Science of the Total Environment 742 (2020) 140931

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Reductions in traffic-related black carbon and ultrafine particle number concentrations in an urban neighborhood during the COVID-19 pandemic

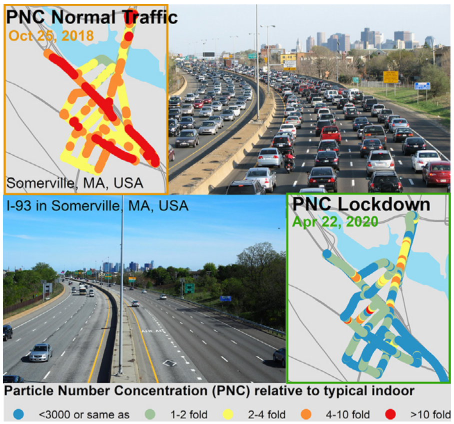
Neelakshi Hudda [a], *, Matthew C. Simon [b], Allison P. Patton [c], John L. Durant [a]

[a] Department of Civil and Environmental Engineering, Tufts University, 200 College Avenue, Medford, MA 02155, USA
[b] Volpe National Transportation Systems Center, U.S. Department of Transportation, Cambridge, MA 02142, USA
[c] Health Effects Institute, Boston, MA 02110, USA

HIGHLIGHTS

- Traffic reduced dramatically during COVID-19 lockdown (71% fewer cars and 46% fewer trucks).
- Neighborhood-scale air quality improved during lockdown compared to pre-pandemic conditions.
- Median total on-road PNC and BC concentrations were 45–69% and 22–56% lower, respectively.
- BC:PNC ratio and fraction of diesel vehicles in the on-road fleet was higher during lockdown.
- BC and PNC reductions, unlike $PM_{2.5}$, were commensurate with traffic reductions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 June 2020
Received in revised form 5 July 2020
Accepted 11 July 2020
Available online 14 July 2020

Keywords:
COVID-19
Lockdown
Black carbon
Particle number concentration (PNC)
Ultrafine particles
Traffic-related air pollution

ABSTRACT

We investigated changes in traffic-related air pollutant concentrations in an urban area during the COVID-19 pandemic. The study was conducted in a mixed commercial-residential neighborhood in Somerville (MA, USA), where traffic is the dominant source of air pollution. Measurements were made between March 27 and May 14, 2020, coinciding with a dramatic reduction in traffic (71% drop in car and 46% drop in truck traffic) due to business shutdowns and a statewide stay-at-home advisory. Indicators of fresh vehicular emissions (ultrafine particle number concentration [PNC] and black carbon [BC]) were measured with a mobile monitoring platform on an interstate highway and major and minor roadways. Our results show that depending on road class, median PNC and BC contributions from traffic were 60–68% and 22–46% lower, respectively, during the lockdown compared to pre-pandemic conditions, and corresponding reductions in total on-road concentrations were 45-69% and 22-56%, respectively. A higher BC: PNC concentration ratio was observed during the lockdown period likely indicative of the higher fraction of diesel vehicles in the fleet during the lockdown. Overall, the scale of reductions in ultrafine particle and BC concentrations was commensurate with the reductions in traffic. This natural experiment allowed us to quantify the direct impacts of reductions in traffic emissions on neighborhood-scale air quality, which are not captured by the regional regulatory-monitoring network. These results underscore the importance of measurements of

---

* Corresponding author.
E-mail address: neelakshi.hudda@tufts.edu (N. Hudda).

https://doi.org/10.1016/j.scitotenv.2020.140931

appropriate proxies for traffic emissions at relevant spatial scales. Our results are useful for exposure analysis as well as city and regional planners evaluating mitigation strategies for traffic-related air pollution.

1. Introduction

Transportation emissions are a major source of air pollution in urban areas (US EPA, 2014). In the weeks following the COVID-19 outbreak in early 2020, many governments instituted shelter-in-place and limited social interaction policies to contain the spread of the disease. As a result, businesses, offices, and schools were closed, and only essential services remained operational. These disruptions caused economic activity in many sectors – including the transportation sector – to decrease dramatically. Consequently, this period offered an unprecedented opportunity to quantify how reductions in transportation emissions affect concentrations of traffic-related air pollutants in urban air.

