RESEARCH PAPER

MEASURING TRAFFIC-RELATED AIR POLLUTION USING SMART SENSORS IN SRI LANKA: BEFORE AND DURING A NEW TRAFFIC PLAN

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ABSTRACT. Motor vehicle emissions are the primary air pollution source in cities worldwide. Changes in traffic flow in a city can drastically change overall levels of air pollution. The level of air pollution may vary significantly in some street segments compared to others, and a small number of stationary ambient air pollution monitors may not capture this variation. This study aimed to evaluate air pollution before and during a new traffic plan established in March 2019 in the city of Kandy, Sri Lanka, using smart sensor technology. Street level air pollution data ($PM_{2.5}$ and NO_2) was acquired using a mobile air quality sensor unit before and during the implementation of the new traffic plan. The sensor unit was mounted on a police traffic motorcycle that travelled through the city four times per day. Air pollution in selected road segments was compared before and during the new traffic plan, and the trends at different times of the day were compared using data from a stationary smart sensor. Both $PM_{2.5}$ and NO_2 levels were well above the World Health Organization (WHO) 24-hour guidelines during the monitoring period, regardless of the traffic plan period. Most of the road segments had comparatively higher air pollution levels during compared to before the new traffic plan. For any given time (morning, midday, afternoon, evening), day of the week, and period (before or during the new traffic plan), the highest $PM_{2.5}$ and NO_2 concentrations were observed at the road segment from Girls High School to Kandy Railway Station. The mobile air pollution monitoring data provided evidence that the mean concentration of $PM_{2.5}$ during the new traffic plan (116.7 µg m^{-3}) was significantly higher than before the new traffic plan (92.3 µg m^{-3}) ($p < 0.007$). Increasing spatial coverage can provide much better information on human exposure to air pollutants, which is essential to control traffic related air pollution. Before implementing a new traffic plan, careful planning and improvement of road network infrastructure could reduce air pollution in urban areas.

KEYWORDS: air quality, mobile air quality sensors, particulate matter, road traffic

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INTRODUCTION

Air pollution is a major global public health issue. According to the World Health Organization (WHO), approximately 7 million people die annually from air pollution exposure (World Health Organization (WHO), 2014), and it is the leading environmental risk factor associated with the global burden of disease. In addition, exposure to polluted air leads to the development and exacerbations of respiratory and cardiovascular diseases

(Pope III et al. 2002), lung cancer (Vineis et al. 2006) and multiple additional diseases. The majority of deaths related to outdoor air pollution occur in South and South-East Asia (HEI International Scientific Oversight Committee, 2010). Despite this, regular mandatory air monitoring in urban environments in South Asian countries is sparse.

In cities and towns across the globe, Traffic-Related Air Pollution (TRAP) is the primary source of air pollution (Matz et al. 2019). Traffic plans have often been changed to ease road congestion in urban areas. These changes in traffic flow can impact air pollution levels, either increasing or decreasing them or making no change at all. Previous research has evaluated ambient air pollution levels using stationary monitors in a limited number of selected areas before and after establishing new traffic plans (Atkinson et al. 2009). However, most of these studies did not evaluate air pollution in different street segments. Air pollution levels may vary significantly in some street segments compared to others. Measuring average ambient air pollution using a low number of stationary monitors may not capture the actual spatial variation of air pollution in the study area. The standard air pollution monitors are expensive, and developing countries like Sri Lanka do not have the funds to establish the required number of monitoring stations to measure air pollution. The development of small sensor technology offers an attractive alternative solution where air pollution can be monitored at a low cost. These sensors have several advantages over standard monitoring stations, such as; they are versatile and can be customized to suit different requirements, including mobile air pollution monitoring. Previous studies have reported the implementation of smart sensors in a mobile air pollution framework. A vehicular wireless sensor network architecture was implemented at the National Chiao-Tung University in Taiwan (Hu et al. 2009), and researchers in Seoul, South Korea, mapped urban air quality using mobile sampling with low-cost sensors and machine learning (Lim et al. 2019). The public buses in Sharjah city, United Arab Emirates, were also used to test an air pollution sensing network (Al-Ali et al. 2010) while in New Jersey and New York, the United States, a fine-grained vehicular-based mobile air pollution measuring technique using solid-state carbon monoxide (CO) sensors and optical analysers (PM) was used to measure 'on road' pollution (Devarakonda et al. 2013). In the city centre of Uppsala, Sweden, an experimental study was conducted on real-time air pollution monitoring using wireless sensors on public vehicles (Kaivonen and C-H Ngai, 2020).

Evaluation of air pollutants in cities along the roads provides the true levels of emissions generated by vehicles as well as the exposure levels to commuters, pedestrians, and individuals who live or work close to these roads. To the best of our knowledge, there has been no traffic-related mobile air pollution monitoring study published in Sri Lanka to date. This study aimed to monitor and evaluate traffic-related air pollution on the roads of Kandy city, Sri Lanka, before and during a new traffic plan.

