Air Quality Regulation in Metropolitan Railways: A Benchmarking Approach

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ABSTRACT

This study examined whether air quality regulations designed for other environments were being applied to metropolitan railways (metros) without consideration of the specific attributes of the metro environment. This is a concern because if regulations are overly restrictive metros may incur unnecessary costs and unreasonable regulation, but if regulations are too lax then the health of workers and passengers is at risk. This study therefore benchmarked the air quality regulations being used by metros. A questionnaire revealed that 16 out of 22 responding metros had air quality regulations, all of which were originally intended for non-metro environments. PM_{10}, carbon monoxide, and carbon dioxide were the most commonly regulated pollutants. Less commonly regulated pollutants included benzene, sulphur dioxide, $PM_{2.5}$ and ozone. Many metros used World Health Organisation recommendations, but for most pollutants there were outliers at both ends of the scale, indicating that regulation in some metros is too lax whereas in others it is overly strict. A set of metro-specific standards is therefore proposed as an international benchmark for metros to use.

1. INTRODUCTION

Air quality in metros[1] has been the subject of public concern and workforce disputes. Some workers have questioned whether their exposure to particulates is within safe limits, and others have suffered carbon monoxide poisoning and successfully won compensation from the metro (*1*).

Metro interiors are unique environments as far as air quality is concerned. Where underground, they are effectively indoor public facilities – but they experience far greater levels of crowding and mechanical activity than other indoor environments, such as offices or movie theatres. Likewise, metros are methods of transport – but unlike road transport, the only vehicles in use during operating hours are electrically powered. Finally, metros are workplaces with a management responsibility to protect staff – but the majority of people in these workplaces are not workers with training and protective equipment, but passengers who are untrained members of the public.

The consequences of having inappropriate standards can be insufficient protection for health (if too lax) or excessive cost for unnecessary mitigation (if too strict). Excessively or insufficiently strict standards could also have legal implications: if metros cannot comply with excessively strict standards they leave themselves open to legal challenges for non-compliance. However, if regulations are too lax, metros may be legally compliant but still be at risk of contributing to health problems, particularly among staff. This paper suggests that metros can mitigate these risks by using internationally benchmarked standards, based on the available evidence and on global metro best practice.

This paper therefore aims to answer the following questions:

- Which pollutants are appropriate for metros to monitor and control?
- What levels are appropriate limits for metros?
- How much agreement is there between different metros' air quality regulations?
- Can a set of evidence-based standards be proposed that would be acceptable to both metro operators and regulators?

To answer these questions, the literature review in Section 2 sets out the available evidence relating to air quality regulation in metros. Section 3 describes how questionnaires were used to examine the air quality standards actually being used by metros. Section 4 summarises the air quality regulations used by metros, and discusses the extent to which regulations in use relate to standards recommended by the literature. Section 5 concludes by showing how the findings could impact metros and proposing a set of standards as good practice for metros to adopt.

2. LITERATURE REVIEW

With the exception of particulate matter (*e.g.2,3*), coverage of actual air quality experienced by metro passengers and staff is limited (*4*). Few studies directly addressed standards or regulations for air quality in metros (*4,5,6*). In 2010, the World Health Organisation (WHO) published a comprehensive meta-analysis of the evidence assessing the impacts of indoor air quality on health (*7*). This followed the 2005 publication of a similar document relating to outdoor air quality (*8*). These documents are considered authoritative sources of evidence-based air quality guidelines. The WHO guidelines are stringent – they represent pollution levels at which safety is proven, and do not take into account ambient levels in a city. The guidelines do recommend interim limits for cities with much poorer air quality (*8*), which

[1] Throughout this paper we refer to 'metros', defined as high density, high frequency urban rail systems, typically with significant underground sections. Such systems are known as 'subways' in the United States.

may also be appropriate for metros with significantly poorer air quality. The following paragraphs outline the available evidence for each pollutant addressed by this study.

Carbon Dioxide (CO_2)

CO_2 levels in metros are closely related to passenger loading in trains (*3,9*) but can be mitigated by ventilation. Chow and Yu suggest that CO_2 in a train compartment should be kept below 1,000ppm (parts per million) (0.1%) to avoid passenger discomfort (*4*). A study of schoolchildren showed that tiredness and difficulty concentrating increased when CO_2 concentrations rose above 1.5%, which has implications for concentration levels of staff performing safety-critical tasks (*10*).

Carbon Monoxide (CO)

CO is produced by incomplete combustion of fuels. Metros do not burn fuel during normal operations, so Park and Ha assumed that the main source of CO in metros is external air intake (*5*). However, CO could also be produced in the metro by fuel-burning engineering equipment, such as diesel trains used when track power is off. Research in the Mexico City and Guangzhou metros confirmed that CO levels in the metro were significantly lower than in motorised surface transport (*11,12*). WHO recommends a maximum indoor exposure to CO of 10μgm^{-3} (9ppm) for 8 hours and 100μgm^{-3} (90ppm) for 15 minutes (*7*).

