Reducing Commuter Exposure to Fine Particulate Matter in the Toronto Subway

Request for Proposal
Addenda

Overall:
- The organization of the sections was changed to create a better flow throughout the RFP. The revised order provides a more logical presentation of information so the reader can more easily understand the material. Specifically, “Community Exposition” now follows “Problem Exposition” and “Stakeholders” now follows “Community Exposition”. Reference Designs were moved down as they will have greater value if the reader has an understanding of the community before reading about them.
- The Design Overview was amalgamated into other sections. Since the Design Overview was one of the later sections of the original document, the new document defines the problem at an earlier stage.
- Illustrations were added at various locations to simplify and clarify complex points.

Abstract:
- The abstract was reworded slightly to give greater emphasis to the selection of Queen’s Part Station as the location for a solution.

Section 2: Definitions:
- The phrase “negative outcomes” was clarified in order to better define a “need” and how it is related to quality of life.
- The definition of “quality of life” was shortened to make it more relevant to the community discussed in this RFP.
- The definition of “engineering design” was added to elaborate on the team’s design values.
- The definition of “PM2.5” was expanded to make it clearer before moving into more technical material.

Section 3: Background Information:
- A discussion of the categories of PM2.5 exposure was added to differentiate between short- and long-term exposures thus helping to clarify the health risk.

Section 4: Problem Exposition:
- The discussion of our selection of Queen’s Park Station as an exemplar was expanded upon; emphasizing the reasons it was chosen. This information is very important in terms of the solution implementation and therefore it is presented earlier than in the original document.

Section 5: Contributing Factors:
- A diagram was added to assist the visualization of what the current subway system looks like.

Section 6: Community Exposition:
- The demographic composition of our community was elaborated on to include commuters with respiratory illnesses, commuters travelling to Union station and the proximity to U of T. These groups represent important subpopulations of the community and highlighting them emphasizes the legitimacy of the community. Additionally this presents information about groups to be considered when evaluating solutions.

Section 7: Stakeholders:
- A discussion of the preferences and point-of-view of the TTC beyond simply lowering particulate matter concentrations were included to give the reader a better understanding of what the TTC’s position. While these are not part of requirements, they are still important to the TTC’s view of solutions that may be implemented.

Section 8: Requirements:
- Objectives, constraints and criteria were further defined and clarified. This included the consolidation of some criteria and constraints. Metrics were added where necessary and codes were referenced to give the reader more insight into specific details that must be considered. Additional interests and preferences of the TTC were removed and placed in the “Stakeholder” section. This prevents what the TTC “wants” from overshadowing what the community “needs”.

Section 9: Reference Designs:
A reference design (the personal respirator) was added to broaden the scope of the set of solutions to include designs that are not specifically implemented in the station. This helps to broaden the design space and increase the breadth of possible solutions.
Abstract

Airborne fine particulate matter is a known health risk to subway users [1]. The concentration of fine particulate matter in Queen’s Park subway station was found to be at levels which may cause material health problems to both commuters and Toronto Transit Commission (TTC) workers.

The purpose of this report is to develop engineering solutions to this problem which are effective, cheap, without adverse impact on commuters and viable for the TTC to implement (these and other requirements are discussed in section 10 (“Design Requirements”) of the request for proposal document). The ultimate goal of solutions is to increase the quality of life of Toronto’s subway commuters by decreasing the occurrence of health problems.

Medical researchers in the field believe there is an overwhelming body of evidence which supports an association between particulate matter exposure and a broad range of adverse health effects. Additionally, there appears to be no “safe level” of particulate matter concentration – any exposure produces negative health effects and the greater the exposure, the greater the effect [1].

The greatest health risks associated with even short-term exposure to this pollutant are an increased incidence of acute myocardial infarction (heart attack) and prevalence of chronic pulmonary obstructive disorders [1] [2] and there may be an association between exposure and the development of Alzheimer’s disease [3]. These health problems significantly decrease both life span and quality of life for those affected. Additionally, short-term particulate matter exposure can aggravate asthma in children and infants and longer-term exposure can increase the risk of lung cancer disorders [1] [2].

Of particular concern is the concentration of particulate matter of a diameter less than 2.5 microns – known as PM2.5 – which has been shown to be positively correlated with both mortality and morbidity disorders [1] [2]. Measurements of PM2.5 levels in the Toronto subway system by ourselves and other groups [3] suggest a likely nominal increase in mortality of between 6.7% and 10.7% above users of other major metropolitan subway such as those in Taipei, New York, Mexico City and Helsinki [2] [4] [5]. In terms of morbidity amongst TTC subway users, the prevalence of chronic obstructive pulmonary disease is likely between 75% and 118% nominally higher than among users of other major metropolitan subways such as those in Taipei, New York, Mexico City and Helsinki [1] [4] [5]. Supporting these disturbing statistics is the observation that the TTC subway PM2.5 concentrations exceed the Government of Alberta’s guidelines on one-hour exposure by up to 3 times [6].

Queen’s Park Station was selected in particular due to the particular high PM2.5 levels exhibited there, the relatively simple layout of the station, and its high number of users. The primary sources of fine particulate matter in the Toronto subway as a whole, and therefore this station, are likely the wheel-rail interface, brake pad erosion and electric arcing of the train’s brush with the track’s “third rail” [7].
Reducing Commuter Exposure to Fine Particulate Matter in the Toronto Subway