Studies document both air quality improvements and lack thereof during the pandemic in different countries around the world. For example, reductions in ambient concentrations of carbon monoxide, nitrogen dioxide (NO_2), and particulate matter mass in the 2.5 ($PM_{2.5}$) and 10

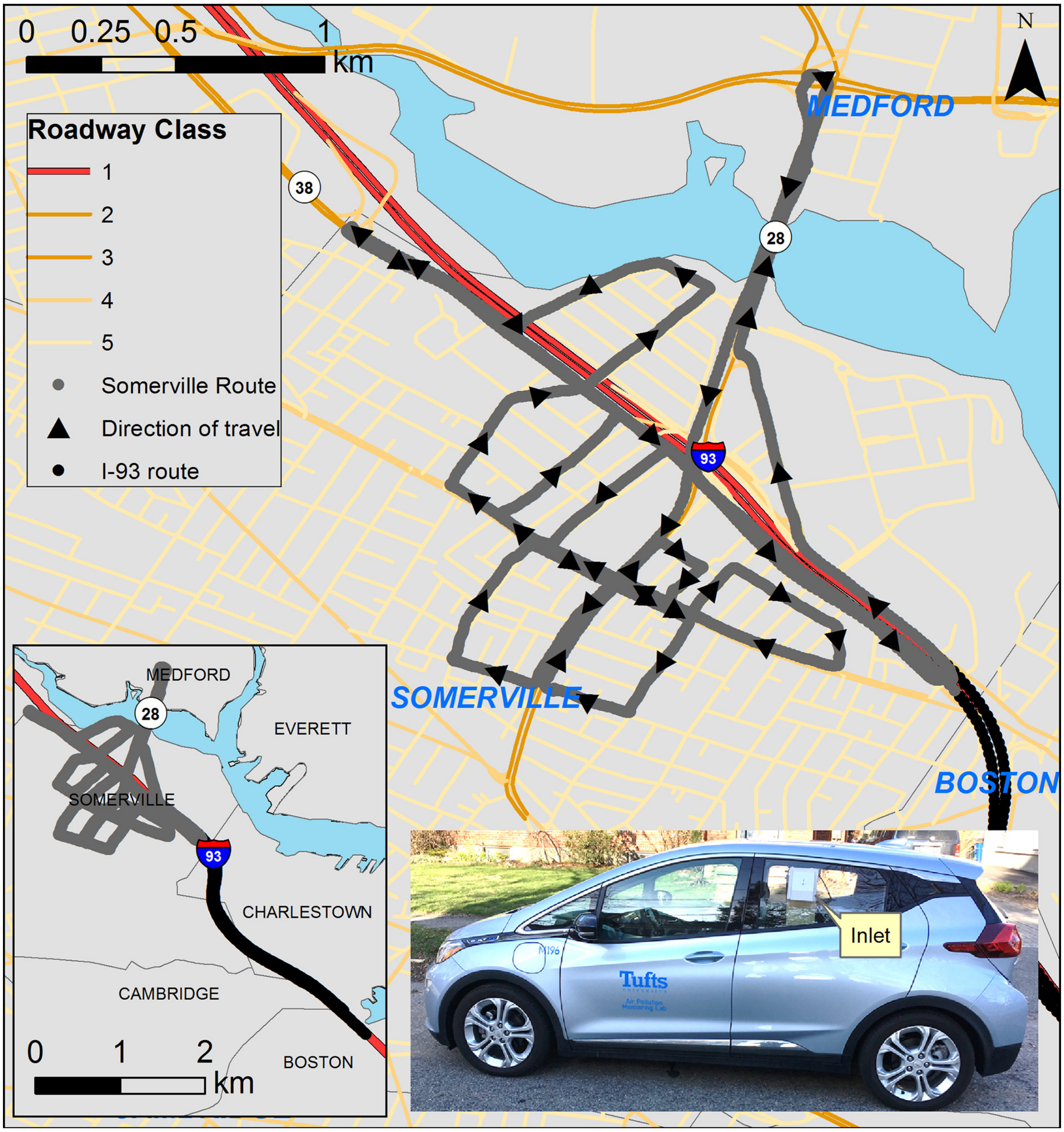


Fig. 1. Somerville mobile-monitoring route (gray line) with arrows indicating the direction of travel. Black line in left inset shows the I-93 monitoring route. The mobile monitoring platform – TAPL – is shown in the right inset.