Sulphur Dioxide (SO_2), Oxides of Nitrogen (NO_x), Peroxyacetyl Nitrate (PAN)

No literature was identified that specifically addressed SO_2, NO_x, or PAN levels in metros. These pollutants are by-products of combustion of fossil fuels, and therefore sources in metros are minimal. However, fuel-burning engineering equipment and diesel trains do produce these. WHO sets an indoor and outdoor air quality standard for Nitrogen Dioxide (NO_2) of 200μgm^{-3} for 1 hour, and 40μgm^{-3} as an annual average (*7,8*). There were no WHO guidelines for PAN, and no indoor air quality recommendation for SO_2. The WHO outdoor air quality recommendations for SO_2 are 20μgm^{-3} 24-hour mean; and 500μgm^{-3} 10-minute mean (*8*). WHO does not set a limit for an eight hour SO_2 exposure period because insufficient data were available to work out what that limit should be.

Ozone (O_3)

O_3 is usually produced by reaction of ambient air with sunlight and so a major source is wholly outside the control of metros. However, a study in Cairo metro found that O_3 levels underground in the metro were higher than those outside. This increase was attributed to electrical charge from trains and daytime lamps (*13*). Lack of sufficient ventilation could also be a factor. For O_3, WHO recommends an eight hour exposure limit of 50ppb (parts per billion) (*8*).

Toxic Volatile Organic Compounds (VOCs)

The term 'VOCs' includes a large variety of chemical compounds, some of which have been studied in metros, such as carbonyl compounds (*14*), formaldehyde, and polycyclic aromatic compounds (*2*) including benzene (*15*). VOCs include a large number of compounds, some of which are more problematic than others. Therefore, different limits are appropriate for different compound (*16*). WHO guidelines state that there is no safe limit for benzene, because it is so carcinogenic. For formaldehyde, WHO guidelines suggest a limit of 100ppb (*7*).

Particulates (PM)

Globally, most particulates are a by-product of fuel combustion. Particulates comprise PM_{10}, particulate matter of diameter ≤10μm, and $PM_{2.5}$, of diameter ≤2.5μm. Particulates in ambient air comprise "sulphate, nitrates, ammonia, sodium chloride, carbon, mineral dust and water."(*17*) However, the majority of particulates in steel-wheeled metros are iron-based, with fractions of quartz, manganese, copper, chromium, and zinc (*6,18,19*). These mainly come from endogenous sources such as braking, wheels on rails, sparking from the conductor rail, and ballast dust (*18*). The influence of ambient air intake varies between studies and cities (*18,19*).

Air quality guidelines for metros need to address the health hazards of the particle types found in metros, not the types found in ambient air. However, this is difficult because research investigating the potential health effects of these endogenous metro particulates has been inconclusive. Studies at the cellular level have found that endogenous metro particulates have greater potential than ambient particulates to cause disease (*6,20*) but that particulate metal concentrations in metros were far below the levels at which the disease risk has been established (*21*). They concluded that there was low potential for health impacts resulting from working in a metro (*21*). Studies of metro staff in Stockholm, where particulate levels are comparatively high (*9*), found no increased risk of lung cancer (*22*) or cardiovascular disease (*23*).

For the mix of particulates found in ambient air, WHO exposure guidelines propose the following limits (*8*):

- $PM_{2.5}$: 10μgm^{-3} annual mean; 25μgm^{-3} 24-hour mean
- PM_{10}: 20μgm^{-3} annual mean; 50μgm^{-3} 24-hour mean

The guidelines do not propose an 8-hour limit.

A study in London Underground found the toxic effects of tunnel dust to be comparable with welding fume. The study also found parallels in terms of particle size, metal content, and type of population that is exposed (generally healthy workers), and therefore suggested using the standard for welding fume as a benchmark for endogenous metro particulates (*6*). The industrial standard for welding fume in the US and UK is 5000μgm^{-3}(*6,24*).

A further finding is that it is the number, not the mass of particulates that is the best indicator of risk, as smaller particles are more dangerous to health (*6*). Therefore it would be better practice for metros to set limits for particulate number rather than particulate mass. However, the established standards use concentration by mass so this study has used the same method.

Conclusions from Literature Review

This paper is the first to consider the effects on metro air quality of a comprehensive range of pollutants. The literature reveals that there is no current consensus on what constitutes acceptable air quality in metros.

Metro air pollution has both endogenous and exogenous sources, and some pollutants are only produced during non-passenger hours. Scarce ventilation can enable build-up of pollutants such as CO_2, VOCs, particulates, and O_3, all of which may have sources in the metro during normal operations. During engineering hours when fuel-burning equipment is used, metro operators can also influence CO, NO_x, and SO_2.

Restricted air flow is a key element influencing metro air quality (*13*) and therefore indoor air quality standards can be appropriate for metros because ventilation is a key method of control both in indoor areas and in metros (*7*). However, where fuel-burning trains or equipment are in use, outdoor air quality standards are more appropriate, and for particulates generated within the metro, industrial limits may provide the best benchmark.