Table of Contents

1. Introduction ........................................................................................................................................... 6
2. Definitions ............................................................................................................................................. 6
3. Background Information ...................................................................................................................... 6
   3.1. PM2.5 Health Risk ....................................................................................................................... 6
   3.2. PM2.5 Exposure Standards .......................................................................................................... 7
   3.3. Subways as an Increased Risk Environment for PM2.5 ............................................................ 7
4. Problem Exposition ............................................................................................................................... 7
   4.1. Risk to Users of Toronto Subway ............................................................................................... 7
   4.2. Comparative Exposure Estimate ............................................................................................... 7
   4.3. Impact upon Quality of Life ....................................................................................................... 8
   4.4 Selection of Queen’s Park Station ............................................................................................... 8
5. Contributing Factors ............................................................................................................................. 8
   5.1. PM2.5 Sources within the Toronto Subway .................................................................................. 8
   5.2. Present State of PM2.5 Mitigation Within Toronto Subway ...................................................... 8
6. Community Exposition ........................................................................................................................ 9
   6.1. Demographic Composition ......................................................................................................... 10
   6.2. Community Awareness .............................................................................................................. 10
7. Stakeholders ......................................................................................................................................... 10
   7.1. Toronto Subway Commuters ..................................................................................................... 10
   7.2. Toronto Transit Commission .................................................................................................... 10
   7.3. Amalgamated Transit Union Local 113 .................................................................................... 11
   7.4. Device Manufacturers .............................................................................................................. 11
   7.5. Public Health ........................................................................................................................... 11
   7.6. Environment ........................................................................................................................... 11
8. Requirements ....................................................................................................................................... 11
   8.1. Objectives ............................................................................................................................... 11
   8.2. Constraints ............................................................................................................................... 12
   8.3. Criteria ...................................................................................................................................... 12
9. Reference Designs ............................................................................................................................... 13
   9.1. Electrostatic Precipitators .......................................................................................................... 13
   9.2. Platform Screen Doors ............................................................................................................. 14
   9.3. Ambient Air Filtration Systems ................................................................................................. 14
   9.4. Personal Respirators ................................................................................................................. 15
10. Conclusion .......................................................................................................................................... 15
11. Appendices ......................................................................................................................................... 16
    Appendix A: PM2.5 Research Studies Summary .............................................................................. 16
    Appendix B: Experimental Findings .................................................................................................. 17
    Appendix C: Interview with Kelly Sabaliauskas, SOCAAR ............................................................. 17
    Appendix D: Interview with Karen Stintz and Glenn de Baeremaker, TTC .................................... 20
1. Introduction

The Toronto Transit Commission subway system faces a health and safety problem due to high concentrations of particulate matter in the subway. This request for proposal will analyze this issue, discuss a community affected by this problem and examine factors contributing to this issue. In addition, this request for proposal will provide reference designs, identify stakeholders and analyze the requirements of a solution - including objectives, constraints and criteria - in order to properly constrain potential solutions. This request for proposal focuses on reducing the health and safety concerns associated with particulate matter in the Toronto subway system.

2. Definitions

2.1 Community: A group of individuals that share a collective characteristic, which links members of the group together. This link may be physical or psychological, such as a geographic region, a common routine, contribution to or membership in a specific entity, or similar beliefs.

2.2 Need: A need is defined as either a physical or psychological requirement that allows an individual to carry on with their life. Once the basic requirements of life are met (food, health, etc.) an individual can move on to pursue greater ambitions. Without having needs met, an individual would experience a lack of something which would bring about a negative outcome in terms of the way they conduct their daily lives. Such negative outcomes would be directly related to reducing the quality of life of the individual.

2.3 Quality of life: There are many definitions of quality of life. Their differences are mostly due to their context – whether or not they are primarily concerned with quality of life in the first or third world [8][9]. Since this RFP is concerned with the quality of life of a group in the first world, we shall adopt a definition with a greater first world bias. Namely, we shall adopt the University of Toronto’s Quality of Life Research Unit’s definition that quality of life consists of belonging (connecting with one’s environments), being (one’s physical, psychological and spiritual success) and becoming (the achievement of personal goals and aspirations) [9]. More specifically we propose that one’s healthiness (particularly with regard to chronic disease) negatively affects one’s quality of life by decreasing the degree to which they can interact with society and experience success in their life.

2.4 Engineering design: We define engineering design as the formal process of producing the best possible solution to an engineering problem, taking into consideration economic and other constraints. Based on this definition, our problem is an engineering design problem for the following reasons. Firstly, our criteria require that the best possible solution to the problem be presented. Secondly, the solution will likely require the use of science and technology to produce a practical remedy - that is, it will require engineering. Lastly, the solution has a huge practical constraint on it - it will need to be viable for the TTC to implement it and this incorporates a number of practical constraints such as cost and safety. Hence the solution will likely satisfy our definition of engineering design.

2.5 PM2.5: Also referred to as fine particulate matter or FPM. PM2.5 designates airborne particulate matter, irrespective of composition, of diameter 2.5 microns or less. It has been identified as a hazardous constituent of air pollution [10].

3. Background Information

The following section provides information regarding PM2.5 risks and current standards that exist.

3.1 PM2.5 Health Risk

PM2.5 has been identified as an air pollutant “of significant health concern” [10]. The Ontario Ministry of Environment states “adverse health effects have been associated with exposure to PM2.5 during both short periods such as a single day, and longer periods of a year or more.” [11]. In support of this claim, a study published by the American Medical Association has shown that an increase of 10 µg/m³ of PM2.5 in the environment can elevate the risk of cardiopulmonary and lung cancer mortality by 6% and 8%, respectively [12]. Additionally, a Harvard study found that a decrease of 10
μg/m³ of ambient PM2.5 (approximately one tenth of the levels in the TTC; see the appendix) resulted in a life expectancy increase of approximately four months [3]. PM2.5 levels in Toronto have been characterized as averaging 15 µg/m³ outdoors and 16 µg/m³ indoors; accordingly, Toronto Public Health estimates that 1,236 premature deaths in 1999 resulted from chronic exposure to PM2.5 [10]. This figure represents only the most serious outcome of fine particulate matter exposure – other, more numerous effects include aggravation of asthma symptoms [13] and induction of chronic bronchitis [10]. Research has also shown that children and the elderly are more susceptible to adverse health effects from PM2.5 exposure than the general population [13] [14].