MATERIALS AND METHODS

Study area

In this study, we focused on measuring, monitoring, and comparing air pollution levels on the roads of Kandy city before and during a new traffic plan was installed. On average, air pollution in and around the city of Kandy is known to be higher compared to other cities in Sri Lanka (Seneviratne et al. 2017) due to it being located in a basin and surrounded by mountains. We measured air pollution on the main roads (where the main traffic flow occurs) of the city of Kandy, including the three main traffic access routes to the Kandy Municipal area (total area of 28.53 Km^2) (Fig. 1.).

The new traffic plan in the city of Kandy

The new traffic plan converted two previously two-way roads, both of which took traffic towards and away from the city (Figure 1, Old Peradeniya Road and William Gopallawa Mawatha), into one-way roads. The new traffic plan meant that all vehicles travelling to Kandy from Peradeniya had to enter William Gopallawa Mawatha, and all vehicles leaving Kandy towards Peradeniya had to use the Old Peradeniya Road. The new traffic planed commenced on 2nd March 2019 for six days,

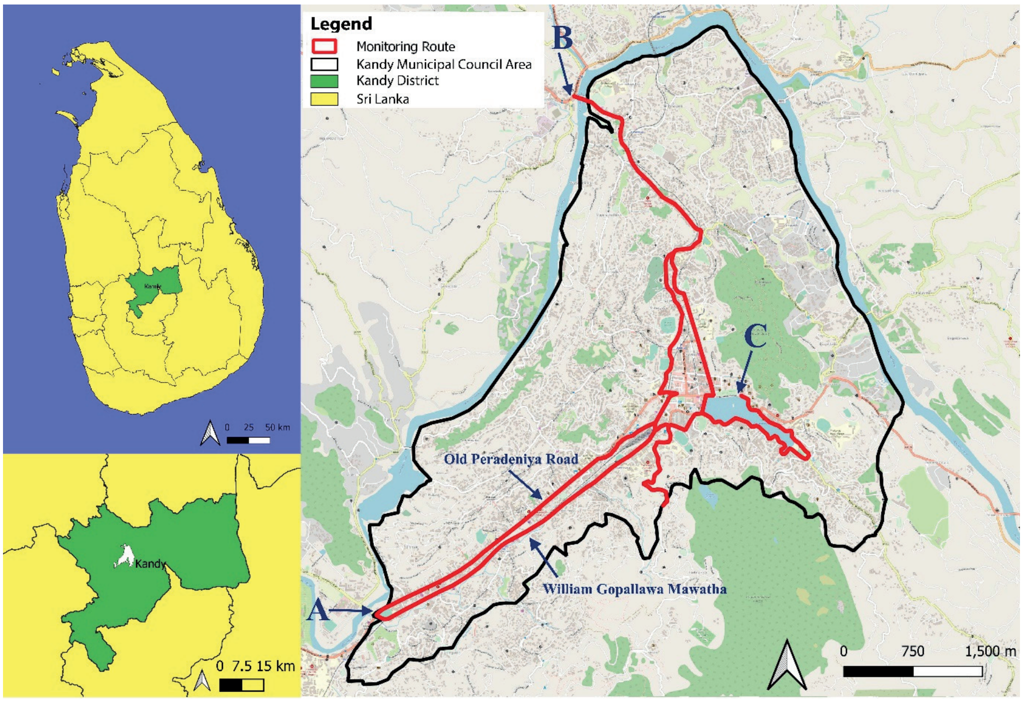

Fig. 1. Study Area; Study area was in and around the Kandy city roads. A- via Peradeniya, B – via Katugastota, and C- via Tennekumbura: three main traffic access to Kandy city

ending on 7th March 2019. Here we defined the period "Before" the new traffic plan as 23rd February 2019 to 28th February 2019, and "During" as 2nd March 2019 to 07th March 2019. Although the change was only made to two roads, the traffic flow of the entire city was affected.

Mobile air pollution monitoring

This study used a small, low-cost mobile air quality measurement device called «Sniffer4D». Sniffer4D (Soarability Technologies Co. Ltd) is used for high-end air quality mapping based on aerial and ground vehicles. It provides real-time operational information such as 2D grid air pollution distribution heat maps, 3D points cloud pollutant distribution heat maps, automated operation report generation, and readable comma-separated value file exports of raw data. The device can be carried by moving vehicles and has an anti-electromagnetic interference carbon fibre casing, an internal suspension mechanism, and an active ventilation system. It transfers geotagged and timestamped air pollution data to analytic software in real-time. The device is integrated with an inhalable particulate matter (PM) sensing module, which detects particles by the laser scattering method, while a high-resolution Nitrogen Dioxide (NO_2) sensing module detects particles up to 5ppb (Specifications of Sniffer4D Mobile Air Quality Mapping System (2019 . 08 . 05), 2019). Each sensing module was calibrated according to its intrinsic properties, and Sniffer4D's performance has been evaluated by a Chinese national-level metrology institute (Sniffer4D – Sniffer4D – Mobile Air Poluttant Mapping System, n.d.).

