Exposure to particulate matter and gaseous pollutants during cab commuting in Nur-Sultan city of Kazakhstan

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Abstract

Exposure to particulate matter, carbon dioxide, and carbon monoxide inside a car during commuting were determined during the period October-November 2017 in Nur-Sultan, Kazakhstan. We choose to follow five bus routes (#10, 18, 19, 37 and 53) that cover the majority of the city's area. CO (ppm), CO₂ (ppm) and PM₁, PM_{2.5}, PM₄, and PM₁₀ mass concentration (μg/m³) were measured in this study. PM₁ was found to be the largest fraction of all sizes of PM. The mean PM₁ concentrations along the forward (backward) paths for each of the five bus routes were measured as 11 ± 14 (11 ± 7), 14 ± 8 (16 ± 6), 25 ± 11 (21 ± 14), 23 ± 8 (15 ± 6) and 76 ± 26 (99 ± 55) μg/m³, respectively. Average CO concentrations among five bus routes (#10, 18, 19, 37 and 53) along the forward (backward) paths were 0.67 ± 0.16 (0.78 ± 0.17), 0.7 ± 0.16 (0.53 ± 0.32), 1.04 ± 0.01 (2.3 ± 0.95), 2.67 ± 1.3 (2.03 ± 0.41), 3.54 ± 3.57 (2.17 ± 0.37) ppm. The mean PM₁/PM_{2.5} and PM_{2.5}/PM₁₀ ratios were 0.96 and 0.91, respectively. Nur-Sultan could be an example for those cities that are under major developments and candidates to be green cities by showing the exposures to atmospheric pollutants across the city. Those cities that are developing themselves as tourist attractions should create maps of PM exposures along major urban routes, and route traffic to exclude tourist areas from being hotspots.

35 **Keywords:** Particulate matter, Carbon monoxide, Exposure, Road traffic, Green City

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1. Introduction

Globally, the exposure to ambient particulate matter (PM) is associated with 4 million deaths (accounting for 7.5% of all deaths) in 2016 (Guo et al., 2018). Only in Europe, the PM_{2.5} exposure was the reason for 432,000 premature deaths in 2012 (EEA, 2015). Air pollution related to traffic is a complex mixture of particles and gaseous compounds that can directly come from the tailpipe exhaust, tire wear and brake, resuspension of road dust, and secondary aerosols (formed through chemical and physical processes) (Viana et al., 2008; Thorpe and Harrison, 2008; Amato et al., 2009; Bahreini et al., 2012). In a close proximity to traffic, commuters can face higher concentrations (Kumar and Goel, 2016; Kumar, et al., 2018; Rivas et al., 2017a; Rivas et al., 2017b; Kumar et al., 2014) particularly during the morning rush hour (Moreno et al., 2009; Gomez-Perales et al., 2007). Exposure to highly variable concentrations of atmospheric pollutants including short-time extreme concentrations during commute may contribute 12-35% of total daily air pollution exposure for commuters (Williams and Knibbs, 2016; Rivas et al., 2016). Furthermore, the transport mode can affect the exposure during the commute. Moreno et al. (2015a, 2015b) reported particle number concentrations (PNC) were ordered as: urban background < underground < tram < walking in a suburban main road < walking and cycling in the city center < bus. However, this order might be different for other pollutants since the highest PM mass concentrations were reported in the subways (Martins et al., 2016a; Adams et al., 2001). In Barcelona, PM_{2.5} concentrations were higher in cars compared to PM_{2.5} concentrations in buses (de Nazelle et al., 2012) similar to what was found in Arnhem (Zuurbier et al., 2010). In London and Dublin, the reverse situation was reported (Adams et al., 2001; McNabola et al., 2008). The commuter exposure inside each transport mode (car, train, or bus) is influenced by the ventilation system and fuel type (Karanasiou et al., 2014). Given different conditions (like fuel type and ventilation rates) in each transport mode, it is challenging to compare the pollutant concentrations among different studies (Karanasiou et al., 2014; Goel and Kumar, 2015a; Kaur et al., 2007) because of the substantial differences in the measurement technologies employed. Knibbs et al. (2011) reported that ventilation rates is a key factor for the transport of the ambient ultra fine particles (UFPs) into the cabin (Knibbs et al., 2011) such that higher ventilation rates increases the penetration of outdoor particles into the bus and cars (Karanasiou et al., 2014; Zuurbier et al., 2010). On the other hand, filtration system of the vehicles can reduce the penetration of outdoor particles into the cabin (Briggs et al., 2008).