3.2. PM2.5 Exposure Standards

PM2.5 exposure falls into two categories – short-term and long-term, with separate standards for each. The EPA and other agencies define short-term exposure as within a period of 24 hours, and long-term exposure as lasting a period of a year or more [58]. As each instance of a commuters’ exposure to PM2.5 in the subways presents a fluctuation in their total exposure over a timescale of less than 24 hours, only short-term exposure standards will be considered in this problem. To mitigate the public health impact of short-term exposure to PM2.5, the Canadian Council of Ministers of the Environment has published a Canada-Wide Standard for ambient PM2.5 concentrations of 30 µg/m³ of air averaged over a 24-hour period [15]. Other bodies have published differing guidelines: Metro Vancouver and Ottawa both list 25 µg/m³ over 24 hours as the standard, as does the World Health Organization [16]. Alberta has also published a 1-hour ambient air quality guideline for fine particulate matter, of 80 µg/m³ [17]. It should be noted that the aforementioned standards are intended to apply to outdoor concentrations; however, Health Canada has issued a document stating that:

“Indoor levels of PM2.5 should be kept as low as possible, as there is no apparent threshold for the health effects of PM2.5 … with respect to indoor PM2.5, Health Canada is not proposing a specific maximum exposure limit, but is recommending that indoor PM2.5, at a minimum, be lower than PM2.5 outside the home.” [18]

3.3. Subways as an Increased Risk Environment for PM2.5

Numerous studies worldwide have identified the subway environment as having inherently higher concentrations of PM2.5 compared to street level: subway systems in London [19], Helsinki [20], New York [5], Barcelona [21], Prague [22], Mexico City [23], and Seoul [24] have all been identified by researchers as exhibiting high concentrations relative to levels above ground. (See Appendix A for details.) In addition, research by the Karolinska Institute of Sweden has shown that airborne particulate in the subway environment specifically can be up to eight times more genotoxic than those found at surface level [25].

4. Problem Exposition

The problem presented by this RFP is such: Develop a means of reducing exposure to PM2.5 for patrons of Queen’s Park Station.

4.1. Risk to Users of Toronto Subway

The aforementioned findings suggest that the presence of PM2.5 in the Toronto subway system would pose a risk to commuters’ health. One study, conducted in 2000 by K.S. Crump of ICF Consulting, found that “subjects who rode the Toronto subway had significantly elevated exposures to PM2.5,” and found the mean PM2.5 concentration in subway to be 159 µg/m³, compared to outdoor levels of 15 µg/m³ [26]. To verify these findings, measurements of instantaneous PM2.5 concentrations were taken using a TSI DustTrak 8520 monitoring device; it was found that levels exceeded those above ground by a minimum factor of four, and generally much more. (See Appendix B for findings in detail.) These findings were confirmed by Kelly Sabaliauskas and Dr. Greg Evans of the Southern Ontario Center for Atmospheric Aerosol Research, who both reported similar results from more extensive testing [27]. In addition, Sabaliauskas also stated that the TTC is not currently pursuing any initiatives toward combatting PM2.5 levels within the subway system[27].

4.2. Comparative Exposure Estimate
Reducing Commuter Exposure to Fine Particulate Matter in the Toronto Subway

Using the Canada-Wide Standard level of 30 µg/m³ and an average daily breathing rate of 22.9 m³ per 24 hours [28], a figure of 687 µg over 24 hours was determined as the upper threshold for safe daily PM2.5 exposure. Using Crump’s measurement of 159 µg/m³, if commuter spends an hour in the subway, their total exposure would amount to 152 µg – 22% of this threshold. Alternately, if the Alberta outdoor hourly guideline is considered, commuters’ exposure to PM2.5 in the Toronto subway over a one-hour period is twice that of the recommended upper limit [17].

4.3. Impact upon Quality of Life

Toronto Public Health has directly stated how “poor air quality in the city can reduce the quality of life for Toronto’s children and adults, and especially for those who face a lifetime of chronic respiratory problems that are made worse by air pollution” [10]. This satisfies the aforementioned definition of quality of life, as poor air quality adversely affects short-term and long-term health. As PM2.5 has been identified as: a) a significant constituent of air pollution, and b) present in very high concentrations in the air of the Toronto subways, it can be inferred that PM2.5 levels on the Toronto subway are detrimental to the quality of life of Toronto commuters.

4.4 Selection of Queen’s Park Station

As reduction of PM2.5 levels in the Toronto subway system as a whole presents a problem outside of the scope of solvability for first-year engineering teams, it was decided to reduce the scope of the problem to a single station. This station was selected for the following reasons:

i) Measurements taken at a number of stations on the Yonge-University-Spadina line showed Queen’s Park Station to have significantly higher concentrations than any of the others studied (see Appendix B). Accordingly, the health risk presented by this station to commuters is greater than any other station tested.

ii) Being one of two enclosed, tunnel-bored stations (the other being St. Patrick Station), the airflow in Queen’s Park Station is relatively simple compared to other stations (see Appendix D), thus fewer parameters would need to be considered when generating a solution.

iii) Queen’s Park Station’s ridership is much greater than that of St. Patrick Station [1]. Hence, its PM2.5 levels affect more people than those of St. Patrick Station.

5. Contributing Factors

The following section highlights the probable sources of PM2.5 and current ventilation systems used by the TTC.

5.1. PM2.5 Sources within the Toronto Subway

A number of sources have been identified as contributing to levels of PM2.5 in subways. Predominantly, studies have identified iron as the major constituent of airborne particulates in subways, pointing to friction between train wheels and rails as the main source [20] [7]. This is corroborated by Crump’s findings, which indicate atypically high concentrations of manganese particulate in the Toronto subway – manganese being a significant constituent of the rails’ alloy [26]. Additionally, erosion of brake pads was identified as contributing to high silicon concentrations in samples taken from the London Underground, that study found the “brake-wheel-rail interface” contributed an estimated 68% to the total particulate levels in the subway environment, and Kelly Sabaliauskas of SOCAAR affirmed that the state of the Toronto subway in regards to PM2.5 generation is similar [3] [29]. Another identified source, namely of carbon particles, is gradual disintegration of the subway cars’ contacts with the third rail due to electric arcing [29]. A final source of PM2.5 in subways is air exchange with the aboveground environment through the ventilation shafts; this can introduce hydrocarbon particulate from combustion processes into the subway microenvironment [22] [30].