In this study, we measured Particulate Matter < 2.5 µm in diameter ($PM_{2.5}$) and NO_2. Data were collected by attaching the Sniffer4D device to a police traffic motorcycle before and during the new traffic plan was in effect. Data were collected before and during the new traffic plan. Monitoring was conducted at regular time intervals – morning (7.00 am – 10.00 am), midday (10.00 am – 1.00 pm), afternoon (1.00 pm – 4.00 pm) and evening (4.00 pm – 7.00 pm). The sensor unit was mounted vertically on the motorcycle's handlebars (Fig. 2.) so that the exhaust plume of the bike did not influence the readings.

Fig. 2. Sniffer 4D sensor mounted on a police traffic motorcycle

The motorcycle's speed was maintained at less than 20 km per hour at all times. When moving along the roads, sniffer4D provides a geographic location (longitude, latitude, and elevation), temperature, humidity, $PM_{2.5}$, and NO_2 concentration at each point at intervals of 1 second.

Stationary air pollution monitoring

The background ambient $PM_{2.5}$ concentration was monitored before and during the new traffic plan with the "Knowing Our Ambient Local Air-quality" (KOALA) air quality device located at the National Institute of Fundamental Studies (NIFS), Kandy (Sri Lanka). KOALA is a low-cost small air quality sensor unit developed by the Queensland University of Technology, Australia. The KOALA sensors unit have already been tested against standard air quality instruments (Liu, Jayaratne, et al. 2020) and successfully used in previous research on air pollution in several countries (Jayaratne et al. 2020; Liu, Zhao, et al. 2020), including in Sri Lanka (Priyankara et al. 2021; Senarathna et al. 2021).

Statistical analysis

Roads were selected based on the main traffic flow. All roads where the main traffic flow was toward the city was included, and the selected roads were divided into 17 road segments (Fig. 3 and Table 1) based on road length, geographic features, and road traffic conditions using ArcGIS (version 10.5. Redlands, CA: Environmental Systems Research Institute, Inc. 2010).

Fig. 3. Categorization of road segments in Kandy city

Point data values of air pollutants ($PM_{2.5}$, NO_2) on each road segment were averaged for each time interval (morning, midday, afternoon and evening) using the ArcGIS software to evaluate the variation of pollutants during the study period. Due to the non-normality of meteorology data, the non-parametric Mann-Whitney U test was performed to evaluate the difference between before and during the new traffic plan was implemented.

To identify air pollution variations in the before and during periods, graphs were plotted by averaging the concentrations of pollutants in each road segment. The paired t-test was used to compare air pollution levels obtained from a mobile air pollution sensor device (Sniffer 4D) before and during the new traffic plan. Further, patterns and trends of air pollution were evaluated. Pollutant data obtained from the KOALA stationary monitor unit were not normally distributed. Therefore, the non-parametric Wilcoxon Signed Rank test was performed to compare the pollutant concentrations before and during the new traffic plan. All statistical tests were conducted using R studio software (RStudio Team, 2020) (version 1.3.1056).

Table 1. Road segments identified in Kandy city

Buffer ID	Details of the road segment
1	Getambe Junction- Mulgampola Junction (Old Peradeniya Road)
2	Getambe Junction – Mulgampola Junction (New Kandy Road)
3	Mulgampola Junction – Kandy Railway Station
4	Mulgampola Junction – Girls' High School
5	Girls' High School – Kandy Railway Station
6	Hantana Road
7	Baladaksha Mawatha + Keppetipola Road
8	Kandy Railway Station – Clock Tower
9	Bogambara Road
10	Clock Tower – Kandy Police Station
11	Lake Round – EL Senanayake Children's Park
12	EL Senanayake Children's Park – Dalada Maligawa
13	Dalada Maligawa – Lake Round
14	Kandy Jaffna Road – Welikanda Railway Station
15	Kandy Police Station – Welikanda Railway Station
16	Welikanda Railway Station – St. Anthony's Boys College
17	St. Anthony's Boys College – Katugasthota

RESULTS

The average $PM_{2.5}$ and NO_2 concentrations of the 17 road segments before the new traffic plan is shown in Fig. 4(A). The highest average $PM_{2.5}$ concentration before the new traffic plan was implemented was at road segment ID 5 (Girls' High School to Kandy Railway Station), and the lowest was at road segment ID 15 (Kandy Police Station to Welikanda Railway Station). The highest and the lowest average NO_2 concentration before the new traffic plan was in road segment ID 5 (Girls' High School to Kandy Railway Station) and road segment ID 2 (Getambe Junction to Mulgampola New Kandy Road), respectively. Average $PM_{2.5}$ and NO_2 concentrations during the new traffic plan by road segment ID are provided in Fig. 4(B). For any given day/any time session, the highest average $PM_{2.5}$ concentration during the new traffic plan was at road segment ID 5 (Girls' High School to Kandy Railway Station) and lowest at road segment ID 6 (Hantana Road). During the new traffic plan, the highest average NO_2 concentration was at road segment ID 5 (Girls High School to Railway Station) and the lowest at road segment ID 15 (Kandy Police Station to Welikanda Railway Station).