In diesel cars and buses, PM₁₀ exposures and median particle concentration were higher compared to electrical buses (Zuurbier et al., 2010). In addition, between vehicles of different manufactures, it is challenging to separate the effect of fuel type from those caused by differences in ventilation system in standard settings (Karanasiou et al., 2014; Knibbs et al., 2009). The utility of Euro

emission standards including Euro 6 in petro- and diesel-fueled vehicles has shown to reduce the level of the exposure to PM in cabins, compared to Euro 0-2 or Euro 0-4, respectively (Campagnolo et al., 2019). Also, installation of diesel particulate filters (DPFs) resulted in reductions in in-cabin PM exposure (Campagnolo et al., 2019).

Other variables such as wind speed, vehicle speed, vehicle air conditioning (filtration), and air exchange rate of the vehicle can affect the passenger exposure to gases and PM (Onat and Stakeeva, 2013; Harik et al., 2017; Ham et al., 2017). In London, Adams et al. (2001a) showed that the route choice and wind velocity influenced the personal PM_{2.5} concentrations during commuting by bus, car, and bicycle, while transport mode did not have a significant impact. Kaur and Nieuwenhuijsen (2009) reported 62% variations in PNC, due to the influence of temperature and wind speed, transport mode, and traffic counts, as the significant predictor variables. Also, only 9% variation in PM_{2.5} concentration was observed to be related to the transport mode with little traffic intensity effect. Wind speed and temperature were significant determinants of PNC during walking and trips by bus and automobile in Montreal (Weichenthal et al., 2008). Rivas et al. (2017a) investigated commuter exposure to particulate matter (PM₁, PM_{2.5}, and PM₁₀), black carbon (BC), and ultrafine particle concentrations for different travel modes along four commuting routes using four different transport modes (car, bus, walk, and subway) in London. Wind speed and ambient concentrations mainly explained the changes in concentration. The commuting route and period of the day had minor influences. The wind speed had the largest effect on PM fractions during the trips by bus (Rivas et al., 2017a).

Recent studies have shown that in-cabin exposure to PM, carbon monoxide, and carbon dioxide has increased because of prolonged traveling times in cars (Harik et al., 2017). They reported that self-pollution coming from the car's engine accounts for approximately 15% and 30% of the commuter's exposure to CO and PM_{2.5}, respectively.

Commuters can be exposed to carbon monoxide resulting from the incomplete combustion in the vehicle engines including private cars, buses, trucks, and motorcycles (Barbulescu and Barbes, 2017; Harik et al., 2017). Thus, traffic congestion or high-speeds can lead to higher CO emissions. Congestion-related exposures occur during the morning and evening rush hour periods (Kim et al., 2015). A systematic mobile monitoring campaign was conducted to assess personal exposures to particulate matter (PM) on a pre-defined route in four transport microenvironments (car, cycle, bus, and walk) (Kumar et al., 2018). Due to the limited physical activity, in car exposures were the lowest and had commensurately low respiratory deposition doses (RDD) for coarse particles. Despite the high concentrations of fine particles, car exposures produced the lowest RDD (Kumar et al., 2018).

Yan et.al. (2015) suggested that it is possible to reduce in-cabin exposure to CO and PM_{2.5} by decreasing vehicle's speed and setting the air conditioner to its recirculation mode (Yan et al., 2015). Yan et.al. (2015) found that air-conditioned buses had higher in-cabin PM concentrations compared to non-AC transports in wintertime due to the presence of the engine exhaust in the cabin to provide heat. Qiu et al. (2017) studied exposure to PM in buses between May and June 2016 in Xi'an, China. Two types of buses: AC (closed window) and non-AC (open window) were studied. In the summertime, Qiu et al. (2017) observed that AC type of buses had higher PM concentrations inside the bus compared to non-AC buses due to the transport of the outdoor PM into the cabin.