5.2. Present State of PM2.5 Mitigation Within Toronto Subway

Presently, the TTC is not actively addressing the issue of PM2.5 concentrations within the Toronto subway system [27]. In the past, the TTC had a maintenance practice of washing the walls of subway stations at two-month intervals, in order to remove accumulated detritus: this helped control PM2.5 concentrations, however this practice was discontinued.
after it was found to cause damage to the station walls [27]. The ventilation system also does little to address PM2.5 levels: the Toronto subway currently uses a passive ventilation system, whereby the piston action of the passing trains forces air through ventilation shafts leading to the surface [31]. These shafts do not feature any sort of scrubbers or filters, and are located within the tunnels as opposed to the stations: this is believed to adversely affect ventilation, and ergo PM2.5 levels, within said stations as a result [27]. It should be noted that St. George station is an exception to this, and features direct, in-station ventilation, so PM2.5 phenomena there have been accordingly characterized as more complex [27]. There are fans present in the ventilation system; however the purpose of these is to provide additional ventilation in the event of a fire, as opposed to providing constant active ventilation [31]. The TTC is currently undergoing a project, forecast for completion in 2019, to upgrade these fire ventilation systems at five “priority stations:” York Mills, Finch, Lawrence, Union, and St. Clair West [32]; however, as such systems would only be active in the event of an emergency, they would contribute little to PM2.5 mitigation.

6. Community Exposition

This section will outline the characteristics of the focal community, namely commuters, affected by the problem of high PM2.5 concentrations in Queen’s Park Station.
6.1. Demographic Composition

The Toronto Transit System provides service to a vast section of the Toronto population; in 2011 a new ridership record was set, reaching a total of 500,219,000 passenger trips [34]. Queen’s Park Station is between the Bay Street Corridor and University community. According to a 2011 Statistics Canada survey, both communities have substantially higher population of youth (ages 15-24) and the Bay Corridor also has a greater number of working aged individuals (ages 25-64) [35][44]. The high concentration of this demographic is likely to result in a higher portion of the community using the subway station. Looking at the surrounding area, there is the University of Toronto and a large number of student residences; this contributes to students being a significant part of the local demographic. Commuting students who use the subway are also very likely to use Queen’s Park Station due to its close proximity.

In addition, a large portion of hospitals are near the station contributes to a part of the community being affected by illness. Although these individuals may not commonly use the subway, they represent the potential portion of the population with respiratory illnesses which may use the subway system. Statistics Canada data illustrates that approximately 9.3% of the general population of Toronto has some form of respiratory related illness [36], this demographics’ quality of life is significantly more affected by exposure to PM2.5. Young children are also at a higher risk from PM2.5, where approximately 12.5% are affected by asthma [37]. Any young children travelling with their parents on the subway must be accounted for when examining demographics around Queen’s Park [13].

Queen’s Park Station is located on the Young-University-Spadina line which makes it a stop for all subway traffic travelling to North or South travelling along this line. While the stops are usually brief, commuters from other locations will be exposed to the high levels of PM2.5 at Queen’s Park, even though they do not specifically live in the community. As well, Queen’s Park is a stop along the way to Union Station. Considering that Union is the central train station for GO and VIA Rail, commuters traveling to and from Toronto via Union have the potential to also pass through Queen’s Park Station.

6.2. Community Awareness

Due to the size of particulate matter, it is not possible to see with an unaided eye [38]; this makes the majority of the population unaware of its presence or health effects. This was confirmed during an interview with the TTC administration, who stated that they could not recall ever receiving a complaint from the public about air quality [27]. However, although the community of subway users may not directly be aware of their situation, numerous studies have shown that this specific community faces issues that do warrant a solution. In summary, although subway commuters may not be fully aware of the hazards associated with particulate matter, the risk is high enough [3] to call for a solution that positively affects the quality of life of the community.

7. Stakeholders

This section will outline the stakeholders involved in the project and their priorities in regards to the development of a solution.

7.1. Toronto Subway Commuters

The primary stakeholders of this document are individuals who use the Toronto Subway System as a means of transportation. Considering the adverse health effects associated with particulate matter, subway users require a solution that reduces their risk. They would not want to put themselves in danger simply because of the choice to use the subway. Commuters will not be wanted to be inconvenienced by the implementation of the solution or require any significant change to their routine. For application to the Toronto Subway System, there would have to be little, if no opposition by commuters.

7.2. Toronto Transit Commission
As stated on their website the, “TTC management regards as paramount, its responsibility for the safety of its customers and employees” [39], thus the TTC would support resolutions concerning passenger health and safety. Systems or devices installed would have to be reliable, and not present commuters with additional hazards or create other problems in the system. Depending on the success of the trial station, system-wide implementation would have to fit within TTC budget constraints [40] or budget amendments may have to be made [41]. Any action in solving this issue must not bring unwarranted criticism to the TTC or damage its image as a public service provider. Additionally, insight gained from the TTC interview (see Appendix E) shows that the TTC would be interested in a solution that minimized their expenditures or, if at all possible, contributes to regaining revenue. This arises from the limited amount of capital available to subway additions, as subway extensions and upgrades also require funding. Other concerns mentioned by the TTC include track fires, suicides, noise and vibration, and fare evasion. The TTC also pointed out as to how it would very much support ideas that lead to increased efficiency as the system has a whole.

7.3. Amalgamated Transit Union Local 113

Values and objectives as defined by ATU Canada[42] [43] must be maintained when a solution is being implemented. Members of the union, including train operators, station service workers, and maintenance crews should not be endangered in the service or maintenance of the implemented device or system. Any changes caused by the chosen solution would have to be reasonable for the members of the union to accommodate; requiring little or no addition training. Due to the long periods of time that many TTC workers spend in the subway, ATU Canada would additionally value solutions that focus on occupational health related to PM2.5.