3. DATA AND METHODS

Data were collected via a survey sent to the operators of metros with broadly similar characteristics and technology in 28 different cities. The metros are members of CoMET, a benchmarking consortium of 14 of the world's largest metro systems[2]; and of Nova, a group of 14 small to medium metros[3]. The sample is globally balanced, with metros in 22 different countries and spread between the Americas, Europe, and Asia and Oceania; and between developed and developing countries. The survey results are covered by an existing confidentiality agreement which stipulates that they may only be reported in an anonymous form. Therefore all data are presented anonymously and labelled A, B, C etc. for reference where necessary.

A pilot study was used to develop the questionnaire by surveying a group of 11 metros to understand which aspects of air quality they had regulations for. The use of a pilot study meant that a consistent questionnaire with all likely aspects of air quality could be presented to all participating metros. This reduced the likelihood of aspects being missed if metros had been simply asked to list all the air quality elements for which they had regulations.

The aspects of air quality identified by the pilot study were cross-checked against the relevant literature. This resulted in particulate sub-types elemental carbon (EC) and organic carbon (OC) being added to the survey after their inclusion in other studies (*2,15*). The final survey asked respondents to report their regulations and prescribed limits for each of the following pollutants, if applicable:

- CO_2 (carbon dioxide)
- CO (carbon monoxide)
- NO_2 (nitrogen dioxide)
- PAN (peroxyacetyl nitrate)
- SO_2 (sulphur dioxide)
- O_3 (ozone)
- VOCs (toxic volatile organic compounds)
- Formaldehyde
- PM_{10} (particulate matter ≤10μm diameter)
- $PM_{2.5}$ (particulate matter ≤2.5μm diameter)
- EC (elemental carbon, also known as BC, black carbon)
- OC (organic carbon)

To ensure completeness, respondents were also given an opportunity to include any pollutants which were not included in the list.

The survey asked respondents to explain the regulatory standards that apply to their metro, including national policy, industrial standards, business regulations and related design codes. In addition, they were asked to provide the following information for each pollutant listed above:

- What standard(s) or law(s) require monitoring to be carried out and prescribe limits
- Prescribed limits
- Tolerance levels (for example, time acceptable)

Responses were validated with follow-up questions to individual participants where appropriate.

[2] CoMET: Beijing, Berlin, Guangzhou, Hong Kong, London, Mexico City, Madrid, Moscow, New York, Paris, Santiago, Shanghai, São Paulo and Taipei.

[3] Nova: Bangkok, Barcelona, Buenos Aires, Brussels, Delhi, Lisbon, Milan, Montréal, Naples, Newcastle, Rio de Janeiro, Singapore, Toronto and Sydney.

The standards and laws in use were analysed to understand their origins and the environments that they were originally formulated to regulate. This assessment aimed to understand the extent to which the regulations in use took into account the unique metro environment, and how relevant these standards were to metros. Metros' limits and tolerances were benchmarked against the standards identified in the literature review. The aim was to understand how closely existing metro standards were related to evidence-based or other established air quality standards. Where necessary, the data supplied were converted between ppm and μgm^{-3} for comparability.

4. RESULTS AND DISCUSSION

Responses were received from 20 of the 28 metros surveyed. Of these, 16 respondents provided information on the prescribed limits and tolerances. Fifteen respondents provided information on standards, policies, or laws requiring them to regulate air quality.

Pollutants for which regulations were reported in the 'other' category included Total Suspended Particulates (TSP), asbestos, and graphite. For VOCs, some organisations reported an overall limit, whereas others reported specific limits for various combinations of benzene, toluene, and xylene. Only pollutants for which regulations were reported by more than one metro have been included in this analysis. This resulted in the exclusion of toluene, xylene, TSP, asbestos, elemental carbon, black carbon, and graphite.

Types of Regulations

Analysis of the different metro air quality regulations in different countries shows that there was no single consensus as to what type of regulations should be used for the metro environment. Among the fifteen metros that provided information on the sources of their regulations, three metros included indoor air quality regulations, of which two metros used indoor air quality recommendations issued by WHO or a local health organisation. Two metros used government guidelines, two metros used industrial standards for some or all of the potential pollutants, and two used general traffic standards designed for the road environment where internal combustion engines are in use. One metro's standards were based on local standards for areas where the public congregates, such as stadia, malls, and movie theatres, and one metro had developed its own standard.

Many of the WHO guidelines include a recommendation for exposure over eight hours (*7,8*). Metro staff are exposed to particulates for longer than commuters, so it follows that if levels are acceptable for a worker to be exposed to them for a whole work shift, they will be acceptable for commuters too. The 8-hour benchmark is therefore used to represent an acceptable level of exposure over a shift, although it is noted that in metros where staff work longer shifts, stricter standards may be appropriate. The 8-hour standards can be used in parallel with a maximum permissible level. The following analysis therefore focuses on standards for 8-hour shifts, with reference to maximum permissible values where appropriate.

Overview of Regulations

A summary of the results is shown in Table 1. Table 1 shows that the number of metros with regulations for each pollutant varies between three (benzene) and twelve (CO and PM_{10}), with a mean of seven metros having regulations for each pollutant.

