥ 95% confidence) in the ACS study. Pope et al., (2002) found that each 10 µg/m^3 increase in $PM_{2.5}$ concentration was associated with an approximate 4%, 6%, and 8% increase risk of all-cause, cardiopulmonary, and lung cancer mortality, respectively (WHO, 2006a). Although statistical uncertainty in risk estimates were observed in the ACS study below a $PM_{2.5}$ concentration of 13 µg/m^3, Dockery et al. (1993) provided evidence indicating that health effects (associated with chronic exposure to $PM_{2.5}$) were likely to occur in the range of 11 to 15 µg/m^3. Although adverse health effects associated with long-term exposures could not be ruled out below this range (11 to 15 µg/m^3), the annual $PM_{2.5}$ AQG (of 10 µg/m^3) was considered a level that, in practice, could be achieved in highly urbanized areas while, at the same time, still being likely to result in reductions in health risks if met (WHO, 2006a).

In addition to an annual AQG, the WHO (2006a) developed three (3) interim targets (Table 5-2). The interim targets were set as attainable goals which could be achieved if continued abatement measures were undertaken (WHO, 2006a). Although the AQG is the desirable endpoint, the interim targets were thought to be useful in measuring progress (over time) as various jurisdictions move towards reducing ambient PM levels to the AQG.

Table 5-2 WHO Annual Air Quality Guidelines and Interim Targets (µg/m^3)[1]

WHO AQG and Interim Targets	PM_{10}	$PM_{2.5}$	Basis
Interim target 1 (IT-1)	70	35	Associated with the highest observed values in long-term health effect studies. Approximately a 15% higher long-term mortality over AQG levels.
Interim target 2 (IT-2)	50	25	Associated with lower risk of premature mortality by approximately 6% (95% CI: 2-11%) relative to IT-1 levels; also associated with other health benefits.
Interim target 3 (IT-3)	30	15	Associated with lower risk of premature mortality by approximately 6% (95% CI: 2-11%) relative to IT-2 levels; also associated with other health benefits.
Air quality guideline (AQG)	20	10	Associated with lowest concentrations over which cardiopulmonary and cancer mortality have been shown to increase (at ≥ 95% confidence) in response to $PM_{2.5}$ exposure in the ACS study.

[1]Source: WHO (2006a)

The WHO (2006a) also developed a 24-hour average AQG for $PM_{2.5}$ of 25 µg/m^3, in addition to a series of interim 24-hour average targets (Table 5-3). The 24-hour AQG for $PM_{2.5}$ is based on the relationship between 24-hour and annual PM concentrations.

Table 5-3 WHO 24-hour Mean Air Quality Guidelines and Interim Targets (µg/m^3)[1]

WHO AQG and Interim Targets	PM_{10}	$PM_{2.5}$	Basis
Interim target 1 (IT-1)	150	75	Represents approximately a 5% increase in short-term mortality over the AQG. This estimate is based on meta-analyses and multicenter studies.
Interim target 2 (IT-2)	100	50	Represents approximately a 2.5% increase in short-term mortality over the AQG. This estimate is based on meta-analyses and multicenter studies.
Interim target 3 (IT-3)	75	37.5	Represents approximately a 1.2% increase in short-term mortality over the AQG.
Air quality guideline (AQG)	50	25	Derived using the relationship between 24-hour and annual average PM concentrations.

[1]Source: WHO (2006a)

The WHO (2006a) air quality guidelines (AQGs) and interim threshold targets (ITTs) have been selected for use in the current HHRA to help characterize health risks associated with $PM_{2.5}$ exposure (Section 6.1). Although the WHO (2006a) AQGs and ITTs do not represent exposure thresholds and/or toxicity data specific to subway $PM_{2.5}$, they were developed by the WHO using large scale long-term exposure studies that can be aligned with specific risks of increased mortality rates. The WHO (2006a) AQGs and ITTs also provide a regulatory structure to drive continuous reduction (or improvement) in $PM_{2.5}$ levels.

5.3 Chronic Toxicity Reference Values for Metals in $PM_{2.5}$

The Expert Panel Report (Appendix A) recommended that the evaluation of the individual airborne metals in subway PM should be undertaken quantitatively using

internationally recognized inhalation reference concentrations, where available. TRVs should be sourced from the following agencies:

- United States Environmental Protection Agency (US EPA);
- Health Canada;
- World Health Organization; and
- California Office of Environmental Health Hazard Assessment (OEHHA).

Subsequent to the Panel discussion, TPH identified that a considerable amount of effort had been made to identify appropriate inhalation TRVs on another TPH air quality project. As such, where there were common metals between the two studies, the previously approved TPH inhalation TRVs were recommended for use in the current HHRA.

Apart from iron, silver, and chromium, TRVs for all metals identified (in Section 3.2) for further assessment (i.e., arsenic, barium, cadmium, cobalt, manganese, and nickel) were previously approved for use in another recent TPH air quality project. Inhalation TRVs (for all metals of interest) that had previously been approved by TPH were reviewed, in part, to ensure that the regulatory agencies that originally published the TRVs had not provided updates since the time of the previous TPH air quality assessment. Table 5-4 presents the chronic inhalation TRVs selected for use in the HHRA.

Table 5-4 Summary of Chronic Inhalation Toxicological Reference Values

Chemical Parameter	Inhalation Toxicological Reference Values		Critical Effect	Toxicological Study / Derivation	Reference
	Type	Value (Units)			
Arsenic	REL	0.015[a] (µg/m^3)	Observed decreases in intellectual function and adverse effects on neurobehavioural development among children	Oral exposure study involving children exposed to arsenic for 9,5 to 10.5 years via drinking water (Wasserman et al., 2004). REL was based on route extrapolation. Supporting study by Tsai et al. (2003).	Cal EPA (2008)
	IUR	0.0064 (µg/m^3)$^{-1}$	Lung cancer	IUR developed using data from an occupational exposure study conducted by Higgens et al., 1986.	HC (2010b)
Barium	TCA	1 (µg/m^3)	Not Available	A NOAEC (of 110 µg/m^3 barium) was derived from a continuous exposure study involving exposure of rats to barium carbonate. Cumulative UF of 100 applied.	MOE (2011); RIVM (2001)
Cadmium	AAQC	0.005 (µg/m^3)	Kidney effects (as indicated by proteinuria associated with proximal tubular dysfunction) and lung cancer as a result of occupational exposures	Study provided consolidated data from seven (7) different epidemiological studies. A reported LOAEL of 0.270 µg/m^3 (Thun et al., 1991). A total UF of 50 (5 for use of LOAEL and 10 for inter-species variation) was applied.	MOE (2007)
	IUR	0.0098 (µg/m^3)$^{-1}$	Lung tumours	18-month inhalation rat study using cadmium chloride aerosol (Takenaka et al., 1983; Oldiges et al., 1984).	HC (2010b)
Chromium (VI)	ReV	0.22 (µg/m^3)	Increase in relative lung weight observed among rats exposed for 90 days.	Glaser al. (1986) — a 90-day inhalation study in rats where the observed critical effect was an increase in relative lung weight. A POD_{HEC} of 60.25 µg Cr (VI)/m^3 was derived based on a NOAEL. A total UF of 270 was applied to the POD_{HEC} 0.22 µg Cr (VI)/m^3.	TCEQ (2014)
	IUR	0.0023(µg/m^3)$^{-1}$	Increased incidence of lung cancer in industrial workers	Data from Crump et al. (2003) and Gibb et al. (2000) were used to derive a final IUR value.	

Chemical Parameter	Inhalation Toxicological Reference Values		Critical Effect	Toxicological Study / Derivation	Reference
	Type	Value (Units)			
Chromium (III)	ReV	0.14 (µg/m^3)	Increased relative lung and trachea weight in rats and widespread inflammatory effects.	Data from Derelanko et al. (1999) — an inhalation study involving rats exposed to chromium sulfate particulate. Data were used to derive a POD_{HEC} of 809 µg/m^3 with an applied total UF of 1,000 to derive a ReV for Cr^{3+} of 0.14 µg/m^3.	TCEQ (2009)
Cobalt	TC	0.1 (µg/m^3)	Reduction in lung function among diamond polishers exposed to airborne cobalt.	Occupational study of diamond polishers (Nermery et al., 1992). WHO established a NOAEC of 1.3 µg/m^3 (adjusted for continuous exposure) and applied a UF of 10 for intra-species variability.	WHO (2006b)
Iron	Interim ESL	5 (µg/m^3)	Prevention of pulmonary siderosis in workers	1,000-fold UF applied to the ACGIH TLV of 5,000 µg/m^3 for iron oxide to prevent pulmonary siderosis in workers from the inhalation of iron particulate.	TCEQ (2019)
Manganese	RfC (µg/m^3)	0.05 (µg/m^3)	Impairment of neurobehavioral function.	Occupational exposure study involving 92 workers exposed to manganese dioxide dust in an alkaline battery plant (Roles et al., 1992). A composite UF of 1,000 was applied to an adjusted LOAEL of 50 µg/m^3.	US EPA (1993)
Nickel	REL	0.014 (µg/m^3)	Chronic active inflammation, macrophage hyperplasia, alveolar proteinosis, and fibrosis.	A NTP (1994) study involving mice and rats exposed to nickel sulphate for 6 hours per day, 5 days per week, for durations between 16 days and 104 weeks. A Human Equivalent Benchmark Dose Lower limit $(BMDL)_{05}$ (HEC) of 1.4 µg/m^3 with the application of a 100-fold UF.	Cal EPA (2012)
	IUR	0.00026 (µg/m^3)$^{-1}$	Lung and nasal sinus cancer rates among Ontario nickel refinery plant workers	Data from several different occupational exposure studies involving refinery workers in Copper Hill, Ontario.	Cal EPA (2011)
Silver	Interim ESL	0.01 (µg/m^3)	argyria – a benign but permanent bluish-grey discolouration of the skin.	Interim Environmental Screening Limit (ESL) based on a NIOSH REL of 10 µg/m^3 for soluble silver compounds with a 1,000-fold UF applied.	TCEQ (2019)

[a] The chronic REL (of 0.015 µg/m^3) protective of children was used in the assessment. The chronic REL protective of adults is 0.044 µg/m^3 (Cal EPA, 2008).
AAQC – Ambient Air Quality Criteria
ACGIH – American Conference of Governmental Industrial Hygienists

Chemical Parameter	Inhalation Toxicological Reference Values		Critical Effect	Toxicological Study / Derivation	Reference
	Type	Value (Units)			

NIOSH – National Institute for Occupational Safety and Health
ESL – Environmental Screening Level
IUR – Inhalation Unit Risk
REL – Reference Exposure Limit
ReV – Reference Value
RfC – Reference Concentration
TC – Tolerable Concentration
TCA – Tolerable Concentration in Air

Iron and silver were not previously included in the other recently completed TPH air quality study. As such, a rationale for the selection of both metals is provided below. While chromium was previously evaluated by the TPH air quality study, more recent information from the TCEQ has been identified and was used in the current HHRA.

5.3.1 Iron

A ranked search of the regulatory agencies cited above (i.e., US EPA, Health Canada, WHO, and OEHHA) did not result in the identification of a health-based chronic inhalation TRV or specific screening-level value specific to iron and/or iron oxide dust. The US EPA Provisional Peer Reviewed Toxicity Value (PPRTV) document for iron and iron compounds (US EPA, 2006) concluded that insufficient data existed (at the time of publication in 2006) to derive a non-cancer or cancer inhalation TRV for iron under the Integrated Risk Information System (IRIS).

Under Ontario Regulation 419/05, the Ontario Ministry of Environment, Conservation and Parks (MECP) reports 'health-based' 24-hour and ½-hour air standards for iron particulate of 4 and 10 µg/m^3, respectively. The ½-hour air standard (of 10 µg/m^3) for iron particulate was originally developed in 1968 by the MECP (formerly the MOE) to prevent rust spotting on painted surfaces. The derivation of this AAQC was, in part, developed using data on car spotting (MOE, 2005b).

In 1985, the MOE completed a second review, focusing on the health effects associated with the inhalation of iron particulate. The results of this review concluded that a 24-hour ambient air standard of four µg/m^3 for metallic iron would be protective of health among the general population (MOE, 2005). This conclusion was, in part, informed by a threshold limit value (TLV) identified for iron particulate (of 5,000 µg/m^3, measured as iron particulate), published by American Conference of Governmental Industrial Hygienists (ACGIH). The occupational TLV was designed to prevent pulmonary siderosis (a form of pneumoconiosis) in workers, resulting from the inhalation of iron particulate. According to the MOE (2005b), the health-based 24-hour AAQC was derived using the original 1968 ½-hour value (of 10 µg/m^3), originally developed to prevent rust spotting on painted surfaces, and a conversion factor of 2.5 which considered the difference in sampling time and the potential for multiple sources of the same contaminant being emitted in one area.

Based on rationale provided by the MOE (2005b), in addition to personal communication with the MECP Standards Development Branch (SDB, 2019), it appears that the occupational TLV (of 5,000 µg/m^3) for iron was not used in any direct, quantitative fashion to derive the 24-hour AAQC but, rather, was used as a point of reference to confirm that the existing 24-hr AAQC (of 4 µg/m^3) is also likely to be protective of health among the general population.

A more recent review conducted of the Texas Commission on Environmental Quality (TCEQ) ESL database reported interim short- and long-term environmental screening levels (ESLs) for iron of 50 µg/m^3 and 5 µg/m^3, respectively, based on the ACGIH TLV of 5,000 µg/m^3 for iron oxide (to prevent pulmonary siderosis in workers from the inhalation of iron particulate) (TCEQ, 2019). The TCEQ applied a 1,000-fold uncertainty factor to the ACGIH TLV to develop an interim long-term ESL for iron of 5 µg/m^3. As such, the chronic TRVs, including the ESL for iron, as summarized in Table 5-4 were selected for used in the HHRA.

5.3.2 Silver

A ranked search of the US EPA, Health Canada, WHO, and OEHHA did not result in the identification of a health-based chronic inhalation TRV or a specific screening-level value specific to silver. The minimal risk levels (MRLs) published by the Agency for Toxic Substance and Disease Registry (ATSDR) and The Ontario MECP air quality standards were also reviewed; however, no inhalation TRVs were identified specific to silver. A query of the TCEQ (2019) ESL database resulted in the identification of a long-term interim ESL for silver of 0.01 (µg/m^3). The TCEQ interim ESL of 0.01 µg/m^3 is based on a NIOSH REL of 10 µg/m^3 for soluble silver compounds with an applied 1,000-fold UF. As such, the chronic TRVs, including the ESL for silver, as summarized in Table 5-4 were selected for used in the HHRA.

5.3.3 Chromium

Lovett et al. (2017) and Chillrud et al. (2004) make the argument that any chromium found in a subway system should be assumed to exist as hexavalent chromium [Cr (VI)] due, at least in part, to the high temperatures involved in the braking process. Although the SAQI dataset currently provides data on total chromium in subway $PM_{2.5}$, there are currently no speciation data (i.e., a breakdown of Cr (VI) and other species) available. As such, the HHRA has assessed total chromium as both Cr (III) and Cr (VI). The assumption that 100% of all chromium present in subway $PM_{2.5}$ is Cr (VI) may be highly conservative; however, in the absence of data prove otherwise, it should be assessed as such to ensure risks are not underestimated.