Additionally, when the AC was on, coarse particles were removed by the filter inside the AC. Higher PM concentrations were observed in areas where transportation and constructions activities were heavily involved (Basagaña et al., 2017). However, the relative importance of these two primary urban sources with respect to commuting exposure needs to further investigation.

Kazakhstan is the ninth largest country by land area in the world and is the focal point of Central Asian countries with low populations (ASRK, 2005). In 2014, Kazakhstan was ranked as the second largest residential coal consumer per capita in the world (Kerimray et al., 2017). Nur-Sultan is the capital city of Kazakhstan located in the north of the country with the population of about 1 million. Nur-Sultan typically experiences a severely cold climate in winter time such that in January 2018, the ambient temperature reached approximately -40°C. Nevertheless, in summertime, the temperature may reach 30°C leading to increased traffic emissions and the highest NO₂ concentrations (Darynova et al., 2018). The number of registered motor vehicles in Nur-Sultan increased to 285,000, a 5.3% increase over previous years (Administrative Police Department, 2017). Nur-Sultan is divided into two zones including the east side (old city) and the west side (new city-under the development). Unlike the available studies, the present study assessed the impact of the city development as one of the socio-economic factors on PM and CO exposures during commuting.

The objectives of this study were to compare the exposure to PM while commuting in the old part of the city with the new part of the city since the old part is dominated by transportation and residential coal burning pollution while the new part of the city experiences construction pollution and to some extent traffic pollution and also to identify the factors influencing the temporal variability of particles in different parts of city.

2. Materials and methods

2.1 Study Location

Nur-Sultan became the new capital city of Kazakhstan in 1997. The city name changed from Astana to Nur-Sultan in March 2019. The Ishim River divides the city into two sides, an old part and the new part of the city. To define commonly used commuting scenarios, five bus routes were chosen to determine exposures across the urban area. Each route started from the new side, passed through the city center, and terminated in the old side. Each bus route includes a number of stops. The measurements were made along each given bus route in the forward and then immediately afterward in the backward direction. Since the DustTrak's pump makes noise, it could not be used in city buses since the noise would disturb the passengers. Thus, measurements were made in a car with closed windows that drove following the bus routes that cover the majority of the urban area. The chosen routes are shown in Supplemental Figure S1. The measurements were in a light-duty gasoline vehicle: Toyota Corolla (2008, $V=1.6 \text{ m}^3$). The car burns 92 Octane gasoline fuel. The speed of the car during the trips was maintained on average in the range of 40-60 km/hour equivalent to the speed of the buses. The car windows were closed, and the air conditioning system was on fresh air mode to approximate the conditions in the city buses. The measurements were conducted during the evening traffic rush period between 5 to 7 p.m. when people were typically commuting. Table S1 shows the measurement schedule.

2.2 Instrumentation

PM concentrations were measured using a DustTrak DRX (DustTrak DRX Aerosol Monitor 8533, TSI, USA). The DustTrak DRX continuously records PM_{10} , $\text{PM}_{2.5}$, PM_4 , PM_{10} , and total PM using light scattering. An Indoor Air Quality Meter (IAQ- TSI, UA model 7545) monitored CO and CO_2 concentrations, temperature, and RH. The sampling time for both instruments was set at 30 seconds. Before each test, the instruments were zeroed. Based on the wind rose for Nur-Sultan, westerly and southwesterly winds frequently influenced Nur-Sultan city during the study period (Figure1) with prevailing wind speed ranging from 5.7 - 8.8 m/s. The average ambient temperature and relative humidity ($\pm$ standard deviation) were $0.3 \pm 6^\circ \text{C}$ and $84 \pm 16\%$, respectively.

Figure 1. The wind rose for Nur-Sultan city during the sampling campaign.