TABLE 1 Summary of Benchmarking Results

Pollutant	N°. metros with regulations	Standard or guideline suggested by literature	N°. metro standards agreeing with literature	Range of regulations in use by metros
CO_2	10	1000 ppm for comfort 15,000ppm for safety	4	1000ppm – 5000ppm (8 hours)
CO	12	9ppm	8	2-35ppm
NO_2	6	200 μgm^{-3} (1 hour) 40 μgm^{-3} (annual average)	1	50-223 μgm^{-3}
SO_2	4	177ppb (10 minutes)	0	7 (24 hour average) – 5000ppb (max)
O_3	5	50ppb	2	25(8 hour average) – 200ppb (15 minutes)
VOC: Formaldehyde	7	100ppb	5	100-300ppb
VOC: Benzene	3	0	1	0-1.57ppb
PM_{10}	12	Combined:	1	24-500 μgm^{-3} (max)
$PM_{2.5}$	5	5000μgm^{-3}	1	35-5000 μgm^{-3} (max)

The third column of Table 1 shows the standards or guidelines suggested by the literature, as discussed in Section 2. For most pollutants, few metros had standards that agreed with those suggested by the literature. However there were some pollutants for which a greater percentage of metros' regulations were in line with the literature: CO (67%), formaldehyde (57%), and to a lesser extent CO_2 (40%). The range of regulations in use by metros varied widely, and will be discussed in more detail in the following analysis of standards used for individual pollutants.

Benchmarking Regulations In Use for Individual Pollutants

Carbon Dioxide

Ten metros had targets for maximum levels of CO_2. Figure 1 below shows the targets for CO_2 reported by metros, with metros anonymously shown on the x-axis and permissible concentrations shown on the y-axis. The green horizontal line shows the comfort guideline suggested by Chow and Yu (*4*). The suggested safety limit is 1.5% (15,000ppm), which is the point at which CO_2 has been shown to reduce mental concentration.

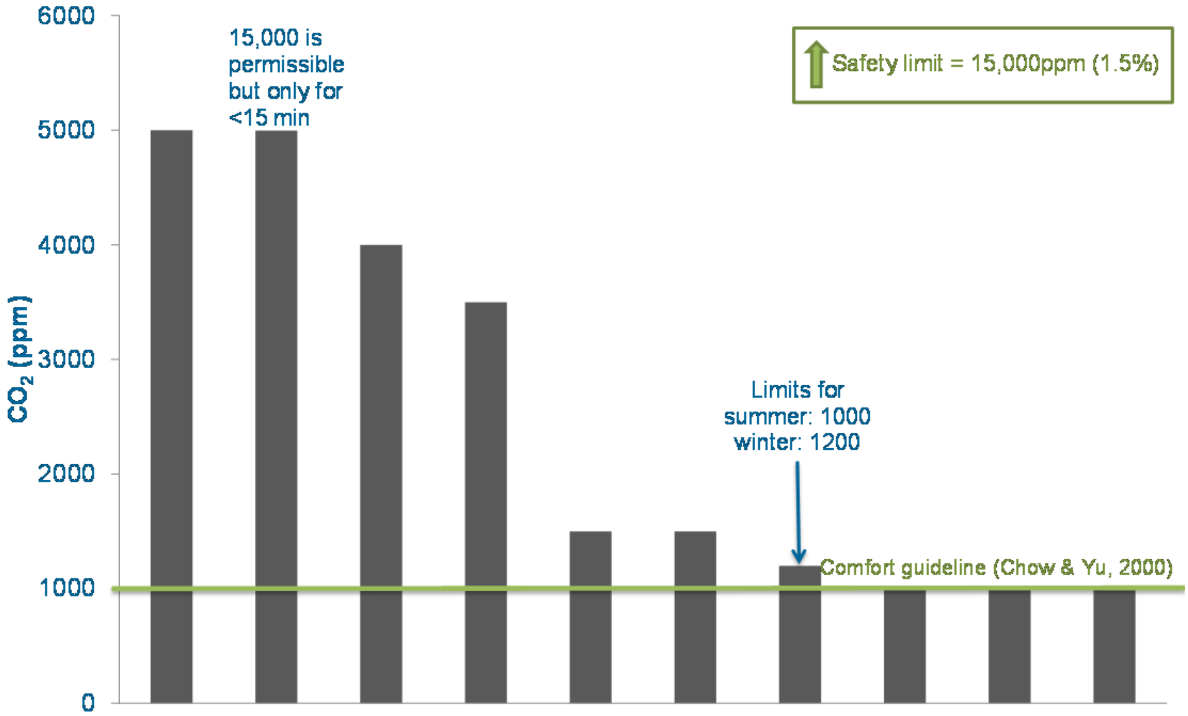

FIGURE 1 Metros' target maximum levels of carbon dioxide.

Four metros' existing limits agreed with Chow and Yu's suggestion of 1000ppm. Of these, one had a slightly higher limit for winter, in recognition of reduced ventilation at that time. Two further metros' limits were relatively close to the comfort guideline. The four much higher CO_2 standards are all safe, but if CO_2 rose to those levels it could cause discomfort for passengers.