7.4. Device Manufacturers

Once a sufficient solution has been determined a company may be required to manufacture the device or install a system that addresses the issue of PM2.5. This company will need to be informed for the specifications of the device or system as well a meeting the criteria set out in this document. Employees will be required both for construction and installation of the chosen solution and must not be subjected to unnecessary danger. Finally, the extent of the project will ultimately affect the company’s profit margins.

7.5. Public Health

Health Canada recommends “Indoor levels of PM2.5 should be kept as low as possible” [44]. As a general requirement to maintain health of the population, efforts must be made to lower health hazards and inform the public.

7.6. Environment

Particulate matter that is not removed from subway stations is capable of reaching outdoor environments. It can then contribute corrosion of materials, reduced visibility, and health issues in animals [45]. The solution to be installed should not create hazardous environmental conditions that outweigh the benefits of controlling particulate matter. Overall, the most amount of particulate matter should be prevented from reaching the environment.

8. Requirements

This section will outline the objectives, constraints and criteria associated with the problem of PM2.5 reduction in Queen’s Park Station.

8.1. Objectives

The following are high-level objectives of the solution:

- To improve air quality in the Toronto Transit Commission subway tunnels by reducing the amount of PM2.5 in the subway tunnels.
- To improve the safety and health of commuters and passengers with regard to their exposure to particulate matter in the TTC subway system.
- The solution must aim to be able to last long periods of time without repair or much maintenance.
- The solution must be aesthetically pleasing and / or un-noticeable.
8.2. Constraints

The proposed solution must adhere to the following constraints:

**Effectiveness:** The solution must effectively remove enough PM2.5 from the Queen’s Park Station environment such that the hourly average is below 80 µg/m³ – this being deemed a safe level for exposure on the timescale of an hour by the Government of Alberta [6].

- Metric: decrease of the average PM2.5 concentration of air inhaled by TTC workers and commuters to below 80 µg/m³.

**Quality of Air:** The solution shouldn’t adversely affect the concentrations of components of air such as carbon dioxide, nitrogen, etc. in such a way that human health is compromised as defined by relevant guidelines.

- Metric: the solution must result in an atmospheric environment which is consistent with Health Canada’s Air Quality Regulations [46] and the Government of Canada’s Occupational Health and Safety Regulations [47].

**Safety:** The solution must be “safe”. That is, it must not materially decrease the safety of either workers or commuters.

- Metric: the probability of direct, short-term harm to commuters and workers as a result of the solution must be within the guidelines set in the NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems [48].

**Power consumption:** The power consumption of the solution must be within appropriate boundaries.

- Metric: the peak and average power consumption must be such that the subway system can support it.

**Noise:** The exposure of both workers and commuters to noise generated by the solution must be within acceptable boundaries. The U.S. EPA defines noise levels of above 45 decibels indoors as producing “activity interference and annoyance” [33]

- Metric: decibel levels measured where workers and commuters would typically experience noise from the solution must be such that there is no damage to hearing and no substantial annoyance.

8.3. Criteria

The following are criteria that must be considered when proposing a solution:

- **Addressing the problem itself:**
  - Particulate matter concentration:
    - The solution should maximally reduce the particulate matter (particularly PM2.5) concentration of air inhaled by TTC commuters and workers.
    - Metric: reduction in nominal concentration.
  - Duration of exposure:
    - As there is “no safe threshold” of exposure to fine particulate matter [1], the solution should reduce the duration of workers’ and commuters’ exposure to particulate matter.
    - Metric: nominal reduction in the duration of exposure to PM2.5.

- **Addressing the symptoms of the problem:**
  - Decreasing adverse health effects:
    - The solution should decrease the prevalence of particulate matter related adverse health effects among commuters and TTC subway workers (for example, myocardial infarction).
    - Metric: reduction in the prevalence of particulate matter related adverse health conditions among commuters and TTC subway workers.
  - Decreasing the exposure of sensitive subpopulations:
    - The solution should decrease the degree to which “sensitive subpopulations” are exposed to particulate matter (some subpopulations, are particularly sensitive to particulate matter).
    - As discussed previously, sensitive subpopulations include infants, children, the elderly, individuals with preexisting cardio respiratory diseases (e.g. asthma, chronic pulmonary obstructive syndrome, atherosclerosis, etc.), individuals with diabetes and individuals with increased exposure to particulate matter outside of the subway [1].
    - Metric: particulate matter concentration and duration of exposure for “sensitive subpopulations” in the TTC subway.

- **Minimizing negative consequences of a solution:**
9. Reference Designs

This section will provide a number of reference designs, indicating multiple avenues by which the problem of PM2.5 in Queen's Park station may be addressed.

9.1. Electrostatic Precipitators

Electrostatic precipitators are industrial-scale devices typically used to purify emissions from chemical processes [50]. Hitachi describes the technology as follows:

“Electrostatic precipitation is a method of dust collection that uses electrostatic forces, and consists of discharge wires and collecting plates. A high voltage is applied to the discharge wires to form an electrical field between the wires and the collecting plates, and also ionizes the gas around the discharge wires to supply ions. When gas that contains an aerosol (dust, mist) flows between the collecting plates and the discharge wires, the aerosol particles in the gas are charged by the ions.” [51]

![Illustration of the operating principle of an electrostatic precipitator](image)

The technology has also been adapted to residential HVAC systems: Canada Mortgage and Housing Corporation reports that electrostatic precipitation in residential settings is both cheaper and more efficient than conventional filtering [52]. Electrostatic precipitators have also been found to produce ozone as a by-product, which can pose a hazard in the subway...
Reducing Commuter Exposure to Fine Particulate Matter in the Toronto Subway

Microenvironment [53] [54]. However, such devices are known to be less efficient when dealing with PM2.5 specifically; an electrostatic precipitator capable of effectively filtering PM2.5 would need to be very large, and likely prohibitively expensive [27]. There is an inherent lack of space in the subway environment, and the TTC has identified cost as an important consideration the development of a solution to this problem [55]; thus, electrostatic precipitation presents an inadequate means of addressing concentrations of PM2.5 in Toronto subways.