(PM_{10}) micrometer size fractions have been reported in China (Bao and Zhang, 2020), India (Mahato et al., 2020; Sharma et al., 2020), Brazil (Nakada and Urban, 2020; Dantas et al., 2020), Spain (Tobías et al., 2020), and Kazakhstan (Kerimray et al., 2020). Based mostly on networks of sparse of regulatory monitors, these studies document improvements at the regional scale (~100s km) from concurrent reductions in emissions from many sources including industry, manufacturing and power generation in addition to transportation. In contrast, in an analysis of a national database derived from >500 regulatory monitors in United States, Bekbulat et al. (2020) found that for weeks after stay-at-home advisories went into effect, changes in average $PM_{2.5}$ and ozone concentrations were inconsistent (both increases and decreases were observed); further, observed reductions were not commensurate with reported reductions in traffic and within the range of variation expected due to meteorology and long-range transport. Similarly, Wang et al. (2020) analyzed severe air pollution events in North China following the outbreak in Wuhan, and concluded that reductions in $PM_{2.5}$ and precursors occurring due to reduced traffic and industrial emissions were modest enough to be outweighed by adverse meteorology.

To date, no studies of which we are aware have reported on changes in air quality at the local scale in near-roadway neighborhoods (<1-km^2 scale) due to the sharp decreases in roadway traffic following the COVID-19 outbreak. Furthermore, in studies of air quality changes during the pandemic, analysis of air pollutants that are predominantly of traffic-origin, or proxies of traffic emissions, are missing or sparse. Our goal was to investigate air quality changes in an area where traffic is the dominant source of local air pollution. To that end, we studied Somerville, Massachusetts (USA), a municipality near Boston ranked 94th percentile for traffic proximity and volume (US EPA, 2019). We measured two unregulated pollutants that are indicators for fresh traffic emissions – black carbon (BC) and ultrafine particles (aerodynamic diameter < 100 nm, reported here using the proxy particle number concentration – on highways and in nearby neighborhoods during the pandemic. Our objectives were to measure the spatial distribution of traffic-related air pollution in a near-roadway neighborhoods, and to compare these measurements to datasets that predate the pandemic to quantify the changes in air quality due to traffic reductions (Padró-Martínez et al., 2012; Patton et al., 2014a; Perkins et al., 2013; Simon et al., 2017).

2. Materials and methods

2.1. Study area

Somerville is the most densely populated city in Massachusetts (7200/km^2) (U.S. Census Bureau QuickFacts: Massachusetts, n.d.). Land use in Somerville is 46% residential, 25% roadways, 10% commercial, 6% open space, and 4% industrial (City of Somerville OSPCD, 2011). Three major highways – Interstate 93 (I-93) and Massachusetts State Routes (SR) 28 and 38 – together carried 230,000 vehicles/day through Somerville in 2019 (William Kuttner, 2020). Our monitoring route (Fig. 1) captured air quality differences between these highways (and other busy roadways) and quieter residential streets. The route was 15.6-km-long and included 6.3 km of Class 2 and 3 roads (i.e., numbered multi-lane but not limited-access highways), 2.7 km of Class 4 roads (i.e., major roads, arterials, and collectors), and 6.6 km of Class 5 roads (i.e., minor streets and roads) as defined by Massachusetts Department of Transportation (MassDOT) (MassGIS, n.d.). We also monitored a 6-km stretch of I-93 (Class 1; ~3 km in each northbound and southbound direction) between Somerville and Boston (Fig. 1 and Fig. A1 in the Appendix).

2.2. Monitoring campaigns

Herein we compare air pollution measurements from the Somerville monitoring route and on I-93 before and during the pandemic lockdown period. The ***lockdown*** period is defined as March 24, 2020 (when the governor ordered that non-essential offices and businesses cease in-person operations (Governor Charlie Baker Orders All Non-Essential Businesses To Cease In Person Operation, n.d.) in addition to schools the week prior) until the last day of our monitoring campaign (May 14, 2020). The Somerville route was monitored during normal traffic conditions in 2018–2019; the I-93 route was monitored during normal traffic conditions in 2012–2013 (Table 1).

2.3. Mobile monitoring

In 2018–2020, monitoring was conducted using the Tufts Air Pollution Monitoring Lab (TAPL), an electric-car-based mobile platform (Fig. 1) fitted with a GPS receiver and fast-responding instruments similar in inlet design to other mobile platforms (Hudda et al., 2013a). In 2012–2013, mobile monitoring on I-93 was performed using the gasoline-powered TAPL (described elsewhere (Padró-Martínez et al., 2012)). Particle number concentration (PNC) was measured using TSI Condensation Particle Counters (CPC; Models 3783 and 3775), and BC was measured using Magee Scientific Aethalometer Model AE33 (we report the 880 nm wavelength data). A freshly factory-calibrated CPC was used for the lockdown-period campaign.