Carbon Monoxide

Twelve metros had regulations for CO. Of these, 8 had a limit of 9ppm (10mgm^{-3}) average over 8 hours, the same as the WHO recommendation. Only 3 metros exceeded the limit, with maximum permissible concentrations of 25ppm, 30ppm, and 35ppm. One metro had a more stringent limit of 2ppm. In addition to these 8-hour guidelines, 1 metro had a target maximum level of 200ppm for 15 minute exposure, more than double the 90ppm maximum recommended by the WHO guidelines.

Nitrogen Dioxide

Seven metros had limits for nitrogen dioxide, as shown in Figure 2. The limits apply for different periods of time, as indicated on the graph. Three respondents did not specify the length of time for which their limits apply.

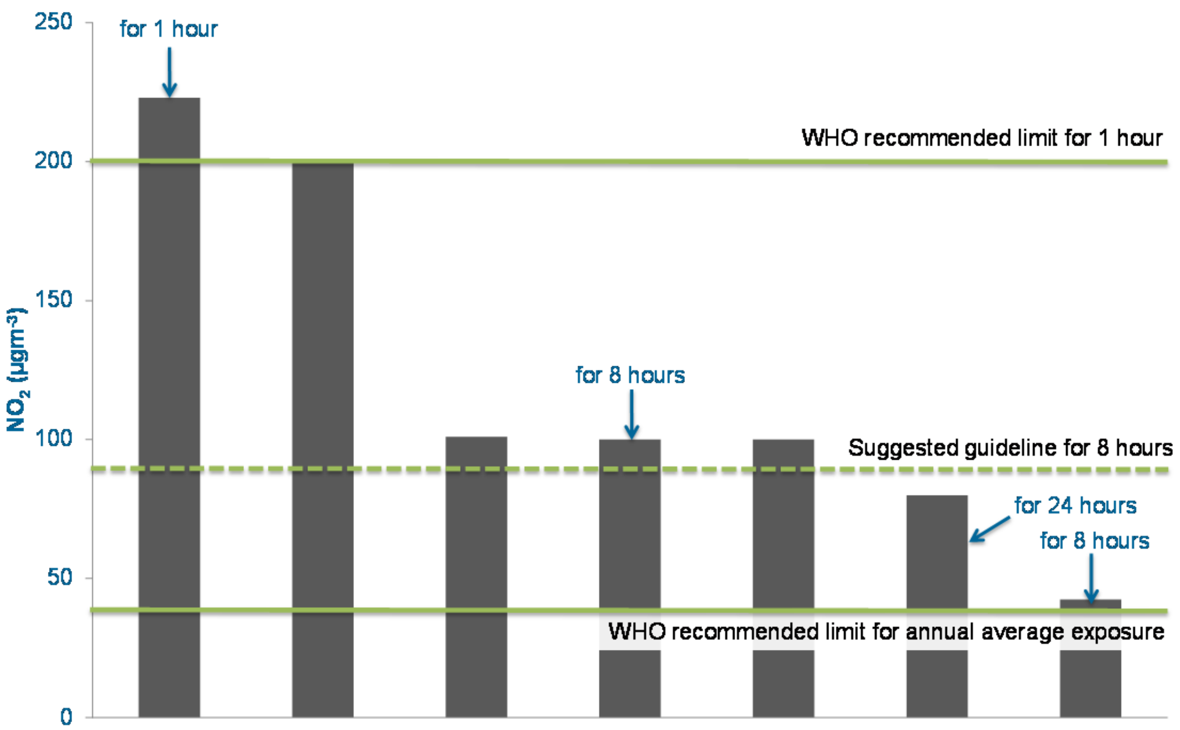

FIGURE 2 Metros' limits for nitrogen dioxide.

WHO provides a guideline for one hour's exposure and for annual average exposure. There was insufficient research data for WHO to recommend a limit for an eight hour working shift. However, for metros with a practical need for guidelines to protect their staff, an 8-hour guideline would be useful. No threshold effects have been found that may affect limits (*7*), so in the absence of more specific evidence an interim guideline is estimated below based on an assumption that harm is linear with exposure time.

WHO recommends an annual average exposure guideline of $40\mu gm^{-3}$. It was assumed that this equals a daily average. An 8 hour shift is $^{1}/_{3}$ of 24 hours, so if there were no other exposure than during the shift, exposure over an 8 hour shift should not exceed 3 times the 24-hour limit. Research shows that the level of NO_2 found in a home without a specific NO_2 source is $15\mu gm^{-3}$ (*7*). Therefore, assuming exposure for $^{2}/_{3}$ of each 24 hour period is $15\mu gm^{-3}$ and the average daily exposure is $40\mu gm^{-3}$, the permitted exposure for an eight hour shift would be $90\mu gm^{-3}$. This is equal to 2.25 times the annual average exposure limit of $40\mu gm^{-3}$.

It is therefore suggested that a limit of $90\mu gm^{-3}$ is used for an eight hour shift until further research becomes available to refine the proposed guideline. This proposed guideline is close to the median and modal standard of $100\mu gm^{-3}$ already in use by 3 metros. As the proposed guideline of $90\mu gm^{-3}$ is based on the annual average and does not take into account probable lower exposure on non-working days, future research may show that a higher limit is acceptable. However, in the absence of further evidence in this area, it may be advisable to err on the side of stringency.