9.2. Platform Screen Doors

A Platform Screen Door (PSD) system is primarily intended to prevent commuters from coming into the path of the subway car. Usually the doors will be connected from the floor to the ceiling; running the length of the entire station. Once a subway car arrives the doors automatically open, permitting commuters to enter [56] [57]. Fully-closed systems tend to prevent particulate matter from leaving the tunnels and reaching the platform.

![Performance Comparison among types](image)

Figure 4: Hyundai PSD comparison chart [25]

A sales pamphlet from Hyundai gives a brief illustration of the benefits of this system. The TTC has looked at systems such as this in suicide prevention, track isolation, automated subway control, and other issues. However, their initial cost estimates for installing a PSD system is $10 million per station [58]. In addition to the high cost, some particulate matter is still able escape through the open doors of the PSD. It is unrealistic for such an expensive and sophisticated system to be used for the sole purpose of lowering PM2.5 exposure.

9.3. Ambient Air Filtration Systems

An ambient air filter is a static system that is installed in specific locations where continual air filtration is needed. The device is always functioning and depending on specification, it is capable of filtering the air in confined space in a certain time span. There are various different methods for filtering the air; however in general, a blower fan will force air through a system of filters. Each filter will collect different types of debris and the resulting exhaust air will have substantially lower levels of contaminates.

![Figure 5: M68 HEPA Air Cleaner [59]](image)

While this system is generally cheaper that platform door system or an electrostatic precipitator, costing $3,000 to $15,000 a unit [59] [60], maintenance costs can be higher. Filters need replacing after a certain number of hours of operation.
operation of the system will lose its effectiveness if this does not occur. This requires additional personnel to be assigned to maintain the filters. In terms of subway commuters, the filtration system may be obstructive and create additional unwanted noise pollution. A new device called an axial-flow cyclone system is currently in development; designed primarily for fine particulate matter removal [14]. However, it is still in a concept phase and likely would have a significantly higher price than conventional filters.

### 9.4. Personal Respirators

In industrial settings, occupational exposure to airborne particulates is typically addressed through the use of personal respirators. Respirators capable of filtering PM2.5 specifically are labeled with the designations N95 and P100 [57]. An example of such a product is shown below:

![Figure 6. 3M 6391 P100 particulate respirator [61]](image)

Respirators require an individualized “fit test” in order to function correctly - it is improbable that this procedure could be performed for the entirety of the subway commuting population of Toronto [62]. Commuters would also be unlikely to favor such a solution – wearing a respirator would involve a change of present habits, and may be perceived as aesthetically unappealing. Deployment of personal respirators as a means of reducing PM2.5 exposure would thus be impractical for the Toronto subway.

### 10. Conclusion

The Toronto Transit Commission subway system faces a health and safety problem due to high levels of particulate matter 2.5 concentrations. This request for proposal recognized the health and safety effects of increased particulate matter 2.5 in the Toronto subway system. This request for proposal also provided a set of requirements for a possible solution as well as provided possible reference designs.
11. Appendices

Appendix A: PM2.5 Research Studies Summary

<table>
<thead>
<tr>
<th>City</th>
<th>Year opened</th>
<th>Subway PM$_{2.5}$ ($\mu g/m^3$)</th>
<th>Subway sample $n$</th>
<th>Outdoors PM$_{2.5}$ ($\mu g/m^3$)</th>
<th>Outdoors sample $n$</th>
<th>Source</th>
<th>Subway observation period</th>
</tr>
</thead>
<tbody>
<tr>
<td>London (summer)</td>
<td>1863</td>
<td>247</td>
<td>44 riders*</td>
<td>34.5</td>
<td>40 cyclists</td>
<td>Adams et al. (2001)</td>
<td>Duration of commute</td>
</tr>
<tr>
<td>London (winter)</td>
<td>1863</td>
<td>157</td>
<td>12 riders*</td>
<td>23.5</td>
<td>56 cyclists</td>
<td>Adams et al. (2001)</td>
<td>Duration of commute</td>
</tr>
<tr>
<td>London</td>
<td>1863</td>
<td>300; 310; 420</td>
<td>3 fixed*</td>
<td>~30</td>
<td>2 fixed</td>
<td>Seaton et al. (2005)</td>
<td>7 am-5 pm 3 days</td>
</tr>
<tr>
<td>New York</td>
<td>1904</td>
<td>62</td>
<td>1 rider*2 samples</td>
<td>13 ±4</td>
<td>37 fixed</td>
<td>Chillrud et al. (2004)</td>
<td>8 h samples</td>
</tr>
<tr>
<td>New York</td>
<td>1904</td>
<td>56 ± 95</td>
<td>33 workers*</td>
<td>13 ±4</td>
<td>37 fixed</td>
<td>This study</td>
<td>8–11 h work shifts 1–3 days</td>
</tr>
<tr>
<td>Stockholm</td>
<td>1950</td>
<td>254</td>
<td>1 fixed*</td>
<td>23</td>
<td>1 fixed</td>
<td>Johansson and Johansson (2003)</td>
<td>7 am–7 pm 2 weeks</td>
</tr>
<tr>
<td>Toronto City</td>
<td>1954</td>
<td>159</td>
<td>6 fixed*</td>
<td>15</td>
<td>185 personal</td>
<td>Crump (2000)</td>
<td>8 h samples</td>
</tr>
<tr>
<td>Mexico City</td>
<td>1969</td>
<td>61</td>
<td>18 riders*</td>
<td>71; 68</td>
<td>16 buses, 28 minibuses</td>
<td>Gómez-Pérez et al. (2004)</td>
<td>Duration of commute</td>
</tr>
<tr>
<td>Helsinki</td>
<td>1982</td>
<td>47.60</td>
<td>2 fixed*</td>
<td>10.17</td>
<td>2 fixed</td>
<td>Aarnio et al. (2005)</td>
<td>Two weeks</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>1999</td>
<td>64 ± 11</td>
<td>14 riders*</td>
<td>106; 145</td>
<td>2 taxis, 15 buses</td>
<td>Chan et al. (2002)</td>
<td>Duration of commute</td>
</tr>
<tr>
<td>Rome</td>
<td>1995</td>
<td>PM$_{10}$ 407</td>
<td>5 fixed*</td>
<td>PM$_{10}$ 101</td>
<td>8 fixed</td>
<td>Rizaisi et al. (2006)</td>
<td>8 am-6 pm 1 day</td>
</tr>
<tr>
<td>Prague</td>
<td>1974</td>
<td>PM$_{10}$ 103</td>
<td>1 rider*108 samples</td>
<td>PM$_{10}$ 74</td>
<td>1 person 108 samples</td>
<td>Brainis (2006)</td>
<td>Duration of commute</td>
</tr>
</tbody>
</table>