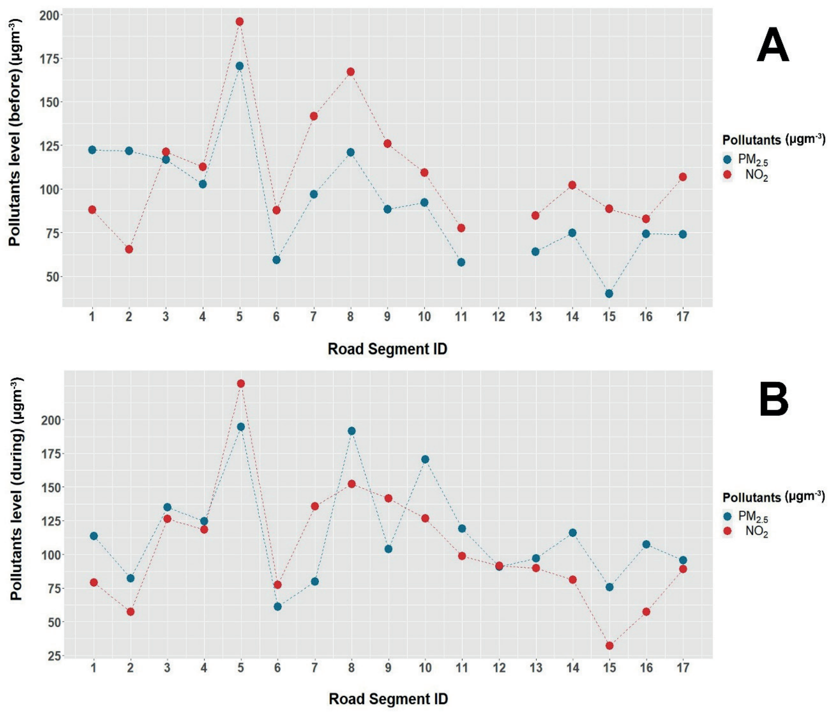

Fig. 4. Temporal changes in the RFD at the control and background points

Fig. 5. shows the average $PM_{2.5}$ variations on each time interval during the new traffic plan. For example, the Morning average indicates the morning average pollution concentration of all days during the new traffic plan by each road segment ID. During the new traffic plan, the average $PM_{2.5}$ was the highest in the morning (131.24 µg m^{-3}), followed by evening (111.67 µgm^{-3}), afternoon (110.27 µg m^{-3}) and midday (106.28 µg m^{-3}).

Average $PM_{2.5}$ and NO_2 levels before and during the new traffic plan by road segment ID is shown in Fig. 6. The results showed a significant increase in PM2.5 concentration during (M = 116.71 µg m^{-3}, SD = 9.86) compared to before (M = 92.32 µg m^{-3}, SD = 8.22), t (15) = -3.14, $p < 0.007$ (two-tailed) the new traffic plan. The mean increase of PM2.5 concentration was 24.39 µgm^{-3} (95% CI: 7.84 to 40.94). The eta square statistic of 0.39 indicated a large effect size. For NO_2, there was no significant difference during (M = 105.58 µg m^{-3}, SD = 46.76) compared to before (M = 109.87 µg m^{-3}, SD = 34.61), t (15) = 0.806, p = 0.433 (two-tailed) the new traffic plan. The average $PM_{2.5}$ and NO_2 at each road segment is shown in Table S1. For stationary air pollution, the Wilcoxon Signed Rank test revealed a statistically significant increment of $PM_{2.5}$ concentration during compared to before the new traffic plan, z = -6.689, p = 0.001, with a small effect size (0.127).

There was no significant difference in total rain between the traffic plan periods (z= -0.408, p = 0.689) and, similarly, there was no significant difference for relative humidity (z = -1.41 p = 0.159). Fig. S1. shows the variation of meteorology data (relative humidity, temperature, wind speed) before and during the new traffic plan. A comparison of average ambient $PM_{2.5}$ variations before and during the new traffic plan for each day is shown in Fig.S2. Fig. S3 shows a comparison of the daily variation of the average ambient $PM_{2.5}$ for the monitoring period; comparatively high levels of $PM_{2.5}$ were recorded during the new traffic plan in the evening times. Summary statistics of KOALA data are shown in Table S2. Fig. 7. shows a scatter plot of average $PM_{2.5}$ variation at 17 road segments before and during the new traffic plan. The background $PM_{2.5}$ concentration measured by the KOALA increased by 13.6% during the new traffic plan period compared to before, the corresponding average $PM_{2.5}$ concentration on the roads increased by 21%. There was a high correlation between $PM_{2.5}$ in each road segment before and during the new traffic plan $R^2 = 0.93$ (Figure 7).