3. Results and Discussion

3.1 Particle mass size distributions during commuting

Based on PM fractions in Figure 2 and Figures S2-S5, the main contributor to PM_{2.5}, PM₄ and PM₁₀ concentrations was PM₁ and was consistently found in all 5 field trips. The contribution of PM₁ ranged from 77-94 % of the total measured mass. The mass fraction of particles in the 1 to 2.5 μm range was in the 0-3% range thus accounting for almost none of the mass along routes 19, 10, and 37. The PM_{1-2.5} mass fraction for routes 18 and 53 were 2.94% and 1.61%, respectively. These results agree with those of Qiu et al. (2017). Rivas et al. (2017) also found that PM₁ was the dominant PM fraction (79%) during commuting using cars in London when the windows were closed, and the AC was operating. When windows were closed (WC), and air conditioner set to fresh air intake (ACFA), the main fraction of PM is PM₁ with 77% or higher contributions to total PM mass concentrations in the afternoon (Qui et al., 2017). With respect to PM₁, similar results were reported by Kumar et al. (2018) for people in cars. They concluded that the concentrations of fine particles (PM_{2.5}) were always lower for all route modes (including walk, car, bus, and cycle) during off-peak times compared to morning and evening peak periods. These lower concentrations were due to lower traffic volumes during off-peak periods and relatively better dispersion conditions compared to the morning and evening peak periods (Kumar et al., 2018). Based on the deposition pattern of particles, Kumar et al. (2016) divided the particles into

3 different size fractions including alveolar (particles with diameters $\leq 4 \mu\text{m}$), thoracic ($4\text{-}10\mu\text{m}$), and inhalable ($10\text{-}100\mu\text{m}$) particles. They found that the highest exposure to alveolar particles, was observed in cars ($222 \pm 26 \mu\text{g}/\text{m}^3$) in morning and ($229 \pm 26 \mu\text{g}/\text{m}^3$) in evening periods. In the evening, car commuters were exposed to the highest concentrations of inhalable, thoracic, and alveoli particles among the different transport modes including auto, rickshaw, car, bus, and motorcycle, suggesting the likelihood of additional particle accumulation inside the car interiors. Although the time spent in this microenvironment is low, the PM concentrations could be very high (Kumar et al., 2016; Nasir and Colbeck, 2009). Previous studies reported that the choice of commuting micro-environments can significantly influence the commuter exposure to traffic-related pollutants (Fernandez- Bremauntz and Ashmore, 1995; Kingham et al., 2013; Chan et al., 2002). Exposure to PM in the car micro-environment depends on the traffic congestion, road network layout, ambient concentrations, and vehicle condition.

Figure 2. PM distribution along the route bus No.53.

The distribution of PM_{10} inside cars depends on several factors including the ventilation rate, presence of a filter, speed of the vehicle, and outdoor weather condition (Harik et al., 2017). In the present study, the percentage of coarse particles was low since the air quality inside the car is controlled by ambient concentrations mainly from exhaust from other vehicles on the road and urban combustion sources (Harik et al., 2017; Kumar et al., 2018). Although ACFA was operated during the 5 trips in this study, this ventilation system was found to remove mainly coarse particles rather than PM_{10} (Qui et. al., 2017; Kumar and Goel, 2016). Ptak and Fallon (1994) found that air filters remove 40-70% of coarse particles. The percentage of coarse particles could be higher in buses compared to the cars (Kumar et al., 2018). One of the possible reasons could be the high rates of particle re-suspension due to flux of travelers at bus stops (Moreno et al., 2015; Rivas et al., 2017; Kumar et al., 2018).

The fraction of particles that can penetrate to the bronchioles and alveoli is small for coarse particles. Therefore, sub-micron (PM_{10}) and fine ($PM_{2.5}$) particles are typically of greater health concern (Tables S2-S5). In the current study, the concentrations of fine particles for different bus routes were similar. The maximum PM_{10} , $PM_{2.5}$, PM_4 , and PM_{10} mass concentrations along the forward path ranged from 29 to 185 $\mu g/m^3$, from 30 to 187 $\mu g/m^3$, from 30 to 192 $\mu g/m^3$, and from 34 to 251 $\mu g/m^3$, respectively. While maximum PM_{10} , $PM_{2.5}$, PM_4 , and PM_{10} mass concentrations along reverse path ranged from 41 to 256 $\mu g/m^3$, from 43 to 256 $\mu g/m^3$, 44 to 259 $\mu g/m^3$, and from 265 to 484 $\mu g/m^3$, respectively. The mean $PM_{10}/PM_{2.5}$ ratio was nearly identical (≈ 0.96) in both traverses (Kumar et al., 2018; Qui et al., 2017), and the average $PM_{2.5}/PM_{10}$ ratio of the car mode in both forward and backward passes was about ≈ 0.91 . The coarse particles include re-suspension of dust, brake and tire wear from the road. Qui et al. (2017) showed that average $PM_{2.5}/PM_{10}$ ratio was significantly high in car mode using air conditioning system. $PM_{2.5-10}$ concentrations were low compared to $PM_{2.5}$ in the current study (Figure 3 and S6). Kumar et al. (2018) reported that the average $PM_{2.5-10}/PM_{2.5}$ ratio in the car mode was about 0.13.