Data are presented as arithmetic means ± arithmetic standard deviation when this information was available.
Rail systems are shown according to the age of the subway system from oldest to newest.
* Fixed—these studies’ estimates of underground PM$_{2.5}$ are based on stationary samples taken on or near the station platform.
* Excludes six workers who worked at an aboveground maintenance shop.

Figure 7: Summary of studies conducted about PM2.5 in the subway environment [5]

![Figure 7: Summary of studies conducted about PM2.5 in the subway environment](image)

Figure 8: PM2.5 levels by composition worldwide [21]

![Figure 8: PM2.5 levels by composition worldwide](image)
Figure 9: Human lung cells exposed to airborne particulate matter. Panels A – C represent subway particles; panel D represents urban above-ground particles [25]

Appendix B: Experimental Findings

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Date</th>
<th>Time</th>
<th>Reading ($\mu g/m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Queen's Park</td>
<td>Above-ground</td>
<td>28-Jan</td>
<td>9:04</td>
<td>12</td>
</tr>
<tr>
<td>Queen's Park</td>
<td>Platform</td>
<td>28-Jan</td>
<td>9:08</td>
<td>239</td>
</tr>
<tr>
<td>Eglinton</td>
<td>Platform</td>
<td>28-Jan</td>
<td>9:31</td>
<td>148</td>
</tr>
<tr>
<td>St. Clair</td>
<td>On-train</td>
<td>28-Jan</td>
<td>9:27</td>
<td>73</td>
</tr>
<tr>
<td>Davisville</td>
<td>On-train</td>
<td>28-Jan</td>
<td>9:29</td>
<td>56</td>
</tr>
<tr>
<td>St. George</td>
<td>Platform</td>
<td>03-Feb</td>
<td>12:05</td>
<td>144</td>
</tr>
<tr>
<td>Bloor</td>
<td>Platform</td>
<td>03-Feb</td>
<td>12:16</td>
<td>135</td>
</tr>
<tr>
<td>St. Patrick</td>
<td>On-train</td>
<td>03-Feb</td>
<td>12:30</td>
<td>166</td>
</tr>
<tr>
<td>Osgoode</td>
<td>On-train</td>
<td>03-Feb</td>
<td>12:31</td>
<td>160</td>
</tr>
<tr>
<td>St. Andrew</td>
<td>On-train</td>
<td>03-Feb</td>
<td>12:31</td>
<td>120</td>
</tr>
<tr>
<td>Union</td>
<td>On-train</td>
<td>03-Feb</td>
<td>12:32</td>
<td>80</td>
</tr>
<tr>
<td>Museum</td>
<td>Platform</td>
<td>03-Feb</td>
<td>12:42</td>
<td>60</td>
</tr>
</tbody>
</table>

Figure 10: Experimental PM2.5 readings from selected Toronto subway stations. (Readings taken by students of the University of Toronto’s Department of Engineering Science, using a TSI DustTrak 8520.)

Appendix C: Interview with Kelly Sabaliauskas, SOCAAR

(Interview conducted by the authors of this RFP at the Wallberg Building at University of Toronto’s St. George campus, in room 123 from 4:00 to 5:00 on February 12, 2013.)

Q: How well did our findings correlate with what you have found experimentally?

- Very consistent
- SOCAAR has performed extensive measurements in subway system
- Started a report w/ Health Canada about 2 years ago, about to publish, concerns both buses and subways
- Techs would get on subways, ride for 3 hours on Bloor-Danforth, Yonge-University-Spadina line
- There is significant variance within a station, so techs would get on train at very middle of platform
- For example Queens Park has a difference factor of 2 based on position
Q: What sort of studies have you done on the subway particulate specifically? How were they conducted? Would you be able to share them with us?

- SOCAA’s main research is on Toronto residents’ exposure
- Unpublished
- Took measurements in 2005
- Health Canada study is nowhere near done
- Performed measurements with P-Trak, Dust-Trak
- Commuting b/w homes and lab, morning and evening
- Took measurements from trains and platforms
- Can share findings with us
- Microaethalometer – tests for black carbon - had to be changed every 3 hours; can go for a week outdoors
- If we want to do more in-depth research on the phenomenon, she can provide a microaethalometer to us
- Not much has changed since Crump
- Had summer students ride a single train for end-end around whole loop
- Trains start at Finch – PM2.5 at maximum when doors are open
- Noticed a gradual decrease when train ventilation system turns on; little spikes when doors open
- Our observations in Rocket cars vs older cars could have been a fluke, i.e. not in favour of Rocket cars
- Will try to dig up some more papers for us

Q: What health risks could PM2.5 pose to commuters? Are these risks moreso long-term or short-term?