DISCUSSION

We found that $PM_{2.5}$ levels were consistently well above the WHO standard in the city of Kandy during both traffic plan periods. For any given time period (morning, midday, afternoon, evening), day of the week, or period (before or during new traffic plan), the highest $PM_{2.5}$ and NO_2 concentrations were observed at the road from Girls' High School to Kandy Railway station (Road Segment ID 5). We found the lowest $PM_{2.5}$ concentrations at Hantana road (Road Segment ID 6) and the Kandy Police station to Welikanda Railway Station (Road Segment ID 15) both before and during the traffic plan.

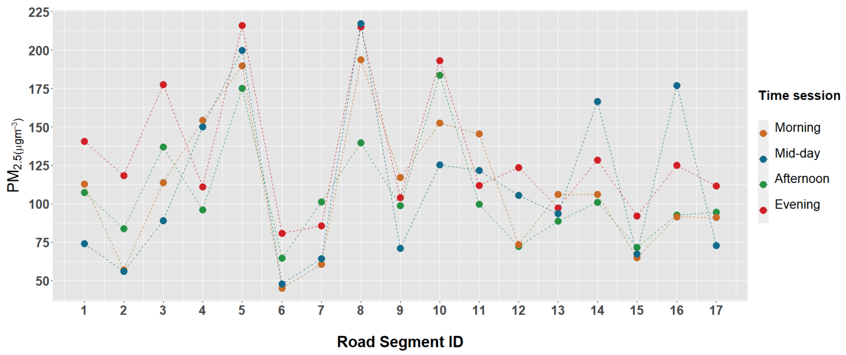

Fig. 5. Average $PM_{2.5}$ variations in each time period during the new traffic plan

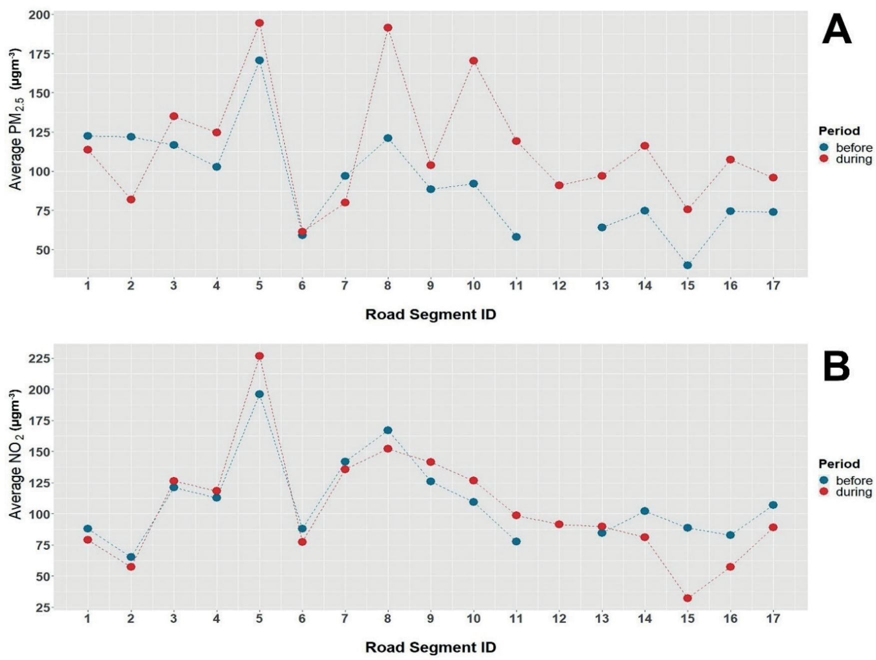

Fig. 6. $PM_{2.5}$ (A) and B) NO_2 (B) level by Road Segment ID before and during the new traffic plan

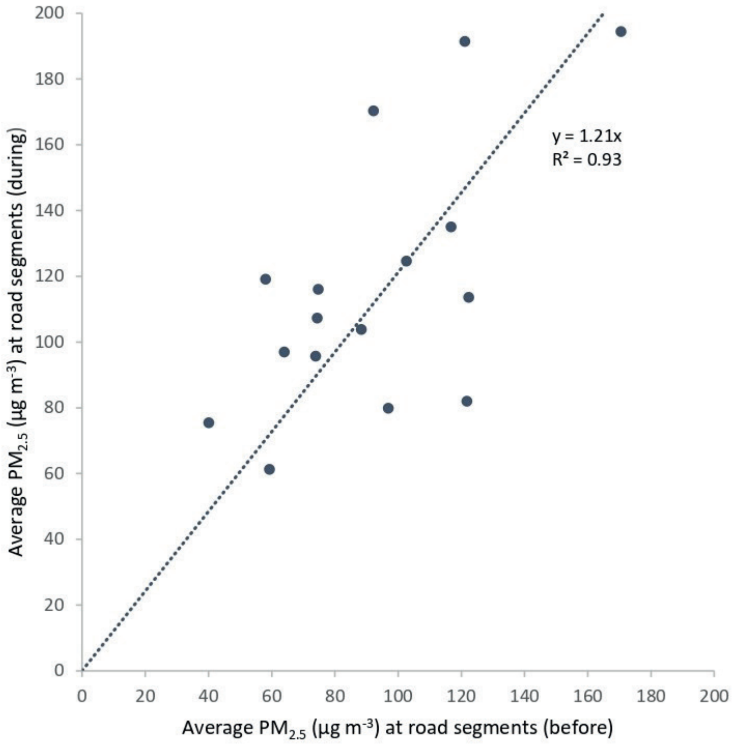

Fig. 7. Scatter plot of average $PM_{2.5}$ variation at 17 road segments, before and during the new traffic plan