Although another recent TPH air quality project (dated October 2015) evaluated total and hexavalent chromium using the inhalation unit risk (IUR) values published by HC (2010b), the project did not identify and/or report on the recently-finalized TCEQ inhalation unit risk (IUR) value for Cr (VI). The IUR values for total and hexavalent chromium reported by HC (2010b) were derived in 1993 as detailed in Supporting Documentation (Health-Related Sections) for Chromium and its Compounds under the Canadian Environmental Protection Act (Priority Substance List) (National Health and Welfare, 1993). At this time, Health Canada has not published a review or a re-evaluation of the 1993 IUR values for total and hexavalent chromium. Briefly, the IUR

for Cr (VI) reported by HC (2010b) was derived using data from an occupational study published by Mancuso in 1975. The IUR value for total chromium was derived based on data from Mancuso (1975) and the assumption that the ratio of Cr (III) to Cr (VI) was 6:1.

The TCEQ Decision Support Document (TCEQ, 2014) represents a recent and comprehensive updated carcinogenicity assessment and modeling exercise for chromium and chromium compounds. As pointed out by the TCEQ (2014), the US EPA has not finalized an updated toxicological review of Cr (VI) since1998, nor has it altered its IUR value since 1984. Similarly, Health Canada does not appear to have published an update or review of their 1993 IUR values.

The TCEQ (2014) indicated that '*using default linear low-dose extrapolation and lung cancer data from a now outdated occupational study (Mancuso 1975) with several significant limitations which make it less suitable for CrVI risk assessment (e.g., exposure groups based on total Cr, no smoking data, lack of representative industrial hygiene survey data), US EPA (1984) derived a URF of 1.2E-02 per µg CrVI/m^3. This outdated US EPA URF is about five times greater than the final URF calculated by the TCEQ (2.3E-03 per µg CrVI/m^3) based on an updated carcinogenicity assessment using different key studies*.'

Given that the TCEQ (2014) has recently finalized a comprehensive carcinogenicity assessment and modeling exercise that has incorporated recent key occupational studies in its derivation that preclude it from the limitations identified in the Mancuso (1975) study, the HHRA has adopted the use of the TCEQ IUR value of 2.3E-03 per µg Cr(VI)/m^3 (Table 5-4).

5.4 Acute Inhalation Toxicity Reference Values for Metals in $PM_{2.5}$

As previously indicated, the Expert Panel Report (Appendix A) recommended that the evaluation of the individual airborne metals in subway PM should be undertaken quantitatively using international TRVs, where available, and that TRVs should be sourced from the United States Environmental Protection Agency (US EPA), Health Canada, World Health Organization, and California EPA. It is noted that neither the Integrated Risk Information System (IRIS), developed and maintained by the US EPA, or Health Canada (HC, 2010b), report acute TRVs.

As with chronic TRVs, TPH made an effort (as part of a previous air quality study) to identify acute inhalation TRVs. A review of these acute TRVs revealed that the previous air quality study relied almost exclusively on ambient air quality criteria (AAQCs) published by the MOE (2012) as a source of acute inhalation TRVs. An AAQC is a desirable concentration of a contaminant based on the protection against adverse effects on health or the environment (MECP, 2012). According to the MECP (2012), AAQCs are set at different averaging times (e.g., 24-hr, 1-hr, and 10-minute) and are

often used in annual reporting of provincial air quality data, environmental assessments, and studies using ambient air monitoring data. The effects considered can be health, vegetation, soil, odour, visibility, and corrosion (among others).

The MECP develops AAQCs used to evaluate the overall air quality resulting from all sources of air contaminants. Provincial air standards, based on the same science as AAQCs, are set under Ontario Regulation 419/05 (O. Reg. 419/05) and are used as benchmarks to evaluate a facility's individual contribution of a contaminant to ambient air under O. Reg. 419/05 (MECP, 2018). The MECP may convert AAQCs to different averaging times so that they align with the structure of O. Reg. 419/05 (MECP, 2018).

Many of the 24-hr and ½-hr AAQC and B1 standards were, in part, derived using meteorological conversion factors to move from an annual average, for example, to a 24-hour or ½-hr averaging time. For example, a factor of 5 is applied by the MECP to move from an annual average to a 24-hour duration, while a factor of 3 is applied to move from a 24-hour to a ½-hour averaging time as set out by the conversion-factor equation in subsection 17(3) of Ontario Regulation 419/05.

In many instances, a chronic TRV has toxicological meaning relevant to the exposure duration (or time frame) for which it was derived. It can be inappropriate to take a chronic toxicity reference value developed from exposures of more than five years (e.g., manganese) and use it to characterize health risks associated with a 24-hour or 1-hour exposure duration. If a compound's toxicological profile indicates that short-term exposures are likely to result in adverse health effects, then an appropriate short-term air standard (e.g., ½-hr, 1-hr, 24-hr, etc.) should be developed and implemented to protect against this endpoint of concern. In some instances, the same compound may have an acute and chronic air standard based on two distinctly different health endpoints of concern. A 24-hour air quality standard that is derived using a meteorology-based conversion factor (of five) to convert from an annual to a 24-hour basis has little, if any, toxicological basis or relevance.

As previously indicated, neither the US EPA IRIS database or Health Canada report acute TRVs. Given the limited availability of acute inhalation TRV data, the following regulatory agencies, beyond the MECP (known to report short-term (or acute) screening levels, standards, and/or guidelines) were consulted:

- California Office of Environmental Health Hazard Assessment (OEHHA);
- The Agency for Toxic Substance and Disease Registry (ATSDR); and
- The Texas Commission on Environmental Quality (TCEQ).

Of the agencies cited above, only the TCEQ reported either a finalized acute inhalation

reference value (ReV), supported by a detailed Discussion Support Document (DSD), or interim short-term Environmental Screening Levels (ESLs) for all metals of interest in subway PM (Table 5-5). The OEHHA published acute 1-hour recommended exposure limits (RELs) for both arsenic and nickel of 0.2 µg/m^3, respectively. The ATSDR also cited an acute minimal risk level (MRL) for cadmium of 0.03 µg/m^3 for exposure durations of between 1 and 14 days. Given that the TCEQ has published finalized acute ReVs and DSDs, detailing the methods and data used to derive each acute 1-hour inhalation ReV (or interim short-term ESL) for all metals of interest, the HHRA has used the acute inhalation TRV data as published by TCEQ (Table 5-5).

Table 5- 5 TCEQ Short-term Interim ESLs and Final Acute ReVs (µg/m^3)

Metal	Type	Value (µg/m^3)	Critical Effect	Toxicological Study / Derivation	Reference
Arsenic	Final acute ReV	9.9	Maternal toxicity in rats documented as rales (abnormal lung sounds) during premating and gestation exposure.	Holson et al. (1999) – study involving whole-body inhalation in female rats. A NOAEL was used to derive a POD_{HEC} of 3,891 µg/m^3 in which a total UF of 300 was applied to derive a ReV of 13 µg/m^3 for arsenic trioxide – arsenic was 76% by weight, resulting in a ReV of 9.9 µg/m^3.	TCEQ (2012)
Barium	Interim short-term ESL	5	Basis of ACGIH TLV is eye, skin, and GI irritation; muscular stimulation.	Barium and soluble compounds as Ba. Occupational Exposure Limit of 500 µg/m^3. 100-fold uncertainty factor applied to lowest occupational exposure limit.	TCEQ (2019)
Cadmium	Final acute [1-hr] ReV	18	Immunotoxicity – decreases in specific antibody-producing spleen cells in female mice.	Graham et al. (1978) – inhalation study involving 6-week old Swiss albino female mice exposed to Cd for 2 hours. A NOAEL of 110 µg/m^3 was used to derive a POD_{HEC} of 554 µg/m^3 in which a total UF of 30 was applied to derive a ReV of 18 µg/m^3.	TCEQ (2016)
Chromium (hexavalent form)	Final acute [24-hr] ReV	1.3	Increase in relative lung weight observed in rats	Glaser et al. (1986) — study involving 8-week old Wistar rats exposed to Cr (VI) via inhalation for 30 days. A POD_{HEC} of 38.71 µg/m^3 to which a total UF of 30 was applied to derive a ReV of 1.3 µg/m^3.	TCEQ (2014)
Chromium (metallic, divalent, and trivalent forms)	Final acute ReV	12	Increased precursor enzymes that are early indicators of lung damage.	Henderson et al. (1979) - an inhalation study involving male and female hamsters exposed to metal sale aerosol as $CrCl_3$. A POD_{HEC} of 10,820 µg/m^3 to which a total UF of 300 was applied to derive a ReV of 12 µg/m^3 for Cr^{3+}	TCEQ (2009)
Cobalt	Final acute [1-hr] ReV	0.69	Respiratory irritation (coughing, expectoration, or sore throat) and reduced FVC in humans.	Kusaka et al. (1986) – an inhalation study involving humans exposed to metal dust for 6 hours. A 1-hour POD_{HEC} of 69.05 µg Co/m^3 to which a total UF of 100 was applied to derive a 1-hr ReV of 0.69 µg Co/m^3.	TCEQ (2017a)
Iron	Interim short-term ESL	50	Prevention of pulmonary siderosis in workers	100-fold UF applied to the ACGIH TLV of 5,000 µg/m^3 for iron oxide to prevent pulmonary siderosis in workers from the inhalation of iron particulate.	TCEQ (2019)
Manganese	Final acute [1-hr] ReV	9.1	Observed inflammatory airway changes in rhesus monkeys.	Dorman et al. (2005) – an inhalation study involving Rhesus monkeys exposed to Mn for a total of 90 hrs over 3 weeks. A POD_{HEC} of 2,720 µg Mn/m^3 based on a LOAEL to which a total UF of 360 was applied to derive a 1-hr ReV of 9.1 Mn µg/m^3.	TCEQ (2017b)
Nickel	Final acute ReV	1.1	Bronchial constriction in humans with occupational asthma.	Cirla et al. (1985) – inhalation study involving 12 metal plating factory workers exposed to an aerosol of nickel sulfate of 300 µg/m^3. A POD_{HEC} of 67 µg Ni/m^3 based on a LOAEL in which a total UF of 30 was applied to derive a 1-hr ReV of 1.1 µg/m^3.	TCEQ (2017c)
Silver	Interim short-term ESL	0.1	Basis of ACGIH TLV for silver is argyria – a benign but permanent bluish-grey discolouration of the skin.	Interim Environmental Screening Limit (ESL) based on a NIOSH REL of 10 µg/m^3 for soluble silver compounds with a 100-fold UF applied.	TCEQ (2019)

5.5 Chemical Mixtures

Exposures of individuals to chemicals in their surrounding environment are not limited to a single chemical in isolation, and rather occur as simultaneous exposures to multiple chemicals (or mixtures). The toxic effects of an individual chemical may be influenced by interactions with other chemicals that present within a given mixture. Although regulatory agencies have established toxic equivalency factors (TEFs) for a select groups of chemicals (e.g., dioxin and furans, polycyclic aromatic hydrocarbons, etc.) that have been shown to act via the same mechanism of toxicity, most toxicity databases do not provided detailed information concerning interactions that may exist between different chemicals (HC, 2012).

Simultaneous exposure to more than one chemical may lead to a combined toxicity that is less than the sum of the individual toxicities (antagonism), equal to the sum of the individual toxicities (additivity or independence), or greater than the sum of the individual toxicities (synergism or potentiation) (HC, 2012). Toxicological interactions are often dependent on the chemicals present in each mixture, the levels of exposure to each chemical, and their toxicological mode of action. Additivity (or antagonism) is thought to be the most typical toxicological interaction at environmentally relevant concentrations or exposures (HC 2012).

Given that chemical exposures within an environmental setting seldomly involve a single chemical, the health effects associated with chemical mixtures should be evaluated to the extent possible. Health Canada (2012) recommends that additive interactions be assumed when chemicals (within a given mixture) have the same mode of mode of action, are structurally similar, and/or act on the same organ or tissue. In other words, health risk estimates should be summed for chemicals with the same mode of action and/or act on the same organ or tissue; otherwise, risk estimates should be evaluated on a chemical-by-chemical basis (Health Canada, 2012).

Information presented in Table 5-4 and 5-5 was reviewed to identify those metals of interest that act via the same mode of action, have a common endpoint, and/or act on the same target organ or tissue under both chronic and acute durations. Those metals identified as having a common mode of action, toxicity endpoint, or target organ were grouped as presented below (Table 5-6). As described in Section 6.2.1.3, health risk estimates for each metal of interest within the same mixture or group (e.g., chronic respiratory effects, etc.) were summed to develop a total HQ or ILCR estimate for each mixture containing metals with a common/similar toxicity endpoint.

Table 5-6 Assumed Additive Interactions Among Metals of Interest

Exposure Route and Duration	Toxicity Endpoint	Metals of Interest
Chronic Inhalation Exposure	neurological effects	manganese and arsenic
	respiratory effects	chromium (VI), chromium (III), barium, cobalt, nickel, and iron
	lung cancer	arsenic, cadmium, chromium (VI), and nickel
Acute Inhalation Exposure	respiratory irritants and effects	chromium (VI), chromium (III), cobalt, iron, manganese, and nickel

6.0 Risk Characterization

Risk characterization is the final step (of the four main stages of risk assessment) and pulls together the results of the exposure and toxicity assessments. The purpose of risk characterization is to provide a descriptive estimate of the potential human health risks associated with predicted exposures of receptors to the COPC(s) identified in the problem formulation. The following sections describe the characterization of human health risks associated with acute and chronic exposure to fine particulate matter and metals of interest.

6.1 Fine Particulate Matter

6.1.1 Chronic Health Risks

The CCME (2012) CAAQSs for $PM_{2.5}$ were developed to 'better protect human health and the environment', but they are also aspirational in nature in that they were designed, in part, to drive continuous improvements in air quality. Due to the pseudo-linear relationship between health and ambient $PM_{2.5}$ concentrations, in addition to the lack of an effects threshold, a specific attainable target concerning the reduction in population exposure (relative to current levels) was developed within which an ambient $PM_{2.5}$ concentration standard could be generated (Health Canada 2019b).

Subway $PM_{2.5}$ is enriched with a variety of metals and has a different composition compared to PM collected from ambient air (Section 5.1.3). Loxham and Nieuwenhuijsen (2019) concluded that there was little direct evidence that exposure to subway PM is more harmful than exposure to ambient PM.

The TSAQ HIA Expert Panel Workshop Report (Appendix A) concluded that there are currently no Canadian or international TRVs that have been developed specifically for subway $PM_{2.5}$. In the absence of sufficient epidemiological or toxicity data, it should be assumed that subway $PM_{2.5}$ has a similar level of toxicity as ambient $PM_{2.5}$ and should, therefore, rely on the research underpinning the Canadian and international guidelines for $PM_{2.5}$ in ambient air.

There are, however, several limitations that must be recognized if a standard hazard quotient (HQ) approach (as illustrated below) is to be used to quantify subway $PM_{2.5}$-related health impacts, including:

- the lack of subway specific $PM_{2.5}$ inhalation TRVs that account for the unique composition of subway $PM_{2.5}$ (Section 5.2);
- the lack of a discernible effect threshold associated with chronic $PM_{2.5}$ exposure and various health endpoints (Section 5.1.2);

- the $PM_{2.5}$ CAAQSs and WHO AQGs were not designed to protect against a specific health effect threshold. They were designed, in part, to improve ambient air quality over time and, by association, public health (Section 5.2); and
- $PM_{2.5}$ standards were designed to be used in conjunction with several years of ambient monitoring data (Section 5.2).

$$Hazard\ Quotient = \frac{Air\ Concentration\ \left(\frac{\mu g}{m^3}\right)\ X\ Fraction\ of\ Time\ Exposed}{Reference\ Concentration\ \left(\frac{\mu g}{m^3}\right)}$$

It must be emphasized that the CCME (2012) $PM_{2.5}$ annual CAAQSs, the annual WHO (2006a) AQGs, and the annual interim target (IT) levels (as discussed in Section 5.2) were developed, in part, from data generated by epidemiological studies that examined the association between $PM_{2.5}$ concentrations and various public health outcomes over prolonged periods of time. For example, the WHO (2006a) annual AQG (10 µg/m^3) represents the lowest $PM_{2.5}$ concentration over which cardiopulmonary and cancer mortality rates were shown to increase (at ≥ 95% confidence) in a long-term exposure study conducted by Pope et al. (2002). As such, the annual $PM_{2.5}$ standards were designed to be used in conjunction with several years of ambient air monitoring data. For example, the metric of the annual $PM_{2.5}$ CAAQS is the 3-year average of the annual average concentrations.