Figure 3. The ratios of $PM_{10}/PM_{2.5}$, $PM_{2.5}/PM_{10}$, and $PM_{2.5-10}/PM_{10}$ for studied forward routes in Nur-Sultan.

3.2 Spatiotemporal evaluation of PM concentrations in Nur-Sultan

Figures 4 and S7-S11 present the temporal variations of the measured PM concentrations along the studied bus routes starting from the new side (Nazarbayev University bus stop) to the old side. As shown, the PM concentrations (PM_{10} , $PM_{2.5}$, PM_4 , PM_{10} , and Total PM) were highest in the old side where major sources include power plants, coal combustion, vehicle emissions, residential burning, and construction.

Figure 4. Temporal pattern of PM concentrations along bus route No 53 in Nur-Sultan, Kazakhstan for the forward path.

Among the studied routes, the highest average PM mass concentration was measured for route No. 53 (Figures S2 to S5). The $PM_{2.5}$ mass concentrations were mainly PM_1 on both passes along this route, and averaged $89 \mu\text{g}/\text{m}^3$. This value is 3.56 and 2.54 times higher than the European Commission daily average value ($25 \mu\text{g}/\text{m}^3$) and U.S. Environmental Protection Agency daily average value ($35 \mu\text{g}/\text{m}^3$), respectively (“NAAQS Table US EPA” 2018) guidelines.

High traffic loads were observed during the rush hour trips along the route No.53, and therefore, the measured PM_1 mass concentrations were mainly associated with traffic emissions (Tang et. al., 2017; Kim et al., 2013; Kumar and Goel, 2016; Goel and Kumar, 2015). At the final stop (stop 25) of route No.53 in the old part of the city (see Table S6) the mass concentration of $PM_{2.5}$ rapidly increased to $258 \mu\text{g}/\text{m}^3$ (Figure 3). This rise was observed during the forward and backward trips that could be attributed to the presence of 2 thermal power plants which are Astana (recently named Nur-Sultan) Energiya Podrazdeleniye (51.202°N , 71.43°E) and Astana Energiya Test-2, Vks (51.187°N , 71.510°E) located close to that area. These thermal power plants widely utilize coal as a fuel. Particulate matter emitted from coal combustion is mainly fly ash and unburned carbon particles that result from incomplete combustions of the coal (Karagulian et al., 2015).

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260 **Figure 5.** Wind rose plotted for the studied period from left to right (above of the picture) are on
 261 02.11.2017 in Nur-Sultan city.

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264 Table S7 presents the mean daily wind speed in different days of the measurements, along
 265 with the average PM_{2.5} concentrations on different routes. Measurements along route No.53 were
 266 made on November 2nd, 2017. According to the meteorological data (www.world-weather.ru), the
 267 wind speed was 1.8 m/sec, which is relatively low compared to the wind speeds on other
 268 measurement days (causing relatively higher PM_{2.5} concentrations compared to other measurement
 269 days). Therefore, the relatively lower concentration of PM_{2.5} along 4 other bus routes could be due
 270 in part to higher wind speeds similar to what has been reported for Nagasaki, Japan (Wang et al.,
 271 2016). The lowest PM_{2.5} concentration (11 µg/m³) was observed for route No.10 when the highest
 272 wind speed (6.1 m/s) was recorded. Based on the information provided in Table S7, the correlation
 273 coefficient between PM_{2.5} level and wind speed was 0.466 for all 5 routes. The observed moderate
 274 correlation supports the partial contributions of the wind speed to PM_{2.5} concentrations inside the
 275 car. Yang et al. (2011) reported that meteorological factors such as wind speed influence the
 276 distribution of PM_{2.5} by reducing the pollutant concentrations. In Nagasaki, Japan, a threshold in
 277 the correlation between wind speed and PM_{2.5} concentration was observed (Wang et al., 2016)
 278 finding that higher wind speeds reduced pollutant concentrations (Wang et al., 2016).