Sulphur Dioxide

Four metros had standards for SO_2, but the standards are for different time limits and there is a great deal of variation, as shown in Table 2. It is difficult to compare these regulations because they relate to different periods of time. It is expected that the shorter the amount of time that the standard relates to, the higher the limit would be. However, the limits of Metros A and B appear particularly high when compared with the WHO guideline for a 10 minute exposure.

TABLE 2 Metros' Limits for Sulphur Dioxide

Sulphur Dioxide (ppb)	**A**	**B**	**C**	**D**	**WHO**	**Proposed**
10 minutes	-	-	-	-	177	-
15 Minutes	5000	-	-	-	-	-
1 Hour	-	-	130	-	-	-
8 hours	2000	1600	-	-	-	16
24-hours	-	-	-	28	7	-
Annual average	-	-	-	18	-	-

Dash (-) indicates no data.

Setting a standard for maximum levels over 10 minutes is therefore the most evidence-based way of managing SO_2 exposure in metros. However, short-term target maximum levels are not as useful for managing the exposure of workers across the duration of a shift. Similarly to NO_2, WHO does not set a limit for an eight hour exposure period because insufficient evidence was available to justify a specific guideline. Although WHO does not set an 8-hour guideline, two metros have very high limits for SO_2. An interim guideline to enable these metros to reduce the risks to their staff, in a similar manner to the interim 8-hour guideline of 2.25 times the annual average that was proposed for NO_2.

Estimating an 8-hour guideline from first principles was more difficult for SO_2 because 'background' SO_2 exposure is very dependent on external conditions (*8*). However, using a similar methodology to that used for NO_2, the same factor of 2.25 times the 24-hour limit gave an 8-hour exposure guideline of 16ppb (45μgm^{-3}). Unlike this study's examination of limits for NO_2, it was not possible to detect a level of agreement between existing limits and the suggested guideline for SO_2.

Ozone

Five metros had standards for O_3. Two metros' limits matched the WHO recommendation for eight hour exposure of 50ppb. One metro had a more stringent standard, of 25 ppb. Two metros had target maximum levels of 200 ppb, four times the WHO 8-hour exposure guideline. However, these were intended for shorter periods of time; one of them is specified as being limited to 15 minutes' exposure. The WHO guidelines do not provide any suggested guideline for maximum O_3 levels for shorter durations. Therefore, the agreement of two metros from two different continents on 200ppb suggests this could be adopted for other metros wanting guidance on an absolute maximum limit for short periods.

Toxic Volatile Organic Compounds

Total VOCs include formaldehyde and benzene, but also include other chemicals that are less dangerous. Rather than focus on VOCs, it is recommended that metros focus particularly on two constituent chemicals of VOCs that are specifically mentioned by WHO in air quality recommendations: formaldehyde and benzene.

Formaldehyde. Seven metros had target maximum levels for formaldehyde, of which five had standards identical or similar to the WHO recommended safe limit of 100ppb. Two of these used the exact WHO limit, two had a limit of 105ppb, and one had a limit of 120ppb. The other two metros had limits significantly exceeding the WHO guideline; one limit was 200ppb and another was 300ppb.

Benzene. The WHO states that there is no safe limit for benzene, meaning that any quantity is too much because it is so carcinogenic. Of the three metros that reported a benzene-specific limit, only one specified that no level was considered safe. Another had a limit of 0.5ppb averaged over an 8-hour work shift, and a second had an annual average limit of 1.57ppb: three times the other metro's limit numerically but effectively even higher as it would be permissible for a longer period of time.

Particulate Matter

Figure 3 illustrates the range of standards reported for PM_{10} and $PM_{2.5}$. Limits for PM_{10} ranged from 40μgm^{-3} to 1000μgm^{-3}, with a median of 150μgm^{-3}. Metros K and L's PM_{10} limits of 40μgm^{-3} and 20μgm^{-3} are more stringent than even the WHO 24-hour guideline for PM_{10} in ambient air, which is 50μgm^{-3}. This benchmarking study therefore provides an opportunity for those metros to negotiate with their regulators for a relaxation of regulations.