Considering the origins of the data used to help develop the standards and their intended use, a direct comparison with mean $PM_{2.5}$ subway platform concentrations during peak weekday hours (Table 4-3) does not seem appropriate. The subway platform is a microenvironment, whereby subway passengers spend a very small proportion of their day (estimated to be anywhere from 2.5 to 5 minutes per day as per Section 4.1.1). As such, subway platform concentrations are not reflective of a subway user's long-term average daily $PM_{2.5}$ exposure. Exposure from other microenvironments, including on-train and ambient air, must be considered when approximating a chronic average daily EPC.

In the absence of an effects-based TRV for subway $PM_{2.5}$, and recognizing the limitations cited above, chronic average daily $PM_{2.5}$ EPC estimates under ambient and combined conditions (i.e., ambient + subway exposure) were qualitatively compared to the CCME (2012) annual average CAAQS for $PM_{2.5}$ of 8.8 µg/m^3 (for compliance by 2020), the WHO (2006a) annual AQG (of 10 µg/m^3), and the WHO (2006a) annual IT-3 of 15 µg/m^3 (Figure 6-1).

For illustrative purposes, the 95% UCLM ambient $PM_{2.5}$ concentration (of 7.5 µg/m^3), calculated using ambient air data collected from two National Ambient Pollution

Surveillance (NAPS) monitoring stations during 2017 (Section 4.2.4), was included in Figure 6-1. As previously discussed, (in Section 4.2.4), the 95% UCLM ambient $PM_{2.5}$ concentration (of 10.5 µg/m^3) calculated from the SAQI dataset was used to derive total (i.e., subway + ambient) $PM_{2.5}$ EPC estimates (Figure 6-1 and Table 6-1).

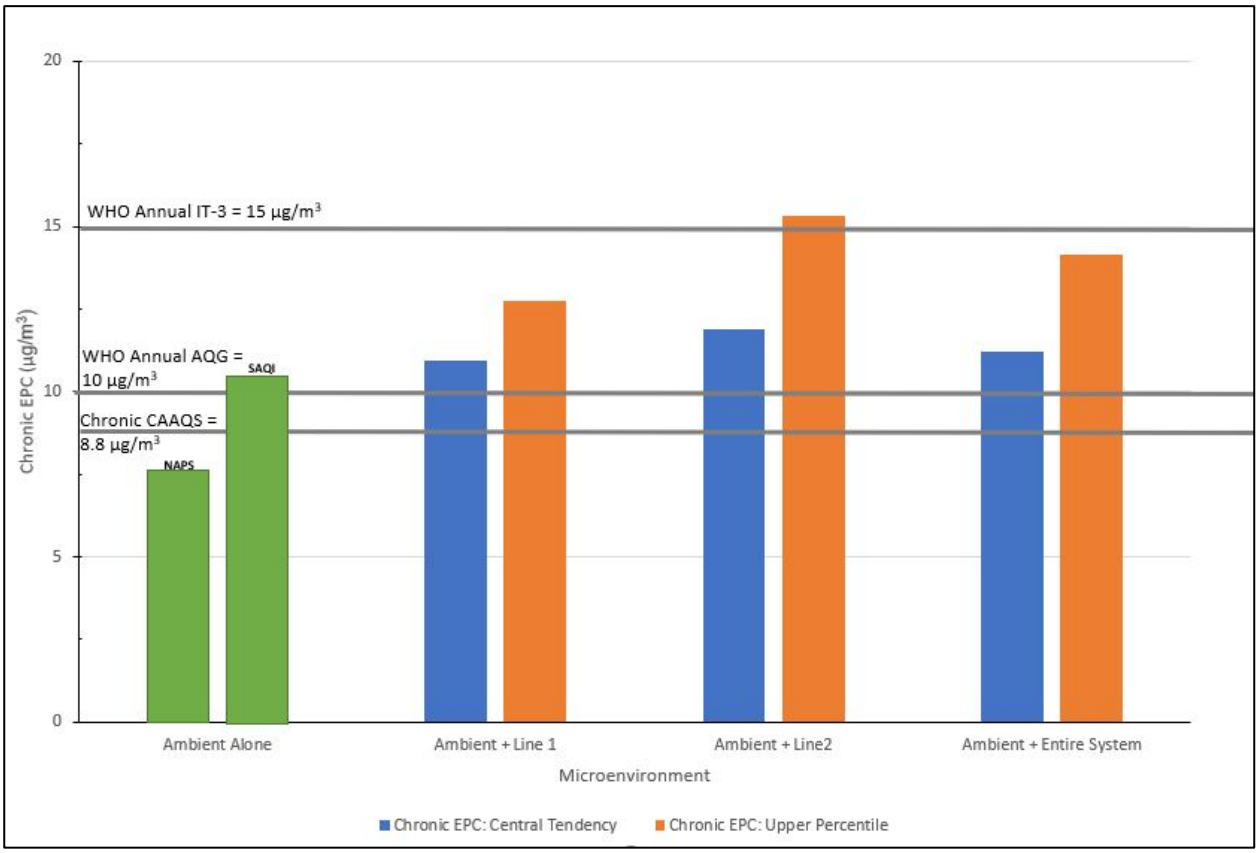


Figure 6- 1 Chronic $PM_{2.5}$ Exposure Point Concentration Estimates (µg/m^3) under Ambient Alone, Subway Alone, and Combined

The 95% UCLM SAQI ambient $PM_{2.5}$ concentration (of 10.5 µg/m^3) marginally exceeds the annual CAAQS and WHO (2006a) AQG of 8.8 µg/m^3 and 10 µg/m^3, respectively. It is noted that the SAQI ambient air quality dataset is somewhat limited in that data were collected between May and August of 2018 and that the dataset is comprised of twenty-three (23) 7-day samples collected from two (2) sampling locations (i.e., 200 College St. and 4905 Dufferin Rd.). The uncertainty surrounding the average ambient $PM_{2.5}$ concentration (of 9.6 µg/m^3) (N=23) from SAQI is greater than that surrounding the ambient $PM_{2.5}$ concentration (of 7.1 µg/m^3) (N =202) from NAPS, as illustrated by the 95% UCLM. It is also recognized that the SAQI ambient air samples were collected from monitoring locations that were situated closer to the downtown core relative to the NAPS monitoring locations. As such, long-term ambient $PM_{2.5}$ EPCs likely exist somewhere between 7.5 and 10.5 µg/m^3.

The total chronic average daily $PM_{2.5}$ EPC estimates (from both ambient and subway-related sources) for Line 1, Line 2 (central tendency), and the entire system (Line 1 and Line 2 combined) are greater than the annual CAAQS (of 8.8 µg/m^3) and the WHO (2006a) annual AQG (of 10 µg/m^3), but are less than the WHO (2006a) annual IT-3 (of 15 µg/m^3) (Figure 6-1). The upper percentile EPC estimate under Line 2 (of 15.3 µg/m^3) is considered approximately equal to the annual IT-3 level.

The WHO (2006a) annual AQG represents the lowest $PM_{2.5}$ concentration over which cardiopulmonary and cancer mortality rates were shown to increase (at ≥ 95% confidence) in the American Cancer Society (ACS) study (Pope et al. 2002). As discussed in Section 5.2.2, the ACS Study observed robust associations between chronic exposure to $PM_{2.5}$ and mortality. The historical mean $PM_{2.5}$ concentration in the ACS study was 20 µg/m^3 (range of 9.0 – 33.5 µg/m^3). The ACS study found that each 10 µg/m^3 increase in $PM_{2.5}$ concentration was associated with an approximate 4%, 6%, and 8% increase in risk for all-cause, cardiopulmonary, and lung cancer mortality, respectively (WHO, 2006a).

Given that no threshold has been identified below which adverse health effects associated with $PM_{2.5}$ exposure are unlikely to occur, the WHO (2006a) has developed Interim Targets (IT-1 through IT-3) associated with specific percent increases in premature mortality relative to the WHO annual AQG (of 10 µg/m^3) (Table 5-2). The WHO's basis (2006a) for selecting an annual IT-3 level of 15 µg/m^3 was its correspondence to a 6% (95% CI of 2%–11%) reduction in mortality risks over the IT-2 level of 25 µg/m^3.

Based on the WHO (2006a) description of each IT level (Table 5-2) and the findings of the ACS study described above, an annual average $PM_{2.5}$ concentration of 15 µg/m^3 (the IT-3 level) is associated with approximately a 2%–3% increase in overall mortality rates relative to the overall mortality rates associated with an annual AQG level of 10 µg/m^3. Given the reported 95% confidence intervals (95% CI of 2%–11%) associated with the reduction in mortality risks (over the AQG) for each IT level, it may be not be possible to clearly distinguish between long-term mortality rates associated with ambient $PM_{2.5}$ concentrations from SAQI (mean of 9.6 µg/m^3 and a 95 UCL of 10.5 µg/m^3) and the total chronic average daily $PM_{2.5}$ EPC estimates (ambient + subway sources) for Line 1 (10.9–12.7 µg/m^3). The total chronic average daily $PM_{2.5}$ EPC estimates associated with Line 2 (11.9–15.3 µg/m^3) and the entire subway system (11.2–14.1 µg/m^3) may result in a 1%–3% increase in the long-term mortality rate over that associated with the annual AQG (of 10 µg/m^3).

Table 6-1 Chronic Average Daily $PM_{2.5}$ Exposure Point Concentration Estimates

Subway Line	Subway Alone EPC ($\mu g/m^3$)		Total EPC (Ambient + Subway) ($\mu g/m^3$)		Percentage of Subway Alone to Total EPC	
	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Line 1	0.49	2.56	10.9	12.7	5%	20%
Line 2	1.46	5.09	11.9	15.3	12%	33%
Entire System	0.77	3.94	11.2	14.1	7%	28%

6.1.2 Acute Health Risks

The TTC (2019) data indicated that most subway users spend approximately one (1) hour in the subway system on any given travel day (i.e., approximately a ½-hour each way). Most of this time is spent riding on the subway train, with up to five (5) minutes a day (in total for both directions) being spent waiting on the platform. As such, exposure to subway $PM_{2.5}$ over a ½-hour to 1-hour duration would be relevant to characterizing acute human health risks.

Currently, there are no health-based $PM_{2.5}$ TRVs designed for use with ½-hour to one-hour exposure durations. The CCME (2012) developed 24-hour average CAAQs for $PM_{2.5}$ of 28 $\mu g/m^3$ and 27 $\mu g/m^3$ (for compliance by 2015 and 2020, respectively) which are to be used in conjunction with the 3-year average (value) of the annual 98^{th} percentile for daily 24-hour average concentrations. Similarly, the WHO (2006a) developed a series 24-hour interim target (IT) levels and a 24-hour AQG. As with the annual CAAQS, the 24-hour standard is not protective of a specific effects threshold but, rather, is designed to be, at least in part, aspirational in nature with the objective of continuous improvement in ambient air quality and, by association, public health.

Given the limitations of the existing $PM_{2.5}$ air quality standards (as discussed above and in Section 6.1.1), a stepwise approach, using the WHO (2006a) IT levels and AQGs (similar to that developed by Moreno et al. (2017; 2018) to encourage transport authorities to aim for progressive PM reductions), has been adopted for use.

Moreno et al. (2017; 2018) used a tiered, or stepwise, approach that corresponds to the WHO (2006a) 24-hour and annual IT levels and AQGs (Table 5-3 and Table 5-4). The goal (or lowest tier to be achieved) is the WHO (2006a) annual $PM_{2.5}$ AQG of 10 $\mu g/m^3$ — the lowest annual concentration at which negative health outcomes have been observed. Moreno et al. (2017; 2018) compared average subway $PM_{2.5}$ platform concentrations (averaged over all operating hours) to both 24-hour and annual average WHO (2006a) IT levels and AQGs. The rationale provided by Moreno et al. (2018) for this approach (i.e., the use of both 24-hour and annual average standards) appears to be related to the expanded scope of the WHO (2006a) IT levels and AQGs. Originally, the WHO (2006a) IT levels and AQGs were applicable to only outdoor ambient air; however,

according to Moreno et al. (2018), the WHO (2017) broadened its scope, such that IT levels and AQGs are to *'…relate to all environments…'* and were considered by Moreno et al. (2018) to be *'…equally appropriate…'* for subways.

On-train $PM_{2.5}$ concentrations have been shown to range from 38% to 47% of the levels measured on subway platforms (Section 4.2.2). As such, exposures of passengers to subway $PM_{2.5}$ (over a ½-hour to 1-hour trip) should consider both the time spent waiting on the platform and riding the train in addition to the $PM_{2.5}$ levels in each microenvironment. The HHRA has, therefore, used acute $PM_{2.5}$ EPC estimates during peak weekday hours (Table 4-11), rather than the $PM_{2.5}$ subway platform concentrations averaged over all operational hours (Table 4-3).

Similar to the methods employed by Moreno et al. (2017; 2018), acute $PM_{2.5}$ EPCs (rather than subway platform concentrations) were compared to the WHO (2006a) 24-hour IT levels and the 24-hour AQG by subway line (Figure 6-2) and station (Figure 6-3). Acute EPCs (calculated for each subway station sampled during the SAQI study) represent a time-weighted average EPC that considers the amount of time spent waiting on the platform (e.g., maximum of 2.6 minutes per trip on Line 1) and riding the train (90^{th} percentile value of 29.3 minutes per trip on Line 1). The acute EPC also reflects the $PM_{2.5}$ concentration on each platform and on-train during peak weekday hours (6am–9am and 3pm–7pm). It is noted that, because the subway train is moving from station to station (within a given subway line), the average on-train concentration, calculated for the entire subway line, was used to approximate the station-specific EPCs presented in Figure 6-3.

The acute $PM_{2.5}$ EPC estimated for Line 1 (84.7 $\mu g/m^3$), Line 2 (183 $\mu g/m^3$), and the combined system (130 $\mu g/m^3$) exceeded the WHO (2006a) 24-hour IT-1 level of 75 $\mu g/m^3$ (Figure 6-2). The WHO (2006a) 24-hour IT-1 level is associated with approximately a 5% increase in short-term mortality over the 24-hour AQG of 25 $\mu g/m^3$. As indicated in Table 5-4, the 24-hour AQG was set based on the annual AQG using a relationship between 24-hour and annual average concentrations. The 24-hour average values represent the 99^{th} percentile of the (typically) lognormal distribution of the daily value (or the fourth-highest daily value of the year). The WHO (2006a) annual AQG represents the lowest $PM_{2.5}$ concentration over which cardiopulmonary and cancer mortality rates were shown to increase (at ≥ 95% confidence) in the ACS Study (Pope et al., 2002).

Although the average acute EPC for Line 1 was estimated to be 84.7 $\mu g/m^3$, there were eight (8) (of the fourteen (14) stations sampled) on Line 1 associated with acute EPCs of less than 85 $\mu g/m^3$, ranging from 78 to 83 $\mu g/m^3$. Acute EPCs for the remaining six (6) stations (on Line 1) ranged from approximately 85 to 102 $\mu g/m^3$ (Figure 6-3). In comparison, the average acute EPC on Line 2 is more than twice that of Line 1 (Figure

6-2) — acute EPCs on Line 2 ranged anywhere from approximately 160 to 197 µg/m^3 (Figure 6-3).