Heavy traffic conditions are usually present on the road from Girls' High School to the Kandy Railway Station) as the main bus stop in Kandy is located there. The road segments where we observed comparatively low pollution levels have a smooth traffic flow. Previous studies revealed that the morning and evening times, associated with the two rush-hour periods, had the highest $PM_{2.5}$ concentrations compared to midday and afternoon in Kandy (Senarathna et al. 2019). The KOALA stationary monitor captured this, where diurnal $PM_{2.5}$ average concentration showed two similar spikes in $PM_{2.5}$ levels, one in the morning and the other in the evening rush hours.

The majority of roads had comparatively higher pollution concentrations during the new traffic plan period than before the traffic plan was implemented. Average $PM_{2.5}$ values from the KOALA stationary monitors showed higher air pollution during the new traffic plan than before. Before implementing the new traffic plan, traffic jams were created mainly in the city centre and immediate surroundings. However, during the new traffic plan, substantial traffic congestion was observed on the roads beyond the city centre as well. When comparing the effect of the new traffic plan on levels of ambient $PM_{2.5}$ in Kandy, we observed an increase of approximately 6 μgm^{-3} (13.6%). However, this increase was approximately 24 µgm-3 (21%) at the street level, indicating a more significant detrimental impact in terms of $PM_{2.5}$ air pollution. The increased $PM_{2.5}$ in the street and ambient levels may have been due to increased vehicle exhaust with slow-moving traffic. Overall, there was a slight increase in NO_2 at the street level before and during the new traffic plan, but this was not statistically significant.

The influence of the precipitation and $PM_{2.5}$ concentration in the atmosphere has been discussed elsewhere (Z. Liu et al. 2020). When considering the region's meteorological conditions, the average temperature in Sri Lanka is higher in March and April. Total precipitation was also lower during that time. This study was conducted only for two weeks in March, and the influence of the mereological conditions was assumed to be the same during the study period.

Over the last decade, smart low-cost sensors have been rapidly adopted for air quality monitoring. Different types of wireless sensor network-based air pollution monitoring systems and their advantages disadvantages have been extensively discussed elsewhere (Khedo and Chikhooreeah 2017). The most significant advantage of vehicular sensor networks over traditional static sensor networks is their ability to conduct measurements over large areas with a small number of sensor nodes. One sensor node can achieve sufficient sizeable geographic coverage by utilizing low-cost portable ambient sensors and the mobility of vehicles(Gaglio and Lo Re 2014). In 2009 Wong et al. (Wong et al. 2009) discussed the advantages of mobile sensing by mounting sensor nodes onto vehicles and several studies have suggested that vehicles could be used to create large-scale air quality monitoring systems. For example, the Mobile Air Quality Monitoring Network (MAQUMON) is a system made up of solid-state sensor nodes mounted on cars that measure CO, NO_2, and O_3. An onboard GPS is used to tag air pollution with precise location and time data. The data is uploaded to a server via a Wi-Fi connection regularly (Völgyesi et al. 2008). Although the vehicle sensor network system for air quality monitoring is very cost-effective with high geographical and coverage technology, there has been no such air quality monitoring study in Sri Lanka to date. Our mobile air quality data can be used by city planners, population health professionals, education leaders, and transportation managers to inform policy and influence decision-making. Although there are many strengths, we also acknowledge some limitations to our study. For example, some data point locations were missed as a result of weak GPS signal strength and only a single mobile sensor unit was used throughout the monitoring period. Having more sensor units would have allowed us to take measurements more frequently and cover additional road segments throughout the city.

CONCLUSIONS

This study showed the spatial characteristics of $PM_{2.5}$ pollution variation before and during a new traffic plan in Kandy, Sri Lanka. Overall, the levels of $PM_{2.5}$ in the city of Kandy were consistently much higher than WHO standards, and changes in traffic plans comparatively increased $PM_{2.5}$ levels on many road segments. Prior to implementing a new traffic plan, careful planning and improvement of road infrastructure should be considered to potentially reduce air pollution in urban areas. Extensive spatial coverage of air quality monitoring by mobile sensor networks enables to determine the level of population air pollution exposure and consider that in traffic planning. Good traffic plans make day-to-day tasks easier while also enhancing the health benefits of its citizens by improving air quality. ■