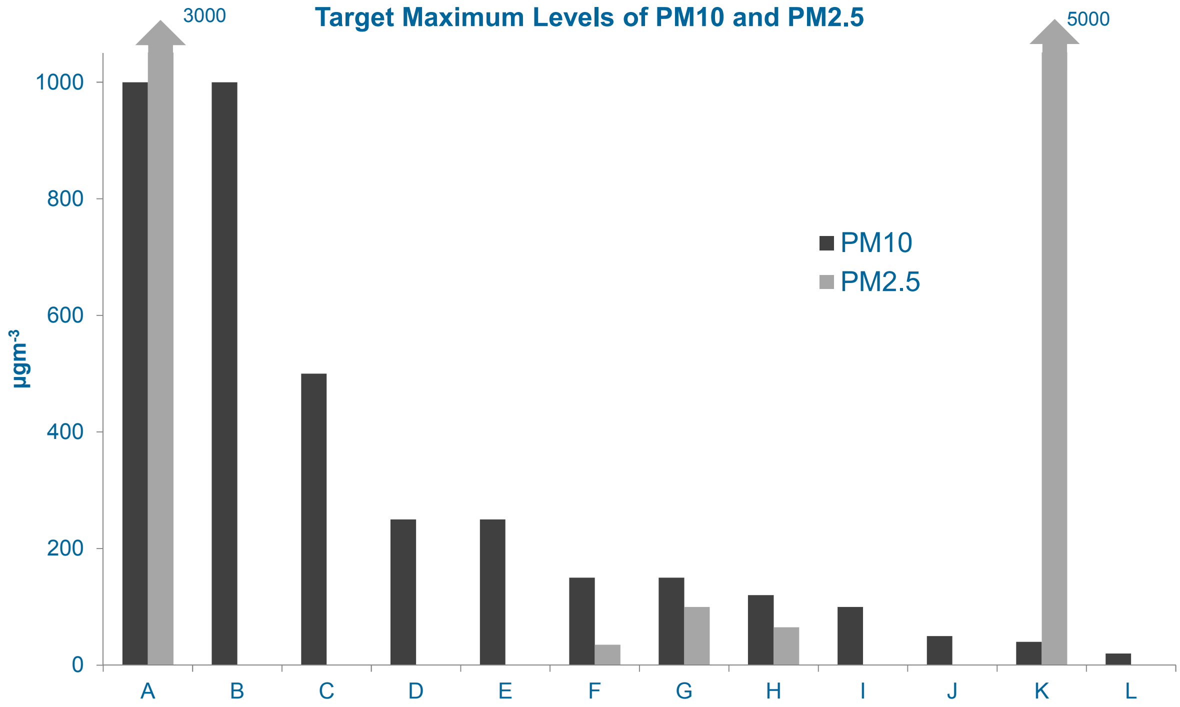

FIGURE 3 Metros' limits for particulate matter.

Standards for $PM_{2.5}$ varied significantly. Three metros' standards were less than their respective PM_{10} standards. Two metros, however, had significantly higher limits for $PM_{2.5}$. These two metros' limits are based on research showing that endogenous metro particulates are similar to welding fume (*6*), and therefore reflect national limits for welding fume concentration. Metro A's limit was recently changed from 5000 to 3000μgm^{-3}.

These variations highlight the lack of consensus on particulates in metros, and can be understood in the context of the inconclusive evidence about the hazards of particulates in metros. Two metros have followed the findings of Seaton *et al* (*6*), but the majority are using limits closer to those used for ambient particulates. Whilst the evidence remains uncertain, relaxing the limits will remain difficult for metros with very stringent regulations.

Summary of Results

The findings of this study are summarised in Figure 4. Each pollutant for which five or more metros reported standards is shown on the x-axis. An individual y-axis for each pollutant shows the concentration limits. For each pollutant, the graph shows the median of the limits reported by metros, the range of limits reported, and the 25th and 75th percentiles. A suggested limit is also shown. For CO_2, CO, O_3 and formaldehyde, the suggested limits are those proposed by WHO. For PM_{10} and $PM_{2.5}$, the limits shown are those proposed by Seaton *et al* (*6*). The WHO guidelines for PM_{10} and $PM_{2.5}$ are not shown as they are based particulates in ambient air, which are chemically different to those in metros (*3,6*). For NO_2 and SO_2, the limits shown are the guidelines suggested in this paper.