The average acute EPC associated with Line 1 (of 84.7 µg/m^3) is marginally greater than the WHO (2006a)'s 24-hour IT-1 level of 75 µg/m^3, and is associated with approximately a 5% increase in short-term mortality over the 24-hour AQG of 25 µg/m^3. However, the acute EPCs associated with Line 2 are more than 2-fold greater than those estimated for Line 1 and are, on average, approximately 2.5-fold greater than the WHO (2006a)'s 24-hour IT-1 level of 75 µg/m^3.

It is noted that EPC estimates represent time-weighted average concentrations (between platform and on-train concentrations) over the duration of a single subway trip (during weekday peak hours), lasting approximately 30 minutes. As previously discussed (Section 6.1.1), the application of the 24-hour IT levels and the 24-hour AQG may not be directly applicable; however, as illustrated in Figures 6-2 and 6-3, acute $PM_{2.5}$ exposures on Line 2 are particularly elevated as compared to 24-hour IT levels, the 24-hour AQG, and exposures on Line 1.

The WHO (2006a) indicated that '*Current scientific evidence indicates that guidelines cannot be proposed that will lead to complete protection against adverse health effects of particulate matter, as thresholds have not been identified. Rather, the standard-setting process needs to achieve the lowest concentrations possible in the context of local constraints, capabilities, and public health priorities…*' As such, efforts to reduce subway $PM_{2.5}$, to the extent technically and/or feasibly possible, will only help to reduce possible adverse health outcomes. Based on Figures 6-2 and 6-3, a reduction in $PM_{2.5}$ levels on Line 2 would be the priority.

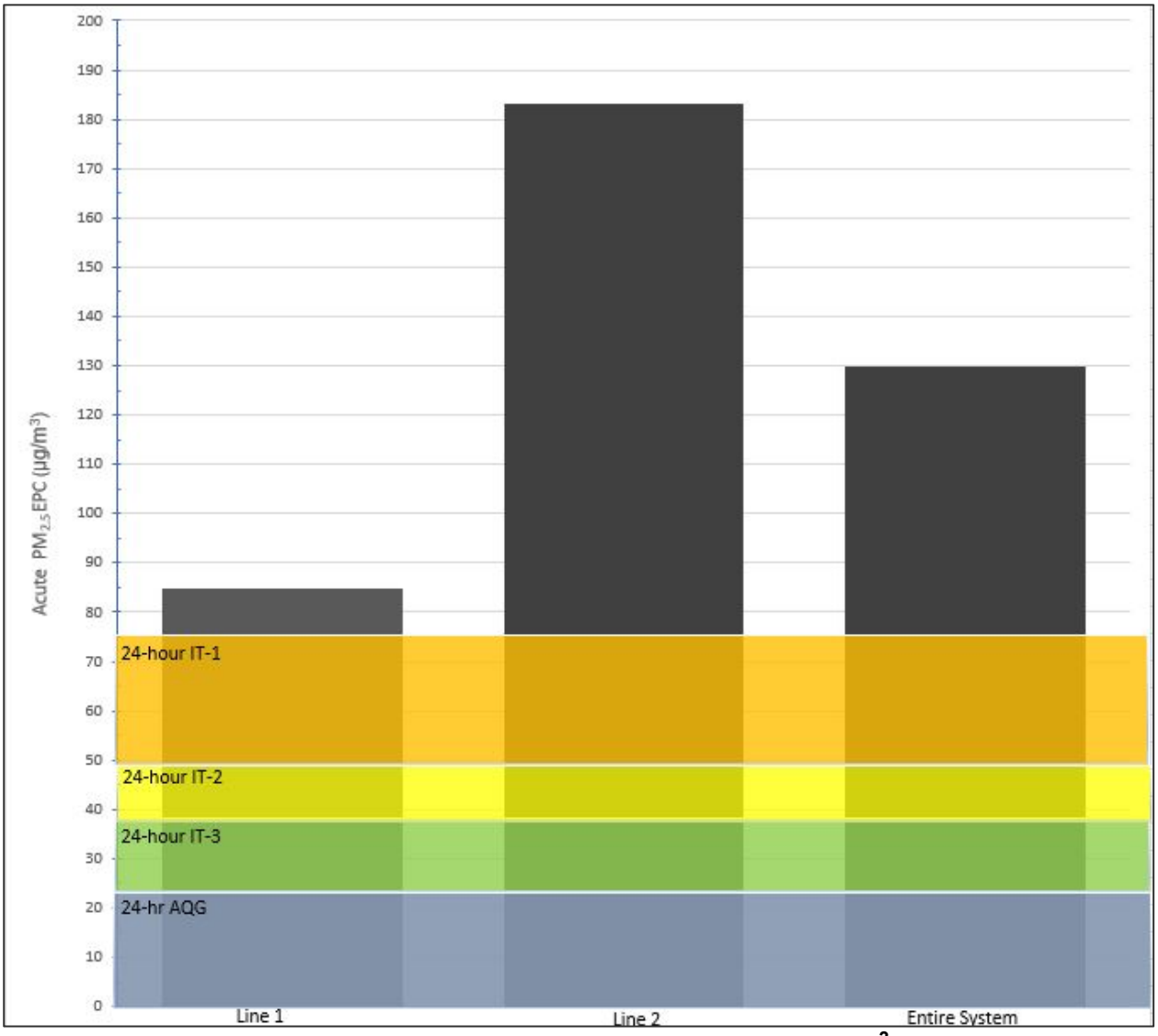


Figure 6-2 Acute $PM_{2.5}$ Exposure Point Concentrations (µg/m^3) by Subway Line During Peak Weekday Hours Compared to WHO 24-hour Ambient Air Guidelines and Interim Targets

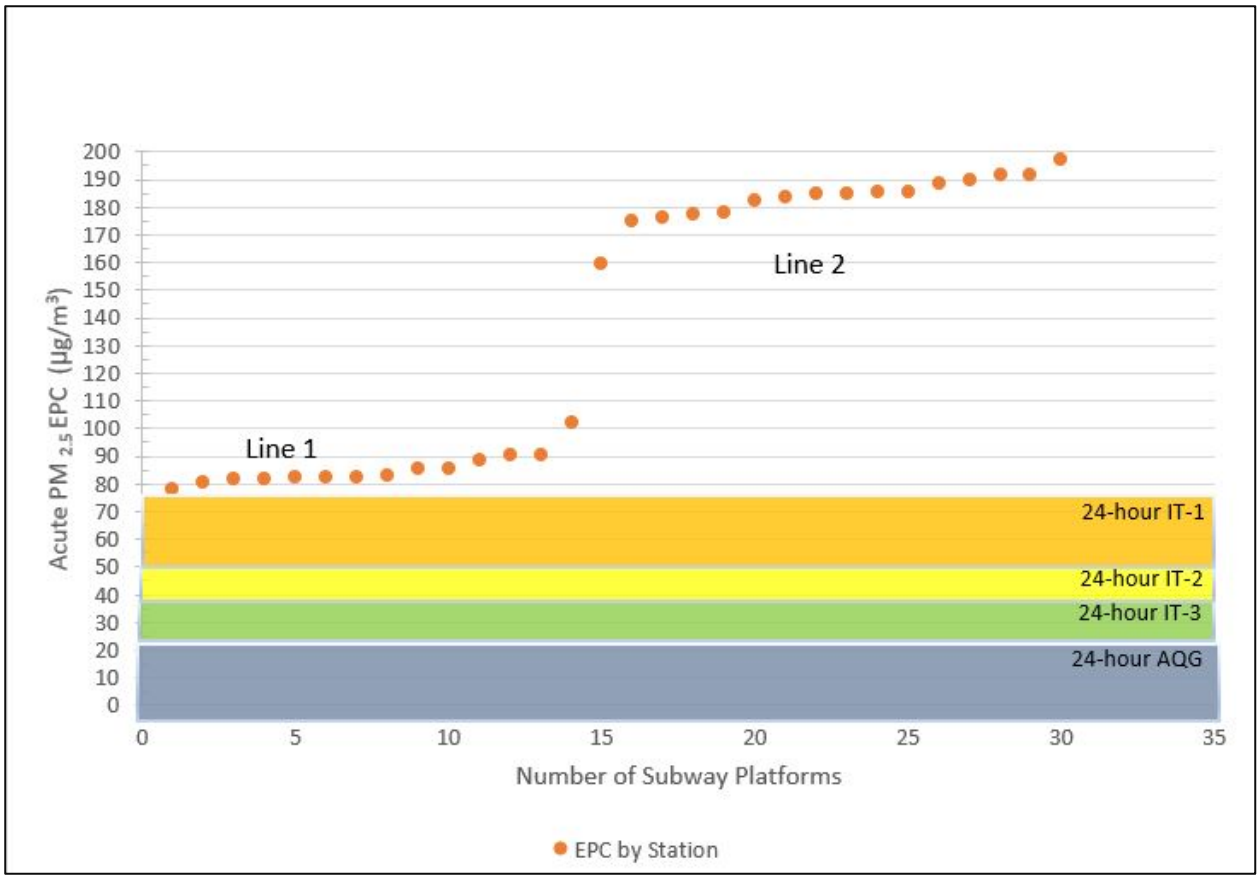


Figure 6-3 Acute $PM_{2.5}$ Exposure Point Concentrations (µg/m^3) by Subway Station During Peak Weekday Hours Compared to WHO 24-hour Ambient Air Guidelines and Interim Targets

6.2 Metals of Interest in $PM_{2.5}$

Unlike $PM_{2.5,}$ most metals of interest identified within subway $PM_{2.5}$ (Section 3.2) have, for the most part, established inhalation TRVs published by reputable regulatory agencies (Sections 5.3 and 5.4). For most metals of interest, a specific non-cancer and/or cancer endpoint has been identified, and an effect threshold (non-cancer) or slope factor (cancer) has been established, upon which the corresponding TRVs were developed. As such, unlike $PM_{2.5}$, traditional risk assessment methods used to quantify human health risks (as discussed in Section 2.1.4) have been applied when evaluating the health risks associated with exposures to the metals of interest.

6.2.1 Chronic Inhalation Health Risks

Chronic inhalation hazard quotient (HQ) values were used to help characterize the long-term health risks associated with non-carcinogenic metals (via the inhalation route), according to the following equation:

$$Hazard\ Quotient = \frac{EPC_{ATD}\ \left(\frac{\mu g}{m^3}\right)}{Chronic\ Inhalation\ Toxicity\ Reference\ Value\ \left(\frac{\mu g}{m^3}\right)}$$

Where:

EPC_{ATD} is inclusive of both subway and ambient chronic exposures and is defined as the average chronic total daily EPC (Section 4.3.1, Exposure Equation 6).

A HQ value of less than one (HQ <1.0) is considered, by Health Canada, to represent a negligible risk (HC, 2010a).
For metals of interest determined to be carcinogenic (i.e., arsenic, cadmium, and hexavalent chromium), only subway-related exposures were considered when estimating an incremental lifetime cancer risk (ILCR).

The estimated incremental lifetime average daily (or EPC_{ILAD}) was multiplied by an inhalation unit risk (IUR) value, resulting in an ILCR estimate, according to the following equation:

$$ILCR = EPC_{ILAD}\ \left(\frac{\mu g}{m^3}\right)\ X\ Inhalation\ Unit\ Risk\ \left(\frac{\mu g}{m^3}\right)^{-1}$$

Where:

EPC_{ILAD} was calculated as per Exposure Equation 7 (Section 4.3.1).
ILCR estimates are typically compared to levels that are deemed 'acceptable, tolerable, or essentially negligible'. The 'acceptable' ILCR is an issue of regulatory policy, rather than science, and is set by various regulatory agencies. Although 'acceptable' ILCR levels are generally considered to range from 1 in 10,000 to 1 in 1,000,000 (1.0E-04 to 1.0E-06), regulatory agencies have typically employed 'acceptable' ILCR levels (i.e., excess cancer risks over and above existing background rates) between 1 in 100,000 (1.0E-05) and 1 in 1,000,000 (1.0E-06) (HC, 2010a).

Analogous to the ILCR estimate, the lifetime cancer risk (LCR) estimate can also be used to assess lifetime cancer risks from multiple sources. Unlike subway-specific ILCR estimates, LCR estimates include cancer risk estimates from all sources (i.e., both ambient and subway-related sources). Regulatory agencies do not recommend 'acceptable' ranges of LCR estimates. As such, LCR estimates have been used only as

points of reference — comparing LCR estimates under ambient conditions alone against LCR estimates from all sources (i.e., ambient + subway-specific sources).

6.2.1.1 Non-Cancer Hazard Quotient Estimates

Tables 6-2 through 6-4 present the central tendency and upper percentile chronic HQ estimates of all metals of interest for Line 1, Line 2, and the combined subway system, respectively. For each subway line and metal of interest, the chronic average total daily exposure point concentration (or EPC_{ATD}) was less than the inhalation TRV value (i.e., a total HQ < 1.0), indicating that chronic non-cancer health risks are considered negligible for all metals of interest (HC, 2010a). Figures 6-4 and 6-5 present the upper percentile chronic HQ estimates for all metals of interest for Line 1 and Line 2, respectively.

However, despite users spending very little time in the subway system relative to time spent under ambient conditions (Section 4.1.1), subway-related health risks (i.e., subway-only HQ values) contribute to much of the total chronic health risk estimate. Of particular note are the upper contribution estimates for barium (72%), chromium (III) (85%), cobalt (85%), iron (91%), manganese (77%), and nickel (70%) from Line 1 (Table 6-2). Contributions of subway-related health risks were even greater for Line 2, with observed upper estimates for barium (92%), chromium (III) (96%), cobalt (94%), iron (95%), manganese (87%), and nickel (87%) (Table 6-3). It is noted that the percent contribution of subway-related hexavalent chromium (Cr (VI)) may be artificially inflated due to the assumption that 100% of the chromium present in subway $PM_{2.5}$ exists as Cr (VI) and that approximately 20% of all chromium in ambient air exists as Cr (VI) (Section 4.2.5).