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APPENDICES

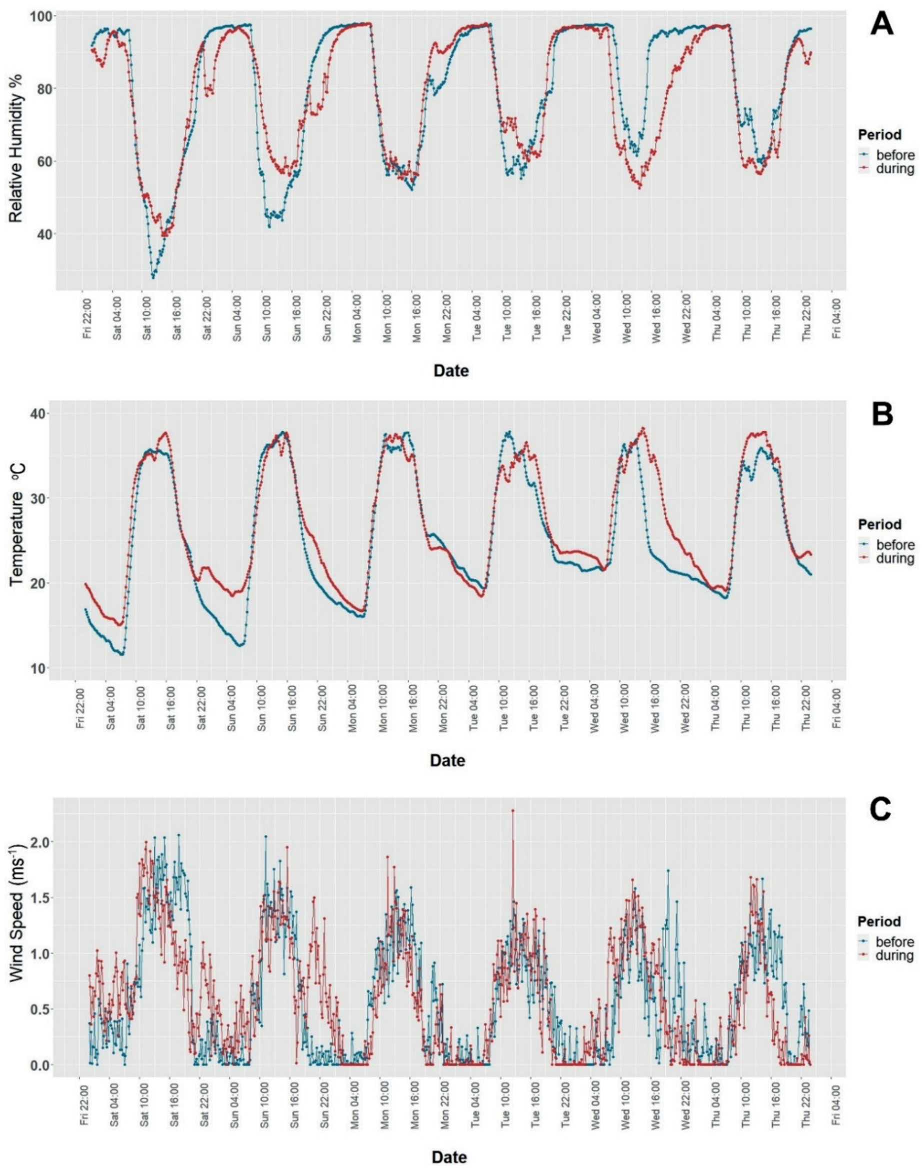

Fig. S1. Comparison of meteorology data variations before (2019-02-23 to 2019-02-28) and during the new traffic plan (2019-03-02 to 2019-03-07) on Relative Humidity (A), Temperature (B) and Wind speed (C)