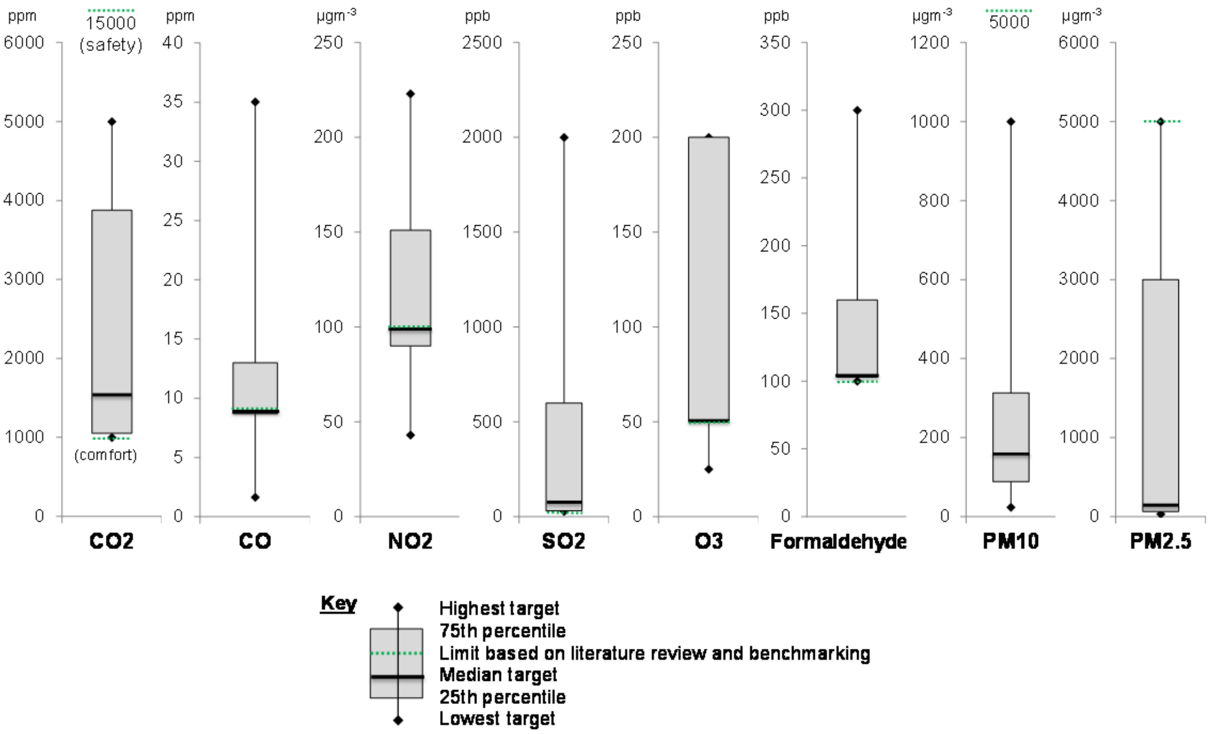

FIGURE 4 Summary of metros' air quality limits.

Figure 4 shows that metros' regulations for some pollutants range widely, particularly for CO_2, O_3 and $PM_{2.5}$. For CO and formaldehyde, the median limits in use are similar to the limits recommended by the literature. The recommended limit for O_3 is also similar to the median limit in use. For CO_2, SO_2 and formaldehyde the suggested limits are less than all or most of the limits in use. This indicates that for these pollutants some metros may be advised to reduce their limits, although for CO_2 this is a matter of comfort not a matter of safety. Conversely, for CO and NO_2 there are some metros that could use these data to make a case for relaxing their standards, in negotiation with their regulator.

5. CONCLUSIONS AND RECOMMENDATIONS

This paper used a benchmarking approach to investigate air quality regulation of CoMET and Nova metros. The results of the benchmarking exercise showed that for the majority of pollutants for which the metros had regulations, there was some degree of agreement with the standards recommended in the literature, as illustrated by the limits for CO and formaldehyde. However, large disparities between the standards used show that there is substantial inconsistency between what is considered 'safe' in various metros.

Benchmarking has revealed CO_2 as an example of a pollutant where overly stringent limits may increase metro costs unnecessarily. It has been shown that safety hazards of CO_2 occur at much higher concentrations than are currently permitted by metros' regulations. The regulations used by metros are therefore more related to the comfort of passengers. For example, CO_2 concentrations in Seoul metro have been measured at an average of 1775ppm with a maximum of 3377ppm (*5*). CoMET and Nova data indicate that this is towards the high end of the typical range measured in metros (*Railway and Transport Strategy Centre, unpublished data*[4]). The implication of this study for Seoul metro would be that the CO_2 level reported is safe (albeit a potential cause of passenger discomfort). However, if the limit of 1000ppm were applied stringently by a regulator, the metro could be fined or require significant investment in ventilation systems to reduce CO_2 levels. The evidence provided by this paper shows that 1000ppm should be a guideline rather than a regulatory limit, enabling metros to benchmark performance and make an economic decision as to whether to make improvements.

The paper has highlighted that there are some pollutants, particularly NO_2, SO_2, ozone and formaldehyde for which short-term exposure limits are appropriate. However, average exposure limits over a shift are also useful for metros to ensure the safety of their staff. Benchmarking has enabled the creation of suggested air quality limits for NO_2 and SO_2 for an eight hour shift. The meta-analysis on which WHO air quality guidelines were based did not have sufficient evidence to recommend a particular limit for eight hours' exposure. However, for metros needing to ensure the safety of their staff, a guideline based on benchmarking can lead to improved conditions. This is exemplified by the case of SO_2, for which two metros were using limits ≥1600ppb, despite a WHO recommendation that maximum levels should not exceed 177ppb. Whilst the proposed 8-hour limits may not be underpinned by the same evidence base as other limits, the WHO recommendations do at least provide a practical guideline for metros.

Inconsistency of regulations was most noticeable in the variation of two orders of magnitude in the regulations for particulates. This reflects the wide variation in the limits recommended in the literature, and the paucity of evidence distinguishing the effects of ambient particulates from endogenous metro particulates. Current use of limits based on evidence for ambient particulates may require metros to take costly mitigation action or risk legal challenge, for what may potentially be a safe level of a less dangerous pollutant. These data enable the wider metro community to open the debate with their regulators, which may stimulate further research. This benchmarking process may enable metros with the most stringent regulations to challenge them on the basis that they are even stricter than the WHO limit for ambient particulates.

This study is the first to consider a wide spectrum of pollutants in relation to metro air quality. It has contributed to the development of the topic by highlighting the dearth of available evidence for some pollutants, drawing attention to some conflicting evidence, and illustrating the large disparity in limits used by metros for some pollutants.

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