Mobile-monitoring data were compiled in spreadsheets by matching instrument time stamps. Data were then aligned with respect to the fastest instrument (i.e., the CPC, 1-s monitoring interval) to adjust for lags in response times. Data were scanned for periods of unreasonable values (such as zeros or PNC readings <100 particles/cm^3) or values automatically flagged by the instruments. A quality assurance protocol, described elsewhere (Patton et al., 2014a), was followed for processing measurements collected with the gasoline-powered TAPL to eliminate possible self-sampling (no measurements were flagged for current analysis). Self-sampling corrections were not needed for the electric TAPL. Further, in the 2012–2013 campaign a butanol-based CPC was used that had a lower d_{50} (4 nm) as compared to the water-based CPC (7 nm) used in the 2018–2020 campaigns; thus, an adjustment factor (based on side-by-side testing of the two CPCs) was used to allow direct comparison of the datasets (see Appendix section A2) (Simon et al., 2018).

2.4. Data acquisition, processing and statistical analysis

Hourly total traffic volumes from counters on I-93 nearest to the study area (Fig. A1) were acquired from MassDOT. Fleet composition during the lockdown was not publicly available for I-93; therefore, we used data from I-90 in Boston (Transportation Data Management System, n.d.). Lockdown-period traffic volumes on other roadways in the study area were not available. Meteorological data collected at Logan International Airport (KBOS) were obtained from the National Centers for Environmental Information (NOAA NCEI, n.d.) and aggregated to hourly resolution. Hourly historical concentrations of BC, NO_2 and $PM_{2.5}$ from regulatory sites in Boston (MassDEP, 2019) were obtained via EPA's AirData and AirNow websites (https://aqs.epa.gov/api; https://docs.airnowapi.org/) and MA Department of Environmental Protection (April 1, 2020 onwards, Leslie Collyer, personal communication, June 5, 2020). Data were obtained for two sites: (a) a site on the shoulder of I-93, just south of Boston, which is part of EPA's near-road network (Von Hillern; ID: 25–025-0044); and (b) a site 6.5 km south of Somerville in Roxbury, which is considered indicative of the urban background (ID: 25–025-0042). See Figs. A2–A3 for locations of these regulatory sites and annual average traffic volumes estimated by the Boston Metropolitan Planning Organization (MassGIS, 2018a) on streets around these sites. Roadway classes were assigned by linking GPS location with MA Executive Office of Transportation - Office of Transportation Planning (EOT-OTP) road data layers (MassGIS, 2018b). Data were analyzed using ArcMap 10.5, R 3.5.1 and 3.6 and MATLAB 2019b.

Table 1
Summary of the different monitoring campaigns used in this study.

Monitoring campaign	Season	Start date	End date	Monitoring days	Laps/Runs[a]	Wind speed[b] (m/s)	Temperature (°C)[b]
			Somerville				
Normal conditions	Fall 2018	Sep 13, 2018	Nov 16, 2018	11	53	4.8 ± 1.9	11.3 ± 6.3
	Winter 2019	Jan 17, 2019	Feb 22, 2019	15	66	3.5 ± 2.5	1.4 ± 4.3
Lockdown	Spring 2020	Mar 27, 2020	May 14, 2020	15	51	5.6 ± 1.6	10.1 ± 4.4
			I-93 between Somerville and Boston				
Normal conditions	Spring 2012	Mar 5, 2012	May 31, 2012	17	33	5.8 ± 2.4	13.1 ± 6.9
	Spring 2013	Mar 2, 2013	May 21, 2013	4	6	6.1 ± 1.8	9.9 ± 5.8
Lockdown	Spring 2020	Mar 27, 2020	May 5, 2020	15	196	5.8 ± 1.3	5.3 ± 3.8

[a] Each mobile-monitoring lap represents one complete run of the Somerville route; each run of I-93 represents one trip along I-93 either from Somerville to Boston or the reverse.

[b] Listed here are the average wind speed and temperature for each campaign but only for the monitoring hours; wind speed and temperature for each monitoring day are listed in Tables A1-A5 in the Appendix.