Table 6-2 Inhalation Hazard Quotient (HQ) Estimates for Metals of Interest (Line 1)

Metal	Chronic Hazard Quotient (HQ) Estimates (unitless)					Contribution of Subway HQ to Total HQ (%)	
	Ambient Alone HQ	Subway Alone HQ		Total HQ (Subway + Ambient)			
	Point Estimate	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Arsenic	0.05	0.003	0.01	0.05	0.06	6	25
Barium	0.014	0.01	0.04	0.02	0.05	33	72
Cadmium	0.46	0.02	0.12	0.48	0.57	5	21
Chromium (VI)	0.001	0.01	0.03	0.01	0.03	87	97
Chromium (III)	0.01	0.01	0.04	0.01	0.05	57	88
Cobalt	0.005	0.01	0.04	0.01	0.04	57	88
Iron	0.03	0.05	0.28	0.08	0.30	66	91
Manganese	0.07	0.05	0.24	0.12	0.31	39	77
Nickel	0.02	0.01	0.05	0.03	0.08	30	70
Silver	0.16	0.01	0.06	0.17	0.22	7	27

Table 6-3 Inhalation Hazard Quotient (HQ) Estimates for Metals of Interest (Line 2)

Metal	Chronic Hazard Quotient (HQ) Estimates (unitless)					Contribution of Subway HQ to Total HQ (%)	
	Ambient Alone HQ	Subway Alone HQ		Total HQ (Subway + Ambient)			
	Point Estimate	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Arsenic	0.05	0.01	0.02	0.05	0.07	13	35
Barium	0.014	0.04	0.15	0.06	0.17	76	92
Cadmium	0.46	0.02	0.08	0.48	0.53	5	15
Chromium (VI)	0.001	0.03	0.10	0.03	0.10	97	99
Chromium (III)	0.01	0.04	0.15	0.05	0.16	88	96
Cobalt	0.005	0.02	0.08	0.03	0.09	82	94
Iron	0.03	0.15	0.53	0.18	0.56	85	95
Manganese	0.07	0.13	0.47	0.21	0.54	65	87
Nickel	0.02	0.04	0.15	0.07	0.17	65	87
Silver	0.16	0.01	0.05	0.17	0.20	7	22

Table 6-4 Inhalation Hazard Quotient (HQ) Estimates for Metals of Interest (Line 1 and 2 Combined)

Metal	Chronic Hazard Quotient (HQ) Estimates (unitless)					Contribution of Subway HQ to Total HQ (%)	
	Ambient Alone HQ	Subway Alone HQ		Total HQ (Subway + Ambient)			
	Point Estimate	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Arsenic	0.05	0.004	0.02	0.05	0.06	8	31
Barium	0.014	0.02	0.10	0.03	0.12	59	88
Cadmium	0.46	0.02	0.11	0.48	0.56	4	20

Chromium (VI)	0.001	0.01	0.06	0.01	0.06	94	99
Chromium (III)	0.01	0.02	0.10	0.02	0.10	75	94
Cobalt	0.005	0.01	0.06	0.02	0.06	69	92
Iron	0.03	0.08	0.42	0.11	0.44	75	94
Manganese	0.07	0.07	0.36	0.14	0.43	50	84
Nickel	0.02	0.02	0.08	0.04	0.10	39	77
Silver	0.16	0.01	0.06	0.17	0.21	6	26

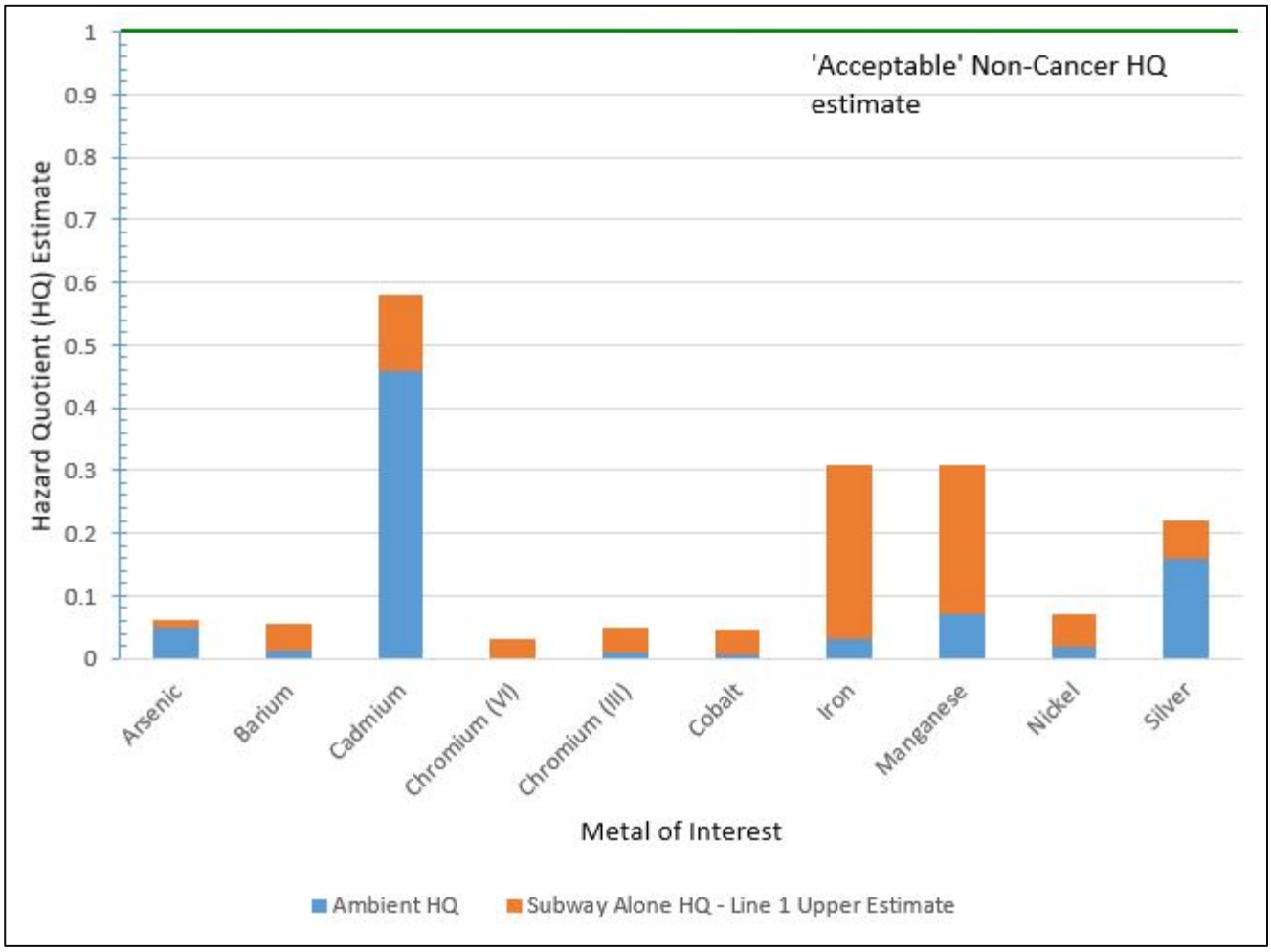


Figure 6-4 Line 1 Upper Estimates of Chronic Inhalation Hazard Quotients for Metals in Subway $PM_{2.5}$

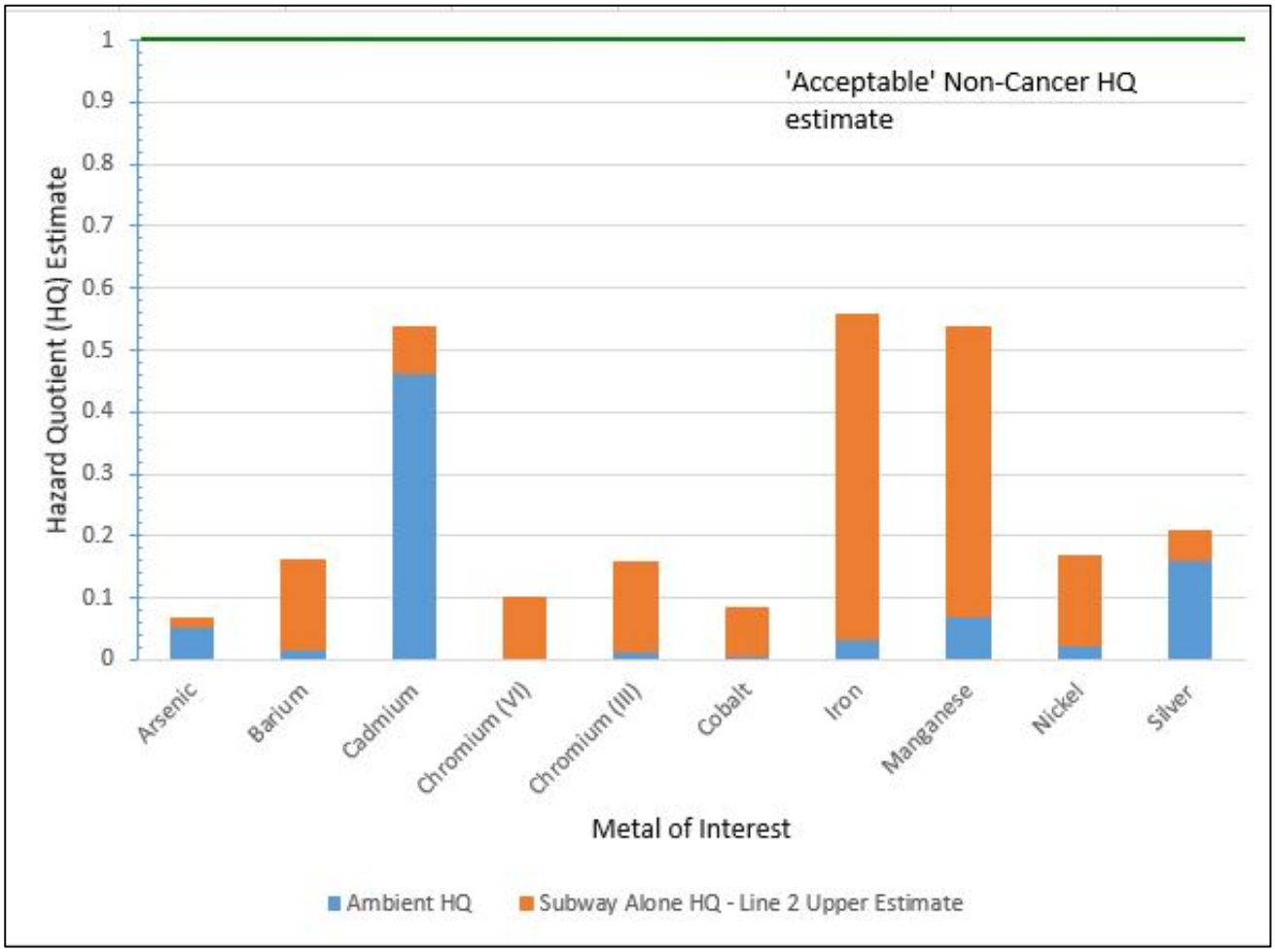


Figure 6-5 Line 2 Upper Estimates of Chronic Inhalation Hazard Quotients for Metals in Subway $PM_{2.5}$

6.2.1.2 Incremental and Lifetime Cancer Risk Estimates

Table 6-5 and Figures 6-6 and 6-7 summarizes the ILCR estimates associated with subway-related exposures and the LCR estimates resulting from exposures to both subway and ambient sources. As previously indicated, ILCR estimates are typically compared to a policy-based 'acceptable level' of incremental risk, often set by regulators at a level between 1 in 100,000 (1.0E-05) and 1 in 1,000,000 (1.0E-06) (HC, 2010a). Health Canada has established that an ILCR in the range of 1.0E-05 and 1.0E-06 is 'essentially negligible' for carcinogenic substances in drinking water, with an ILCR of 1.0E-05 having been widely accepted by federal agencies involved with contaminated site risk assessments (HC, 2010a). TPH and the MECP has set a policy-based 'acceptable' or de minimis level of incremental (or additional) lifetime cancer risk of 1 in 1,000,000 (1.0E-06).

With the exception of Cr (VI), all ILCR estimates fell within the range considered by Health Canada as 'essentially negligible' (1.0E-05 to 1.0E-06). ILCR estimates for arsenic, cadmium and Cr (VI) exceeded an ILCR level of 1.0E-06 (Table 6-5). The lifetime probability of developing cancer in North America is approximately 40% or 0.4, according to HC (2010a). As such, an ILCR of 1.4E-05 to 4.9E-05 (associated with Cr (VI) on Line 2) increases an individual's lifetime cancer risk from 0.40000 to 0.40001 to 0.40005.

As previously discussed (Section 4.2.5), despite the results of the TTC (2018) occupational study (which was unable to detect Cr (VI) in subway particulate matter (above the analytical method of quantification)), the HHRA assumed that 100% of all chromium measured in subway $PM_{2.5}$ existed as Cr (VI). As such, the ILCR estimates associated with Cr (VI) (Table 6-5) may over-estimate actual Cr (VI)-related health risks.

Table 6-5 Incremental and Lifetime Cancer Risk Estimates

Metal of Interest	LCR[2]	ILCR (Subway Alone)[1]		LCR (Ambient + Subway)[2]	
	Point Estimate	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Line 1					
Arsenic	**4.4E-06**	2.7E-07	**1.4E-06**	**4.7E-06**	**5.7E-06**
Cadmium	**2.3E-05**	**1.1E-06**	**5.8E-06**	**2.4E-05**	**2.8E-05**
Chromium (VI)	4.0E-07	**2.6E-06**	**1.4E-05**	**3.0E-06**	**1.4E-05**
Nickel	8.7E-08	2.7E-08	1.4E-07	1.2E-07	2.8E-07
Line 2					
Arsenic	**4.4E-06**	6.6E-07	**2.3E-06**	**5.1E-06**	**6.6E-06**
Cadmium	**2.3E-05**	**1.1E-06**	**3.8E-06**	**2.4E-05**	**2.6E-05**
Chromium (VI)	4.0E-07	1.4E-05	**4.9E-05**	**1.4E-05**	**5.0E-05**
Nickel	8.7E-08	1.6E-07	5.5E-07	2.4E-07	6.3E-07
Entire System (Line 1 and Line 2)					
Arsenic	**4.4E-06**	3.8E-07	**1.9E-06**	**4.8E-06**	**6.2E-06**
Cadmium	**2.3E-05**	**1.1E-06**	**5.4E-06**	**2.4E-05**	**2.7E-05**
Chromium (VI)	4.0E-07	**6.0E-06**	**3.1E-05**	**6.4E-06**	**3.1E-05**
Nickel	8.7E-08	5.6E-08	2.9E-07	1.4E-07	3.7E-07

[1]ILCR – Incremental Lifetime Cancer Risk Estimates resulting from subway related exposures alone. ILCR estimates are typically compared to policy-based acceptable or de minimis levels of incremental lifetime risk.
[2]LCR – Lifetime Cancer Risk Estimates were developed by multiplying either ambient or ambient plus subway exposures by the appropriate chemical-specific inhalation unit risk value. Provides a relative comparison between ambient and total risk levels.
Bold values – represent either ILCR and/or LCR estimates that exceed the TPH policy-based acceptable or de minimis ILCR level of 1.0E-06.