- Information about PM2.5 in general:
- Ambient air – exposure linked to increased heart attack, 2 days later
- Exact mechanism not actually known
- Experiments done at UofT exposure facility – people exercise or sit
- Results in change in blood pressure
- Bloodwork also done – inflammation noticed
- Dissection has shown accumulation in brains, livers, intestines of animals
- Another mechanism in which PM2.5 acts is through inhaled particles: particles believed to be able to travel through nerve at top of nose (olfactory bulb) that connects to brain; possible link to Alzheimers
- Chronic exposure: places that see largest decrease in PM see largest life expectancy (shown in study by Pope, 2010 – increase seen of 8 months).
- PM2.5 is a “big deal” - no safe level, new research shows we need to keep “trying to lower the bar”
- Acute exposure: physiological changes - increased rate of asthma, stroke, cardio problems. Conclusively shown – effect real.
- Chronic exposure: increased likelihood of lung cancer. May be important risk factor in diabetes.
- Pollution in general: pregnant mothers living near major roadway more likely to be premature births, smaller baby, smaller cranial radius.
- Clues as to impact upon commuters – iron is quite reactive in lung tissue; shown by in vitro cell exposure – mice, human lung tissue.
- Study by Lee, 2003 – cells undergo oxidative stress as a result of PM2.5. More metals, the worse
- 3 levels of systemic oxidative stress: 1) cells are somewhat oxidized; 2) cells release antioxidant; 3) cell death
- This is detailed in review papers
- Post doc at SOCAA has done a study in the Netherlands: had subjects use exercise bikes on subway platforms, found a decrease in peak inspiration

Q: How would the exposure of a subway user compare to that of a non-subway user in Toronto?

- Worst day in Toronto – historical data is available from Ministry of Environment – had max concentration of 50ug
- Typically less than 30ug - usually less than 10 in winter
- Don’t really see less than 60ug on platform; but it is a short exposure
- In regards to CWS - can’t necessarily use outdoor to apply to indoor
- No standard per se for occupational settings; however there is “no safe level”
- Epidemiological work to date has been inadequate, but can make some inferences:
  - Metals are more reactive in the body, and exposure to high PM2.5 is proven to be unhealthy
  - PM2.5 in Toronto subway is in very high concentration, and is high in metal content - so chances are subway particulate is very bad.

**Q: What sources would you expect to be generating these particles? Do you know what the composition would be?**

- We believe there to be three main sources: wheel-rail (iron; not a lot can be done about this), wheel-brakepad, contact shoe-third rail (carbon, “phenomenal concentrations”; not much can be done about this either)
- Ambient air is also a contributor – not a significant one though
- Mainly composed of iron and carbon
- Should note that the Dust-Trak is not calibrated for measuring PM2.5 in Toronto – calibrated w/ Arizona road dust, different optical properties than Toronto nitrates and sulfates; should divide outdoor (not indoor) Dust-Trak readings by a factor of 2.3-2.4
- Study performed by a first-year summer student (Zhang) to relate PM2.5 concentrations to formulation of brakepad – assumed it was only source
- To identify source, do the following:
  - Go to Queens Park, write down exactly when trains enter and leave
  - Should be a big spike after each train stop
  - Need high time resolution
- Dust not believed to be blowing in from tunnel, as there is no correlation w/ wind velocity – thus likely a result of braking
- Queens Park is enclosed, would be the simplest environment to test in
- St Patrick is another candidate – enclosed, circular, tunnels are isolated from each other
- Eglinton not the best choice, as it is partially outdoors

**Q: Are you aware of any technologies in existence that could reduce particulate exposure in the subways?**

- PM2.5 is a major problem in every subway around the world
- Several urban centers – namely in Asia – do not have same PM2.5 problem
- Ascribe this to glass doors, e.g. in Seoul
- Prague metro was flooded in 2002, measurements were taken before and after – flooding reduced the concentration.
- Washing walls helps reduce PM2.5 levels. TTC used to do this every two months, but stopped after it was found to cause damage to the walls
- Electrostatic precipitators are ineffective with PM2.5 – an efficient enough one would be very expensive and large
- Montreal has incredibly low PM2.5 – “phenomenally”
- Reasons: 1) Rails are made of wood 2) Wheels are not steel, but rubber
- Better brakepads would help problem – Rocket may have taken care of this?
- PM2.5 is notoriously hard to remove; also travels very far, up to 1000s of kms

**Q: Is TTC doing anything about PM2.5 currently?**

- TTC is aware of SOCAAR and their findings - OHS people there know all about it
- SOCAAR’s TTC contact is Naomi
- TTC is not doing anything about it to Kelly’s knowledge
- Health Canada has sat down with TTC OHS, told them about their findings – TTC is “just starting to wake up to the problem.”
- Research on PM2.5 has been ongoing since 1990s
- Ventilation is another means
In Toronto, air is pumped in from tunnels; active ventilation is not in the place needed (i.e. station platforms)
- It is present in St. George though; PM2.5 levels there are more complex
- Union station also interesting - one side really high, another lower b/c close to outdoors
- Traffic is also a source of PM2.5, due to air intake vents
- There are no scrubbers / filters on traffic-level air intakes
- Air conditioning reduces PM2.5 levels – pulling out water also pulls out particulate with it

Appendix D: Interview with Karen Stintz and Glenn de Baeremaker, TTC

(Interview conducted by the authors of this RFP at Toronto City Hall, from 3:00 to 4:00 on February 5, 2013.)

- Air quality has not been identified as a significant issue by the TTC
- General public has never given feedback about air quality – many complaints about noise and vibration though
- Capital has been allocated to fire ventilation at Yonge and Lawrence; details available online
- Looking at retrofitting second exits to stations
- 68 Rocket cars will be implemented in total – a staff report can be obtained
- Platform doors as a future investment – very expensive though, but have been allocated in budget already
- Royal York and Eglinton have been particular sources of noise and vibration complaints
- Perceived risk, i.e. nuisance, is of greatest concern to TTC
- Squealing wheels is a problem
- Carbon monoxide, carbon dioxide have been identified as potential air quality issues
- PM2.5 is “not urgent”, hasn’t been accommodated for in the budget

Appendix E: Relevant Documents

- Canada Occupational Health and Safety Regulations, SOR/86-304
- 2013 - 2022 TTC Capital Budget
Appendix F: Queen’s Park Station Layout
12. Works Cited


Reducing Commuter Exposure to Fine Particulate Matter in the Toronto Subway


Reducing Commuter Exposure to Fine Particulate Matter in the Toronto Subway