279 Different spatial patterns were observed in the PM concentrations for routes No.53 and
 280 No.10 during the forward paths (Figure 5 and S12). Although many PM sources were located in
 281 the old side of the city, the PM concentrations were higher on the new side for these routes at the
 282 initial bus stops located on the new side. The dominant wind direction in Nur-Sultan was from the

new side (western part) to the old side (eastern part) during measurements on routes No.53 and No.10. The ambient particles were transported by wind from the right side to the left side in these two days. Therefore, in new side we witnessed higher PM concentration than old side in studied days. These findings are in agreement with previous studies showing that wind direction had a vital role in transporting pollutants to the downwind areas (Wang et al., 2016).

3.4 CO distributions

Table S8 shows the CO and CO₂ concentrations inside the car for the different driving routes. The highest mean values for CO and CO₂ were found to be 2.9 ppm and 1003 ppm, respectively, for route No.53. The main reason that may have driven this observation could be the considerable traffic (traffic jam) and slow or stop-and-go driving that tend to increase emissions (Barbulescu and Barbes, 2017; Yadav et al., 2017).

Figures 6 and S13 show the temporal changes in CO and CO₂ concentrations for route No. 53 along the forward and backward paths. In Figures 7 and S14, the black line represents the route No.53, while the red rectangle demonstrates the region where the highest carbon monoxide concentrations were measured. Higher CO concentrations were observed along route No.53 compared to other bus routes (Figures 7 and S14).

Figure 6. CO and CO₂ concentrations for route No. 53 along the forward path on 02.11.2017 in Nur-Sultan.

Based on these results, CO concentrations observed along all bus routes met the European Commission and US Environmental Protection Agency standards (8.11 ppm and 9 ppm, respectively) ("NAAQS Table| US EPA" 2018). The highest values for CO and CO₂ were 5.8 ppm and 1413 ppm, respectively at stops No.7 to No.9 located in the red rectangular area shown in Figures 7 and S14.

Figure 7. PM₁ concentration changes based on values at bus stops along bus route No. 53 in Nur-Sultan, Kazakhstan.

The forward and backward profiles were not similar likely due to the different traffic volumes and changing metrological conditions between the two trips. Tables S9 and S10 show the maximum concentrations of CO and CO₂ at the bus stops for the different bus routes. Elevated concentrations of both gases were found along right bank of the Ishim River (old part of city), except for route No.53 that was subjected to a traffic jam. The traffic volume was significantly higher on the old side of Nur-Sultan compared to the new side. Additionally, two operating thermal power plants and the railway station are located in the old side of the city and likely contributed to the elevated CO and CO₂ concentrations.

In this study, we have presented the data for a part of the world where the air quality information is poorly known. Central Asia including Kazakhstan has very poor record of the air quality research. We also used the bus routes to help define major routes through the city and thus, provide more comprehensive exposure estimates. It is found that power plants and train station could be two major sources of pollution in a city which can impact commuter exposure.

4. Conclusions

Nur-Sultan was established as the capital of Kazakhstan in 1997 and is divided into two parts, the old city and new city, with different pollution sources of PM including power plants, coal combustion for space heating, vehicle emissions, and construction. The city wants to serve as a destination hub for central Asia and attract tourists as well as providing a healthy environment for its residents. Thus, its air quality is important, particularly exposure when moving around the city. To advise the officials responsible for the design of city transport, tourist attractions and air quality management to improve public health, this study investigated the exposure to PM, CO, and CO₂ in cars along five bus routes connecting the old and new parts of the city and covering a large fraction of the city area. The old part of the city was found to have higher PM in the car due to higher traffic volumes, power plant emissions, and the railway station. The dominant PM fraction was PM₁ when the air conditioning was operating. Exposure to CO was always below the US EPA and European standards inside the cars. However, there were routes where the PM concentrations during the ride exceeded US EPA and European standards. Thus, the residents of Nur-Sultan or tourists may be differentially exposed depending on where they live or where they need to go in Nur-Sultan.

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