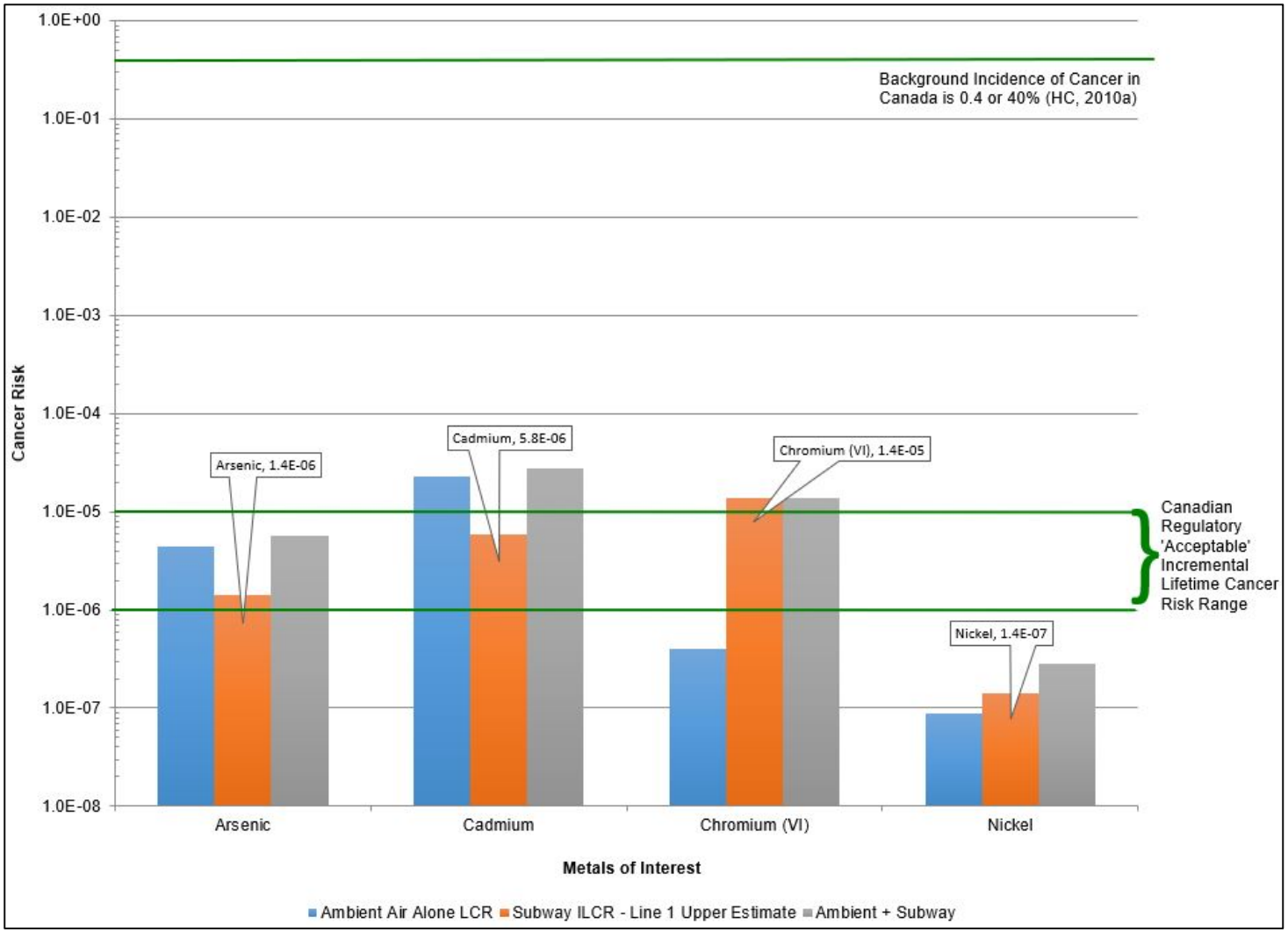


Figure 6-6 Line 1 Upper Estimates of ILCRs and LCRs for Metals in Subway $PM_{2.5}$

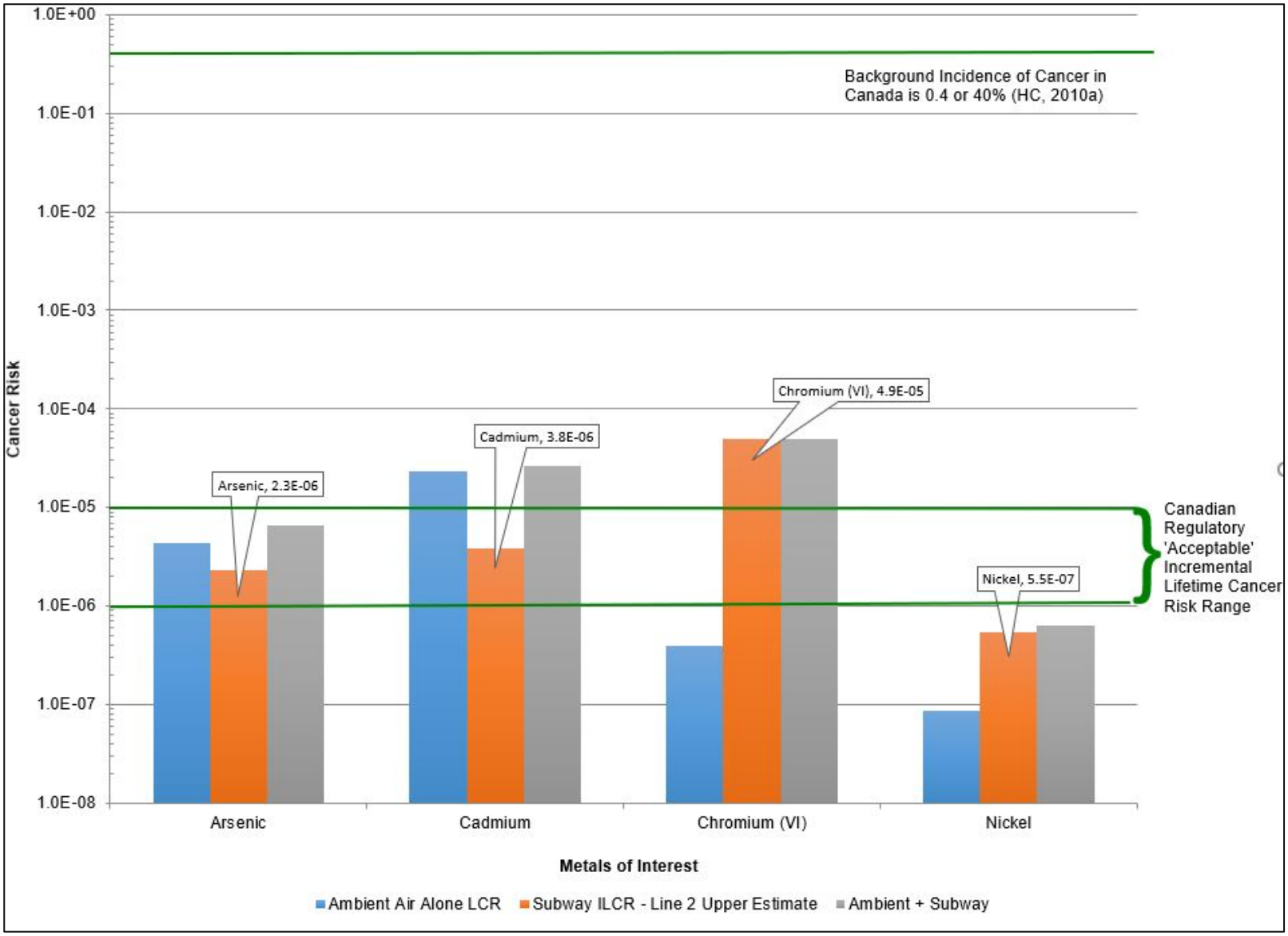


Figure 6-7 Line 2 Upper Estimates of ILCRs and LCRs for Metals in Subway $PM_{2.5}$

6.2.1.3 Chemical Mixtures – Additive Chronic Health Risk Estimates

As discussed in Section 5.5, metals identified as having a common mode of action, toxicity endpoint, or target organ were grouped together (Table 5-6). Chronic health risk estimates (HQ values) for each metal of interest within a group (e.g., chronic respiratory effects, neurological effects, lung cancer, etc.) were summed to develop a total HQ and/or ILCR estimate (Tables 6-6 and 6-7, respectively). Except for the upper percentile total HQ estimate of respiratory effects (for Line 2), all total HQ estimates were below a HQ value of 1.0. The upper percentile total HQ estimate of respiratory effects for Line 2 (of approximately 1.1) was driven primarily by subway-related exposures to iron (0.56), barium (0.17), and nickel (0.17). An upper percentile total HQ estimate of 1.1 is not considered substantively different from a HQ value marginally below a value of 1.0 and, therefore, is considered essentially negligible, as HC (2010a) would interpret an HQ value <1.0.

Table 6-6 Chronic Health Risks Associated with Specific Non-Cancer Effects

Non-Cancer Effect	Chronic Hazard Quotient (HQ) Estimates (unitless)				
	Ambient Alone HQ	Subway Alone HQ		Total HQ (Subway + Ambient)	
	Point Estimate	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Line 1					
Neurological Effects	0.12	0.05	0.25	0.17	0.36
Respiratory Effects	0.08	0.09	0.44	0.16	0.52
Line 2					
Neurological Effects	0.12	0.14	0.49	0.26	0.61
Respiratory Effects	0.08	0.31	**1.1**	0.38	**1.1**
Entire System (Line 1 and Line 2)					
Neurological Effects	0.12	0.07	0.38	0.19	0.50
Respiratory Effects	0.08	0.15	0.75	0.22	0.83

Table 6-7 Incremental and Lifetime Cancer Risk Estimates Associated with Lung Cancer

Type of Cancer	LCR (Ambient)	ILCR (Subway Alone)		LCR (Ambient + Subway)	
	Point Estimate	Central Tendency	Upper Percentile	Central Tendency	Upper Percentile
Line 1					
Lung Cancer	**2.8E-05**	**4.0E-06**	**2.1E-05**	**3.2E-05**	**4.8E-05**
Line 2					
Lung Cancer	**2.8E-05**	**1.6E-05**	**5.6E-05**	**4.3E-05**	**8.3E-05**
Entire System (Line 1 and Line 2)					
Lung Cancer	**2.8E-05**	**7.5E-06**	**3.8E-05**	**3.5E-05**	**6.5E-05**

[1]ILCR – Incremental Lifetime Cancer Risk Estimates resulting from subway related exposures alone. ILCR estimates are typically compared to policy-based acceptable or de minimis levels of incremental lifetime risk.
[2]LCR – Lifetime Cancer Risk Estimates were developed by multiplying either ambient or ambient plus subway exposures by the appropriate chemical-specific inhalation unit risk value. Provides a relative comparison between ambient and total risk levels.
Bold values – represent either ILCR and/or LCR estimates that exceed the TPH policy-based acceptable or de minimis ILCR level of 1.0E-06.

The total incremental lifetime lung cancer risks associated with subway-related exposures were estimated to be anywhere from 4.0E-06 to 2.1E-05 (for Line 1) and 1.6E-05 to 5.6E-05 for Line 2 (Table 6-7). In practical terms, this translates to an increase in an individual's lifetime cancer risk from approximately 0.40000 (40%), as stated by HC (2010a), to 0.400004 (40.0004%) to 0.40002 (40.002%) for Line 1 and an increased risk from approximately 0.40000 (40%) to 0.40002 (40.002%) to 0.40006 (40.006%) for Line 2.

6.2.2 Acute Inhalation Health Risks

Acute inhalation hazard quotient (HQ) values were used to help characterize short-term health risks associated with non-carcinogenic metals, according to the following equation:

$$Hazard\ Quotient = \frac{EPC_{Acute}\ \left(\frac{\mu g}{m^3}\right)}{Acute\ Inhalation\ Toxicity\ Reference\ Value\ \left(\frac{\mu g}{m^3}\right)}$$

The EPC_{Acute} represents the short-term (or acute) exposure while in the subway system (Section 4.3.2, Exposure Equation 7). A HQ value of less than one (HQ <1.0) is considered, by Health Canada, to represent a negligible risk (HC, 2010a).

The TTC (2019) data indicated that most subway users spend approximately one (1) hour in the subway system on any given travel day (i.e., approximately a ½-hour each way). Most of this time is spent riding on the subway train, with up to five minutes a day (in total, both directions) spent waiting on the platform. As such, exposure to metals in subway $PM_{2.5}$ over a ½-hour to 1-hour duration would be relevant to characterizing

acute human health risks. Acute EPCs represent a time-weighted average EPC that considers the amount of time spent waiting on platforms and riding the train during peak weekday hours (6am–9am and 3pm–7pm) (Section 4.3.2). EPC_{Acute} estimates for Line 1, Line 2, and the entire system were compared with acute environmental screening levels (ESLs) or acute inhalation reference values (ReVs) (Table 5-6) to develop acute HQ estimates (Table 6-8).

With the exception of barium (for Line 2) and iron (for Line 2 and the entire system), all acute HQ estimates were less than a value of one (HQ < 1.0) (Table 6-8). For Line 2, acute exposures to iron were estimated to be approximately twice the TCEQ (2019) acute interim ESL for iron (of 50 µg/m^3), resulting in a HQ value of 1.9. As described in Section 5.3.1, the acute (and chronic) interim ESLs for iron originate from an occupational threshold limit value (TLV) published by the ACGIH (of 5,000 µg/m^3 for iron oxide), which is designed to prevent pulmonary siderosis (a form of pneumoconiosis) in workers chronically exposed to iron particulate. The TCEQ applied 1,000- and 100-fold uncertainty factors to the ACGIH TLV in order to develop interim long- and short-term ESLs for iron of 5 and 50 µg/m^3, respectively.

There is a high level of uncertainty associated with all screening levels; however, by their very nature, screening levels are, to the extent possible, developed using a precautionary approach. The ACGIH TLV TWA (of 5,000 µg/m^3) for iron represents the lowest occupational exposure limit available and is meant to protect workers from pulmonary siderosis. As described by ACGIH, TLVs refer to *"…airborne concentrations of chemical substances and represent conditions under which it is believed that nearly all workers may be repeatedly exposed, day and day, over a working lifetime, without adverse health effects."* To this end, the acute ESL for iron used in the HHRA is 100-fold less (*i.e.,* 50 µg/m^3) than a TLV TWA (of 5,000 µg/m^3) designed to protect workers from repeated 8-hour exposures over the course of a working lifetime. Given the magnitude of the acute HQ value (1.9) and the basis of the TCEQ (2019) interim short-term interim ESL value, it is unlikely that pulmonary siderosis (the chronic health endpoint used in the derivation of the interim ESL) will occur as a result of an acute exposure event.

Although the acute HQ estimate for barium (for Line 2) marginally exceeded a value of 1.0 (at 1.1), this quantitative estimate does not result in a conclusion that would substantively differ from a HQ that is marginally lower than a value of 1.0 when considering the level uncertainty associated with most TRVs and assumptions made in the exposure assessment. Similar to iron, the TCEQ acute interim ESL for barium was derived by applying a 100-fold uncertainty factor to an occupational TLV designed to prevent eye, skin, and GI irritation and muscular stimulation in workers who are repeatedly exposed throughout an 8-hour workday, for a working lifetime.

Table 6-8 Acute Health Risk Estimates of Metals of Interest in $PM_{2.5}$

Metal of Interest	Acute Hazard Quotient (HQ) Estimates		
	Line 1	Line 2	Entire System (Line 1 and Line 2)
Arsenic	0.001	0.001	0.001
Barium	0.2	**1.1**	0.7
Cadmium	0.001	0.001	0.001
Chromium (VI)	0.1	0.6	0.3
Chromium (III)	0.02	0.1	0.04
Cobalt	0.2	0.4	0.3
Iron	0.9	**1.9**	**1.4**
Manganese	0.04	0.1	0.1
Nickel	0.02	0.05	0.03
Silver	0.2	0.2	0.2

6.2.2.1 Chemical Mixtures – Acute Health Risk Estimates

As detailed in Section 5.5, one common acute health effect (i.e., respiratory irritation and pulmonary effects) was identified among the metals of interest. Respiratory effects were found to be common effects associated with acute exposures to chromium, cobalt, iron, manganese, and nickel. Summing the individual acute HQ values for chromium (III), chromium (VI), cobalt, iron, manganese, and nickel resulted in total acute HQ values associated with respiratory HQs of 1.2, 3.1, and 2.1 for Line 1, Line 2, and the entire system, respectively (Table 6-9).

Considering the magnitude of the acute total HQ estimate for Line 2 and the entire system (of 3.1 and 2.2, respectively), it is plausible that acute respiratory effects such as irritation, pulmonary inflammation, and/or bronchoconstriction may occur in some individuals as a result of short-term exposures to a mixture of metals found in subway $PM_{2.5}$ during peak weekday hours.