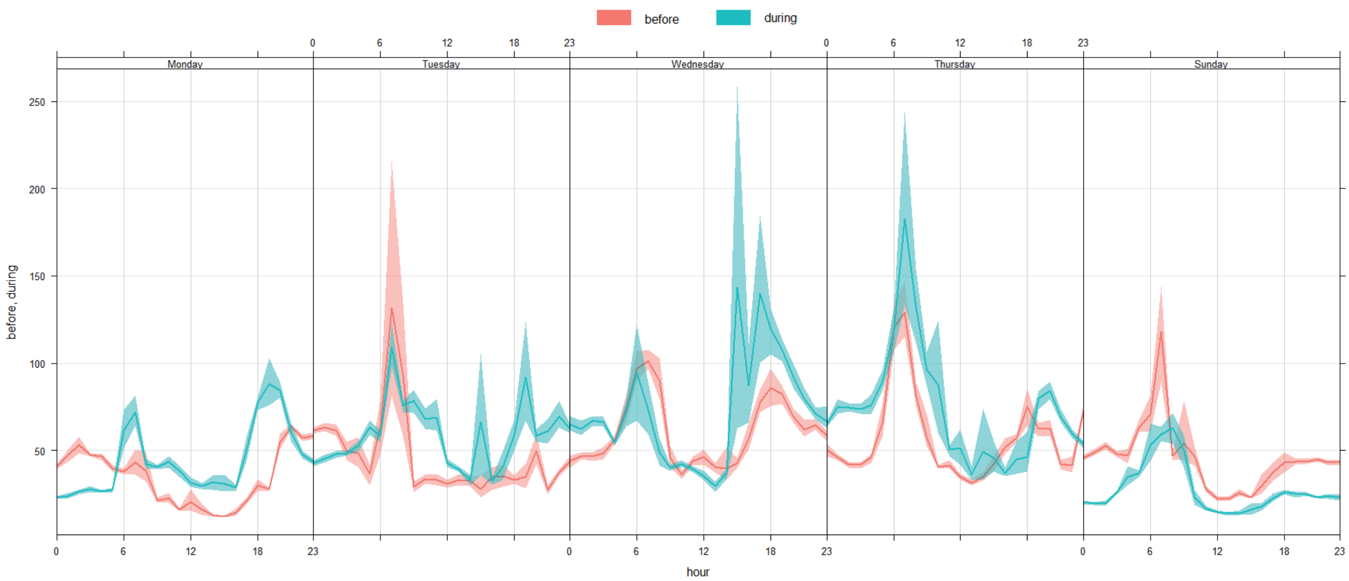

Fig. S2. Comparison of average $PM_{2.5}$ variations before and during the new traffic plan for each day of the study period

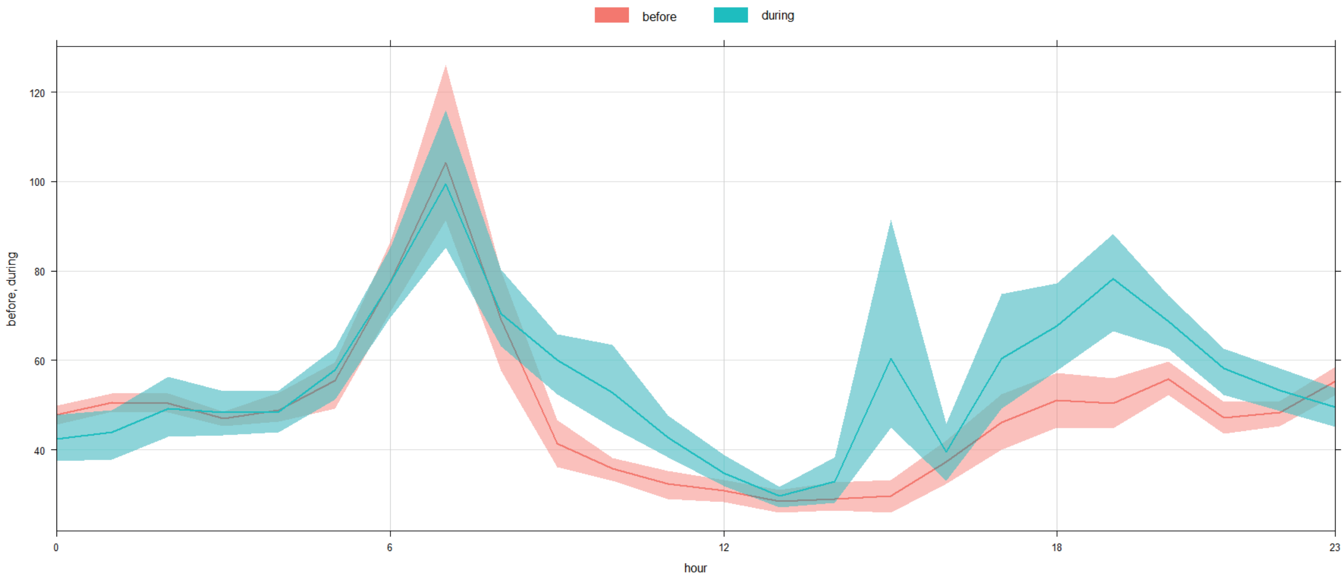

Fig. S3. Comparison of average daily PM2.5 representations before and during the new traffic plan

Table S1. Average pollutant levels at each road segment before and during the new traffic plan

	$PM_{2.5}$ (μgm^{-3})		NO_2 (μgm^{-3})	
Road Segment ID	before	during	before	during
1	122.34	113.65	88.01	79.12
2	121.79	81.99	65.42	57.18
3	116.79	135.02	121.24	126.40
4	102.61	124.63	112.72	118.26
5	170.52	194.47	195.88	226.69
6	59.29	61.26	87.91	77.23
7	96.90	79.86	141.73	135.63
8	121.07	191.45	167.14	152.19
9	88.36	103.86	125.95	141.66
10	92.17	170.38	109.36	126.57
11	58.07	119.13	77.53	98.56
12		90.85		91.32
13	64.00	96.96	84.66	89.89
14	74.73	116.06	102.23	81.12
15	40.06	75.47	88.60	32.22
16	74.40	107.32	82.71	57.39
17	73.93	95.76	106.89	89.11

Table S2. Summary statistics of KOALA data on PM2.5 before and during the new traffic plan

	Traffic plan period	
	Before	During
Mean	48.62	55.23
Standard Deviation	28.525	39.000
Percentile 25	34.00	31.00
Percentile 50	44.00	47.00
Percentile 75	57.00	70.00