Table 6-9 Acute Health Risk Estimates of Chemical Mixtures

Metal of Interest	Acute Hazard Quotient (HQ) Estimates		
	Line 1	Line 2	Entire System (Line 1 and Line 2)
Chromium (VI)	0.1	0.6	0.3
Chromium (III)	0.02	0.1	0.04
Cobalt	0.2	0.4	0.3
Iron	0.9	**1.9**	**1.4**
Manganese	0.04	0.1	0.1

Nickel	0.02	0.05	0.03
Total HQ – Respiratory Effects	**1.2**	**3.1**	**2.2**

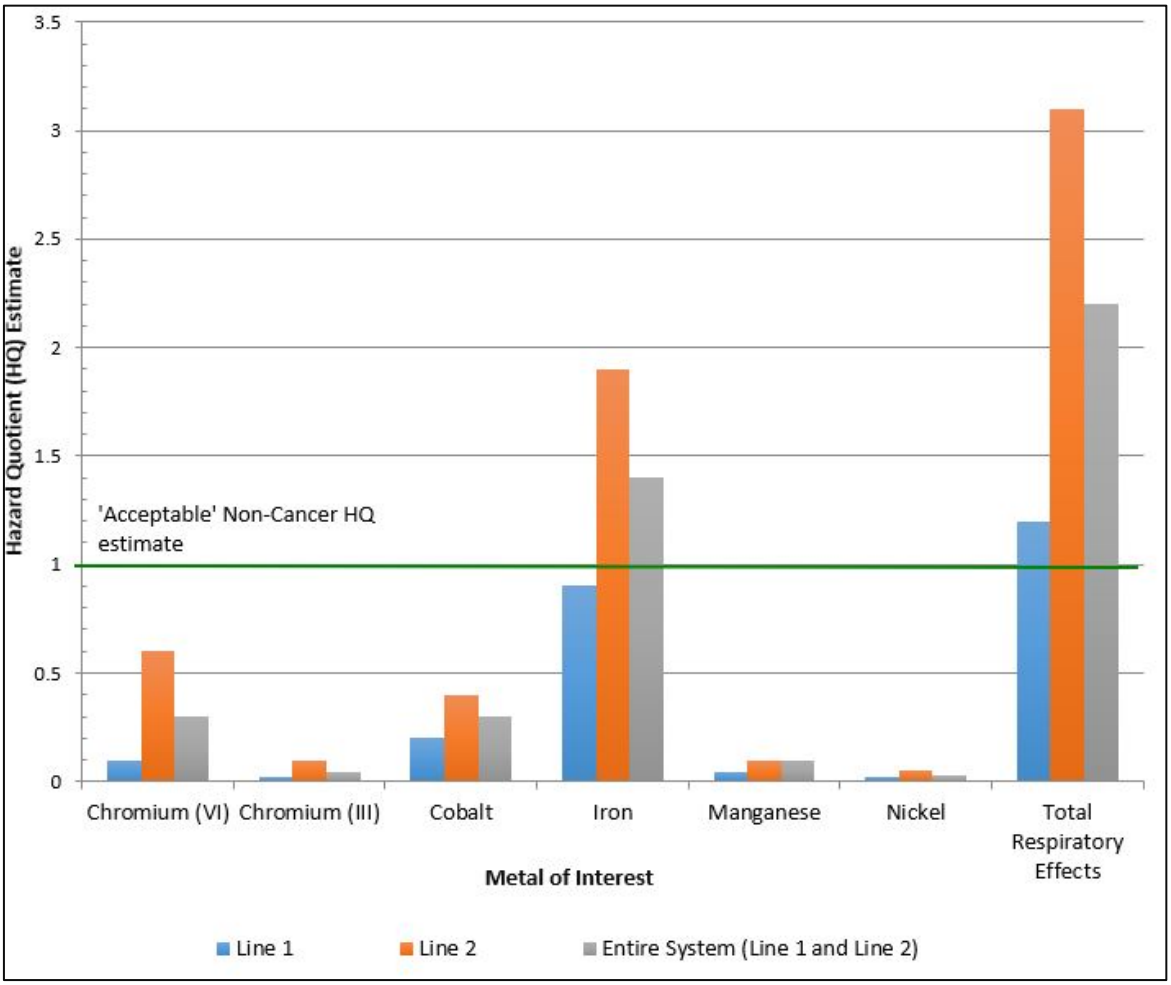


Figure 6-8 Upper Estimates of Acute Inhalation Hazard Quotients for Individual Metals in Subway $PM_{2.5}$ and Total Respiratory Effects

7.0 Discussion of Uncertainties

Numerous assumptions have been made throughout HHRA that help to ensure that the assessment, in light of uncertainties, overestimates (rather than underestimates) potential exposures and health risks. The net effect of these multiple assumptions and input parameters used throughout the HHRA process ensures the protection of human health. The following provides a discussion of the assumptions used and the uncertainties that exist throughout the exposure and hazard assessments.

7.1 Uncertainties in the Exposure Assessment

- Chromium in subway $PM_{2.5}$ has not been speciated and, therefore, the proportion of total chromium in subway $PM_{2.5}$ that exists as Cr(VI) is unknown. Lovett et al. (in press) and Chillrud et al. (2004) make the argument that any chromium found in a subway system should be assumed to exist as Cr(VI) due, at least in part, to the high temperatures involved in the braking process. It is noted that the TTC (2018) speciated chromium in the respirable particulate size fraction (as defined under Ontario Regulation 833) and was unable to detect Cr(VI) above the limit of quantification (approximately 0.03 µg/m^3). Given that the source of Cr(VI) may influence where within the particle size distribution Cr(VI) is found, the absence of Cr(VI) (above the level of quantification) in respirable particulate size fraction cannot be used to rule out the presence Cr(VI) in $PM_{2.5}$.

- Average chronic daily EPCs represent the long-term average daily exposure to $PM_{2.5}$ on an annual basis. The central tendency and upper percentile chronic EPCs rely, in part, on assumptions concerning frequency of subway ridership (i.e., three days per week, 48 weeks per year for the central tendency and 5 days per week for 50 weeks per year under an upper percentile estimate). Any alterations to these assumptions would impact the chronic EPCs

- The ambient air quality dataset collected as part of the SAQI was considered the most appropriate dataset to use in the approximation of chronic EPCs (Section 4.2.4). The SAQI ambient air quality data resulted in a mean ambient $PM_{2.5}$ concentration of 9.6 µg/m^3 (with the 95% UCLM estimated at 10.5 µg/m^3). Data collected by the National Ambient Pollution Surveillance (NAPS) program in 2017 (at both the Downsview and Resources Road Stations) resulted in an annual average $PM_{2.5}$ concentration of 7.1µg/m^3 (N=202) and an estimated 95% UCLM of 7.5 µg/m^3. The SAQI ambient air quality sampling was conducted over the summer months only and from two sampling locations (i.e., 200 College and 4905 Dufferin) situated closer to the downtown core. As such, there is uncertainty as to whether the smaller SAQI ambient air quality dataset is truly representative of ambient conditions within an urban environment.

- Loxham and Nieuwenhuijsen (2019) noted that the proportion of transition metals found in underground PM that are water-soluble and, therefore, bioavailable, was less than the proportion of water-soluble metals found in ambient PM, collected from urban sources. Although subway $PM_{2.5}$ has been shown to contain elevated levels of metals relative to ambient PM, without considering the water-soluble fraction, the concentration of bioavailable metal present in underground PM may be overestimated (relative to ambient PM). The HHRA has assumed that all metals present in subway $PM_{2.5}$ are 100% bioavailable.

- The HHRA has evaluated the risks of adverse health effects resulting from exposures to metals in subway $PM_{2.5}$. The HHRA has not evaluated health risks posed by larger PM fractions, such as PM_{10}. Although fine particulate ($PM_{2.5}$) itself is often considered a greater concern to human health than PM_{10}, the metal content in the larger subway PM size fraction (*i.e,* PM_{10}) is unknown. Metals in PM_{10} are relevant and likely applicable to the same inhalation TRVs used to evaluate metals in $PM_{2.5}$. As such the health risks associated with metals in the subway PM_{10} size fraction are unknown at this time.

7.2 Uncertainties in the Hazard Assessment and Risk Characterization

- The body of scientific evidence gathered to date indicates that exposure to $PM_{2.5}$ is associated with a variety of serious adverse health effects, including premature death, where no discernable effects threshold has been identified. As such, the $PM_{2.5}$ concentration below which adverse health outcomes are not expected to occur, if one exists, is currently unknown;
- Based on the recommendations provide by the TSAQ HIA Expert Panel, a review of the scientific literature by Loxham and Nieuwenhuijsen (2019), and absence of sufficient epidemiological or toxicity data, specific to subway PM, the HHRA has assumed that the toxicity of subway $PM_{2.5}$ is similar to that of ambient PM, despite subway PM being heavily enriched with a variety of different metals;
- The use of 24-hour ambient air quality standards and guidelines (designed to be used with upper percentile 24-hour concentrations taken from multiple years of ambient air quality monitoring) to comment on the risk of adverse health outcomes resulting from a 1-hour exposure to subway $PM_{2.5}$ is uncertain, at best. However, in the absence of sufficient acute toxicity and epidemiological data, 24-hour ambient air quality standards and guidelines were used to comment on potential health outcomes, recognizing the limitations of doing so.
- With the exception of the TCEQ (2019) short-term interim ESL value, no acute inhalation TRVs for iron published by a reputable regulatory agency was identified. The short-term ESL used to characterize iron-related acute health risks is founded on chronic exposure durations and related health endpoints (i.e., an ACGIH TLV TWA designed to protect workers from pulmonary siderosis who may be exposed day after day, for an entire working lifetime to iron particulate). Although the interim ESL was designed with a precautionary approach in mind, the toxicity associated with short-term exposure to iron particulate remains a source of uncertainty in the HHRA.

8.0 Summary of Findings

8.1 Fine Particulate Matter

Current scientific evidence indicates that no effects-based thresholds have been identified for PM (below which adverse health effects are not expected to occur) — therefore, PM guidelines that achieve complete protection against adverse health effects resulting from PM exposure cannot be designed (WHO, 2006a). As such, any efforts to reduce subway $PM_{2.5}$ to the extent technically and/or feasibly possible will help to reduce possible adverse health outcomes.

Subway $PM_{2.5}$ is enriched with a variety of metals and has a different composition compared to PM collected from ambient air (Section 5.1.3). A review of the existing scientific literature by Loxham and Nieuwenhuijsen (2019) concluded that, although further research is needed, there is little direct evidence that exposure to subway PM is more harmful than exposure to ambient PM. This conclusion may, in part, have been a result of inconsistencies identified between the results of in person exposure studies and *in vitro* toxicity tests. The authors indicated that while a variety of effects were measured following in vivo (or in person) exposure, no evidence was found that these measured effects were of any clinical significance (Loxham and Nieuwenhuijsen, 2019).

The TSQA HIA Expert Panel concluded that, in the absence of sufficient epidemiological or toxicity data, it should be assumed that subway $PM_{2.5}$ has a similar level of toxicity as ambient $PM_{2.5}$.

8.1.1 Chronic $PM_{2.5}$ Exposure Point Concentrations

The mean $PM_{2.5}$ concentrations on Toronto subway platforms over all operational hours on Line 1 and Line 2 were 138 µg/m^3 (range: 73 µg/m^3 to 292 µg/m^3) and 291 µg/m^3 (range: 71 µg/m^3 to 416 µg/m^3) respectively (Table 4-3). These average $PM_{2.5}$ concentrations fall within the range of concentrations found in other subway systems around the world, as observed by Moreno (2017). However, it is noted that the mean $PM_{2.5}$ subway platform concentration on Line 2 (of 291 µg/m^3) is at or near the upper limit of the range presented by Moreno (2017) with concentrations at some individual stations (on Line 2) exceeding those reported by Moreno (2017).

However, the highest concentrations of $PM_{2.5}$ were observed during peak weekday hours when ridership is highest in the subway (Section 4.2.1). The 95% UCLM $PM_{2.5}$ concentrations on subway platforms along Line 1 and Line 2 during peak weekday hours were 165 µg/m^3 (range from 80 µg/m^3 to 383 µg/m^3) and 385 µg/m^3 (range from 95 µg/m^3 to 536 µg/m^3), respectively (Table 4-3). The average $PM_{2.5}$ subway platform concentration on Line 2 of 385 µg/m^3 (95 µg/m^3 to 536 µg/m^3) during peak weekday hours is considered very high; however, a direct comparison between subway platform

concentrations and an annual $PM_{2.5}$ guideline was not considered appropriate. A subway platform is a microenvironment, where subway users spend a very small proportion of their overall day. As such, subway platform concentrations are not considered representative of a subway user's long-term average daily $PM_{2.5}$ exposure. Therefore, exposure from other microenvironments, including on-train and ambient air, were also considered when approximating a total chronic average daily EPC. As such, a $PM_{2.5}$ subway platform concentration (of 385 µg/m^3) on Line 2 was estimated to be associated with a total chronic average daily EPC of between 11.9 and 15.3 µg/m^3 (Section 4.2.5) after accounting for all microenvironments.

It may be not be possible, in practice, to measure a distinct difference between long-term mortality rates associated with an ambient $PM_{2.5}$ concentration of 10.5 µg/m^3 (calculated using the SAQI data) and the total chronic average daily $PM_{2.5}$ EPC estimates (ambient + subway sources) for Line 1 (10.9 to 12.7 µg/m^3). However, the total chronic average daily $PM_{2.5}$ EPC estimates associated with Line 2 (11.9 to 15.3 µg/m^3) and the combined subway system (11.2 to 14.1 µg/m^3) could result in a 1–3% increase in long-term mortality rates over those associated with the annual AQG (of 10 µg/m^3) (Section 6.1.1).

Under the assumptions and data used in the HHRA, reducing the mean $PM_{2.5}$ subway platform concentration, measured during peak weekday hours, on Line 2 by 74% (from 385 µg/m^3 to 100 µg/m^3) would result in approximately a 10–25% reduction in the total chronic average daily $PM_{2.5}$ exposure.

8.1.2 Acute $PM_{2.5}$ Exposure Point Concentrations

Acute EPCs represent time-weighted average concentrations (between platform and on-train concentrations) over the duration of a single subway trip (during weekday peak hours) lasting approximately 30 minutes.

There are no health-based $PM_{2.5}$ TRVs designed for use with ½-hour to 1-hour exposure durations — furthermore, the application of the 24-hour ambient standards, 24-hour IT levels, and/or the 24-hour AQG (designed for use with upper percentile 24-hour ambient air concentrations taken from multiple years of monitoring data) to acute EPCs may not be directly relevant. However, recognizing the limitations cited in Section 6.1.1, acute $PM_{2.5}$ EPC estimates for Line1 (84.7 µg/m^3), Line 2 (183 µg/m^3), and the entire subway system (130 µg/m^3) exceeded the WHO (2006a) 24-hour IT-1 level of 75 µg/m^3 — a 24-hour concentration associated with approximately a 5% increase in short-term mortality over the 24-hour AQG of 25 µg/m^3.

Although the acute EPC associated with Line 1 (of 84.7 µg/m^3) is marginally greater than the WHO (2006a) 24-hour IT-1 level (associated with approximately a 5% increase in short-term mortality over the 24-hour AQG of 25 µg/m^3), the acute EPC associated

with Line 2 is approximately 2-fold greater than that of Line 1, approximately 2.5-fold greater than the 24-hour IT-1 level of 75 µg/m^3, and 7-fold greater than the 24-hr AQG (of 25 µg/m^3). As such, efforts to reduce subway $PM_{2.5}$ concentrations on Line 2 (to the extent technically and/or economically feasibly possible) will only help to reduce possible adverse acute health outcomes.

Under the assumptions and data used in the HHRA, reducing the mean $PM_{2.5}$ subway platform concentration on Line 2, measured during peak weekday hours, by 74% (from 385 µg/m^3 to 100 µg/m^3) would result in an equal (74%) reduction in the acute $PM_{2.5}$ EPC estimate (from 183 µg/m^3 to 47.6 µg/m^3). This reduction would result in an acute EPC comparable to the WHO (2006a) 24-hour IT-2 level (of 50 µg/m^3), which is associated with approximately a 2.5% increase in short-term mortality over the mortality rate associated with the 24-hour AQG.

8.2 Metals of Interest in Subway $PM_{2.5}$

8.2.1 Chronic Health Risk Estimates

For each subway line and metal of interest, the chronic average total daily exposure point concentration (or EPC_{ATD}) was less than its respective inhalation TRV value (i.e., a total HQ <1.0), indicating that chronic non-cancer health risks associated with each individual metal of interest were considered negligible (HC, 2010a).

ILCR estimates for arsenic, cadmium and Cr (VI) exceeded an ILCR level of 1.0E-06, considered by TPH and the MECP as a de minimis level of incremental risk. With the exception of Cr (VI), all ILCR estimates fell within the range considered by Health Canada as 'essentially negligible' (1.0E-05 to 1.0E-06). The lifetime probability of developing cancer in North America is approximately 40% or 0.4, according to HC (2010a). As such, an ILCR of 1.4 E-05 to 5.4E-05 (associated with Cr (VI) on Line 2) increases an individual's lifetime cancer risk from 0.40000 to anywhere from 0.40001 to 0.40005 (or 40.001% to 40.005%). HHRA assumed that 100% of all chromium measured in subway $PM_{2.5}$ exists as Cr (VI) and, therefore, the ILCR estimates associated with Cr (VI) likely overestimate actual Cr (VI)-related health risks (Section 4.2.5).

8.2.2 Acute Health Risk Estimates

With the exception of iron (on Line 2 and the entire system), all acute HQ estimates were less than, or approximately equal to, a HQ value of 1.0. On Line 2, acute exposures to iron were predicted to be approximately twice the TCEQ (2019) acute interim ESL for iron (of 50 µg/m^3). Given the magnitude of the acute HQ value (1.9) and the basis of the TCEQ (2019) interim short-term interim ESL value (Section 5.3.1), it is unlikely that pulmonary siderosis (the chronic health endpoint used in the derivation of

the interim ESL) will occur as a result of an acute exposure event. Although the short-term interim ESL for iron is likely conservative by design, it must be recognized that the interim ESL is based on exposure data obtained from an occupational study and, as such, uncertainty remains concerning the potential adverse health outcomes associated with short-term exposures to high levels of iron.

8.3 Chemical Mixtures

Metals identified as having a common mode of action, toxicity endpoint, or target organ were grouped together (Table 5-6). Chronic health risk estimates (HQ values) for each metal of interest within an “effects” grouping (e.g., chronic respiratory effects, neurological effects, lung cancer, etc.) were summed to develop a total HQ or ILCR estimate (Tables 6-6 and 6-7, respectively). Non-cancer health risks associated with simultaneous exposure to multiple metals were considered essentially negligible, as HQ values were either less than, or equal to, a value of 1.0.

The upper ends of the estimated incremental lifetime lung cancer risk ranges associated with simultaneous exposure to multiple subway-related metals (i.e., arsenic, cadmium, chromium (VI), and nickel) on both Line 1 (4.0E-06 to 2.1E-05) and Line 2 (1.6E-05 to 5.6E-05) fell outside the range considered by Health Canada as ‘essentially negligible’ (1.0E-06 to 1.0E-05). However, it is recognized that the ILCR estimates (for lung cancer) are dominated by the ILCR associated with Cr (VI) (Table 6-5). Due a lack of chromium speciation data specific to the $PM_{2.5}$ fraction, all chromium in subway $PM_{2.5}$ was conservatively assumed to exist as Cr (VI) (Section 4.2.5). As such, ILCR estimates for Cr (VI) and, by association, estimates of lung cancer risk, can only decrease in proportion to the percentage of chromium that exists as Cr (VI) in subway $PM_{2.5}$.

9.0 Discussion and Conclusions

The results of the TSAQ HHRA indicate that concentrations of $PM_{2.5}$ are elevated throughout Toronto's subway system. The mean $PM_{2.5}$ concentrations on Toronto subway platforms recorded during weekday peak hours (when ridership is at its greatest) on Line2 (385 µg/m^3) are 2.3 times greater than on Line 1 (165 µg/m^3). In comparison, the ambient concentration of $PM_{2.5}$ in Toronto's outdoor environment is 7.5 reference µg/m^3.

Similar to other subway systems around the world that employ the use of a conventional steel-wheel steel rail arrangement known to generate steel 'rail dust' through friction (Bukowiecki, et al., 2007), the airborne $PM_{2.5}$ is largely comprised of metals (e.g., iron, barium, chromium, cobalt, manganese, nickel, etc.). As such, the metal enriched $PM_{2.5}$ found in Toronto's subway differs greatly in composition from the $PM_{2.5}$ found in a typical ambient urban environment (e.g., water-soluble ionic species - $SO4^{2-}$, $NO3^-$, Cl^-, $NH4^+$ and carbonaceous species – organic carbon, elemental carbon, etc.).

Subway-specific $PM_{2.5}$ toxicity values have not been developed to evaluate potential health impacts for subway riders. Loxham and Nieuwenhuijsen (2019) concluded that although the toxicological effects of subway PM exposure may be different from the effects associated ambient $PM_{2.5}$ (likely due to the unique characteristics of subway $PM_{2.5}$), it is not the case that subway $PM_{2.5}$ related effects are greater than the effects associated with ambient $PM_{2.5}$. Canadian and international guidelines for ambient $PM_{2.5}$ are predicated on the fact that PM is a non-threshold contaminant, meaning there is no level below which adverse health effects are not expected to occur (WHO, 2006a; HC, 2013). Therefore, the HHRA assumed that the subway $PM_{2.5}$ was similar in toxicity as ambient PM and as such, used the WHO (2006a) annual (chronic) and daily (acute) health-based benchmarks to place subway PM concentrations into context.

The WHO (2006a) provides a series of interim targets and guidelines for annual (or chronic) exposure to $PM_{2.5}$. They range from an air quality guideline (AQG) of 10 µg/m^3 to an interim target (IT-3) of 15 µg/m^3. When $PM_{2.5}$ exposures of subway ridership on Line 1 and Line 2 were combined with exposures from ambient air, it was determined that Line 1 exposure estimates were largely consistent with the WHO (2006a) AQG, while Line 2 estimates were between the AGQ (10 µg/m^3) and the IT-3 (15 µg/m^3) and should be interpreted as aspirational targets to drive continuous improvement in AQ to the degree possible. Priority should be given to reduce $PM_{2.5}$ concentrations on Line 2, such that long-term combined exposures (i.e., subway plus ambient) better align with the AQG of 10 µg/m^3. This recommendation is consistent with Health Canada's guidance to strive for continual improvement (or lowering) of ambient $PM_{2.5}$ levels.

The HHRA used an approach similar to that of Moreno (2017) to benchmark acute $PM_{2.5}$ exposure (over an individual subway ride) against the WHO (2006a) $PM_{2.5}$ 24-hr

guideline and interim targets. The acute $PM_{2.5}$ exposure estimate for Line 1 was similar to the WHO IT-1 (75 µg/m^3); however, the Line 2 $PM_{2.5}$ exposure estimate was approximately 2.5-times greater than the WHO IT-1 and Line 1 exposure estimate. The $PM_{2.5}$ exposure estimates on both lines are considerably higher than the concentrations measured in Toronto's ambient air. Again, priority should be given to mitigation efforts on Line 2 to lower $PM_{2.5}$ exposures among the subway ridership.

Nine metals in subway $PM_{2.5}$ were evaluated for their potential to have adverse non-cancer and cancer health outcomes (chromium, cadmium, arsenic, manganese, nickel, iron, barium, cobalt, and silver). International regulatory agencies have published inhalation toxicity reference and inhalation unit risk values for these metals that allow for the evaluation of non-cancer and cancer health risks from exposure to the individual metals of interest. Long-term (or chronic) exposure estimates to airborne metal concentrations (in the $PM_{2.5}$ size fraction) on both Line 1 and Line 2 were below their respective non-cancer toxicity reference values. Given the magnitude of the acute iron exposure estimate on Line 2 (i.e., approximately twice the interim ESL value) and the basis of the TCEQ (2019) ESL, it was considered unlikely that pulmonary siderosis (the chronic health endpoint used in the derivation of the short-term ESL for iron) would occur as a result of a single acute exposure event.

Incremental lifetime cancer risk (ILCR) estimates for arsenic, cadmium and Cr (VI) exceeded an ILCR level of 1.0E-06, considered by TPH and the MECP as an 'acceptable' or de minimis level of incremental lifetime risk. With the exception of Cr (VI), all ILCR estimates fell within the range considered by Health Canada (HC, 2010a) as 'essentially negligible' (1.0E-05 to 1.0E-06). In the absence of laboratory confirmation, the HHRA conservatively assumed that all chromium present in subway $PM_{2.5}$ existed as chromium (VI). Despite the necessity of the conservative assumption used, an ILCR estimates range from 1.4E-05 (or 1.4 in 100,000) to 4.9E-05 (or 4.9 in 100,000) for chromium (VI) were found to exceed the upper end of the range considered to be essentially negligible (i.e., 1.0E-5 or 1 in 100,000). Speciation of subway $PM_{2.5}$ samples for chromium (VI) would reduce the uncertainty associated with chromium (VI) risk estimates.

It is possible that transient (i.e., short-lived; passing; not permanent) respiratory effects such as irritation, pulmonary inflammation, and/or bronchoconstriction may occur in some individuals as a result of simultaneous short-term exposures to multiple subway-related metals found in subway $PM_{2.5}$. The upper end of the incremental lifetime lung cancer risk estimates associated with simultaneous chronic exposure to multiple subway-related metals on both Line 1 (4.0E-06 to 2.1E-05) and Line 2 (1.6E-05 to 5.6E-05) were greater than the range considered by Health Canada as 'essentially negligible' (1.0E-06 to 1.0E-05). It is recognized that the ILCR estimates (for lung cancer) are dominated by the ILCR associated with Cr (VI).

Acute exposures to the $PM_{2.5}$, and the associated mixture of metals that may occur over an individual ride, particularly on Line 2, are high enough that transient (i.e., short-lived, passing or not permanent) respiratory effects and/or symptoms may be experienced among some susceptible individuals. More specifically, it is possible that transient respiratory effects (breathing problems) could be experienced among asthmatics, those with COPD, and even potentially in healthy adults. The effects may include detectable differences in lung function, respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, rhinitis and general asthmatic symptoms). It may also be possible that one could detect the biomarkers of lung inflammation. The high iron content in subway $PM_{2.5}$ appears to dominate acute health risks associated with exposures to mixtures of metals in $PM_{2.5}$.

Acute exposures to ambient $PM_{2.5}$ have been shown to result in an increase in respiratory and cardiovascular related effects. The US EPA (2009) and HC (2013) indicate that multiple lines of evidence exist to conclude that there is likely a causal relationship between respiratory effects (i.e., lung function decrements, respiratory symptoms, and lung inflammation) and acute $PM_{2.5}$ exposure. Exposure to ambient $PM_{2.5}$ levels can result in increased respiratory emergency room visits and hospital admissions. A reduction of Line 2 $PM_{2.5}$ levels would be expected to decrease the potential for transient respiratory effects and symptoms among the subway ridership.

The area of scientific investigation of potential health risks from exposure to subway air quality is still in its infancy. Although there is a decade's worth of measurements illustrating the elevated concentration of $PM_{2.5}$ in subway systems around the world, there is a paucity of epidemiological, *in vivo*(health monitoring of individuals using subway) and *in vitro*(laboratory studies) research to determine the actual health risks posed by subway air quality.

Of tremendous benefit to the TSAQ HHRA is the recent systematic review published by Loxham and Niewenhuijsen (2019) on the *Health Effects of Particulate Matter in Air Pollution in Underground Railway Systems – a Critical Review of the Evidence.* This article identifies the peer-reviewed scientific research in the field, provides critical review and synthesis of the findings in the field, and allows for the TSAQ to be placed into context with the international research.

Loxham and Nieuwenhuijsen (2019) reviewed four studies that specifically investigated the human health effects associated with acute exposures to subway PM (including $PM_{2.5}$) with people using the subway over a 1 to 2-hour period. Effects were evaluated using a variety of different *in vivo* endpoints (e.g., increased activated T cells, blood T cell counts, coagulation markers, lung function decrements, heart rate variability, etc.). Three of the four studies stated the average airborne $PM_{2.5}$ concentrations that volunteers were subjected to range from 22 to 77 $\mu g/m^3$. Of note, Klepczynska Nystrom et al. (2010) conducted an acute exposure study in Stockholm where no effects on lung

function were observed in the 20 healthy adult volunteers exposed to an airborne $PM_{2.5}$ concentration of 77 µg/m^3 for 2 hours during afternoon rush hour. The Stockholm concentrations are similar to the acute exposure estimate on Line 1 (of 84 µg/m^3); however, the exposure estimate on Line 2 (183 µg/m^3) is almost 2.5 times greater than the reported concentration in the Stockholm study.

Loxham and Nieuwenhuijsen (2019) concluded:

> *From the small number of studies, there is little evidence that the physicochemical characteristics of underground PM translate to a significantly increased risk of adverse health effects in underground railway workers or commuters, although it is clear that further work in this area is required.*

The weight of scientific evidence suggests that while measurable effects on some endpoints have been observed across several in person (in vivo) studies, there is a general lack of evidence for the effects being as clinically significant as laboratory (in vitro) studies suggest (Loxham and Nieuwenhuijsen, 2019). However, Line 2 $PM_{2.5}$ concentrations appear to be much higher than those reported in the systematic review and, as such, caution should be exercised as to how this literature can be used to draw conclusions concerning health impacts associated with Line 2 exposures.

Overall, the results of the TSAQ HHRA indicate that the levels of $PM_{2.5}$ (and by association, a number of metals) are high enough to warrant remedial action, particularly on Line 2. Any reduction in $PM_{2.5}$ platform concentrations would also lower concentrations of associated metals. Long-term exposure to subway air quality increases an individual's overall annual exposure to $PM_{2.5}$ by approximately 13 to 45% on Line2 and 3 to 21% on Line 1. ILCR estimates for arsenic, cadmium and Cr (VI) exceeded an ILCR level of 1.0E-06, considered by TPH and the MECP as an ‘acceptable’ or de minimis level of incremental lifetime cancer risk With the exception of chromium (VI), which is associated with a high degree of uncertainty due to the lack of speciation data, all incremental lifetime cancer risk estimates for individual metals were either below or within the range of risks considered by many regulatory agencies, including Health Canada, as essentially negligible (i.e., 1.0E0-6 to 1.0E-05). Short-term exposures to subway air quality, particularly on Line 2, may on occasion, result in transient (i.e., short-lived; passing; not permanent) respiratory symptoms (i.e., coughing, shortness of breath, chest tightness, general asthmatic symptoms) and/or a decline in lung function for children and adults with asthma, adults with COPD, and perhaps even healthy adults.

Given the results of the TSAQ HHRA, the lack of studies evaluating the human health effects of subway particulate exposure, and the causal relationship between many adverse health outcomes and exposure to fine particulate matter under ambient conditions, it is reasonable to conclude, despite the uncertainty that exists, that health

risk estimates associated with exposure to Toronto's subway air quality, particularly on Line 2, are elevated. Similar conclusions have been reached for the London Underground (COMEAP, 2018) and the Metro red line (subway) in Los Angeles (Lovett et al., 2017)

Although the limited research in the field suggests these effects may not be clinically significant, further research should be undertaken to reduce the uncertainties identified in the HHRA and to better understand the potential health impacts of Toronto subway users.

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