On-road mobile measurements reflect the local background and on-road emissions by local traffic. Further, to quantify the reduction in traffic contributions to air pollution during the lockdown, we needed to compare lockdown-period data to datasets preceding the pandemic while controlling for day-to-day and seasonal variation in the local background. Therefore, we estimated the local background as the 5th percentile on-road value (similar to several previous mobile monitoring studies (Hudda et al., 2013b; Simon et al., 2020; Hudda et al., 2014)) per road class per lap of the monitoring route. The local traffic contribution component of the total on-road measurement was then quantified by subtracting the estimated background from the mean and median on-road concentration (per road class per lap). Differences between road

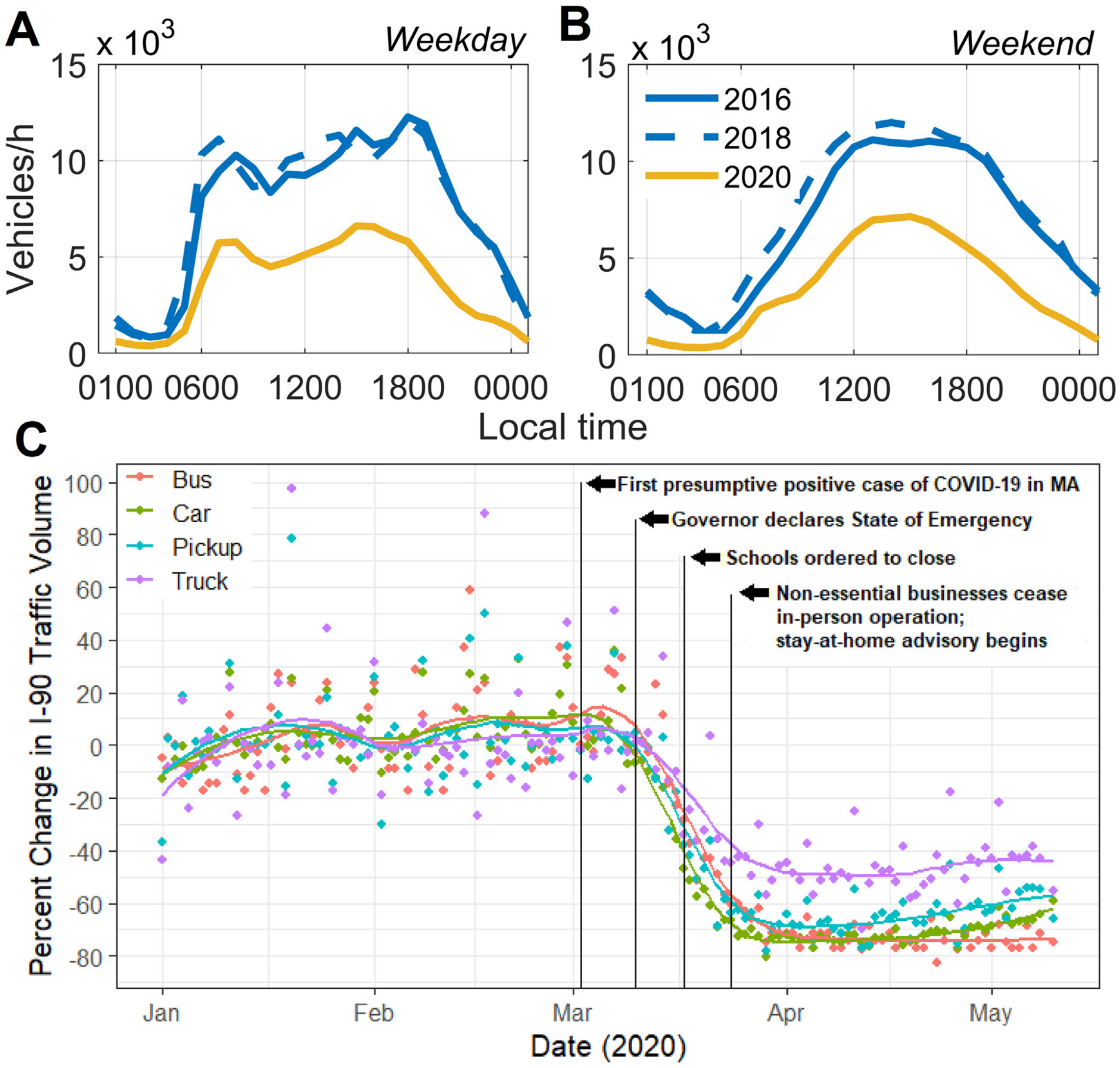


Fig. 2. (A)-(B): Diurnal traffic volume (vehicles/h) on (A) weekdays and (B) weekends on I-93 in Somerville between March 24 and May 14 for two years preceding the pandemic (2016 and 2018) and 2020, the year of the pandemic. See Fig. A1 for location of traffic counters. (C) Percent change in daily median traffic volume (relative to median January 2020 weekday and weekend/holiday traffic volumes) on I-90 near downtown Boston between January 1 and May 10, 2020 for four vehicle types. Solid lines represent loess (local regression) fit trend lines.

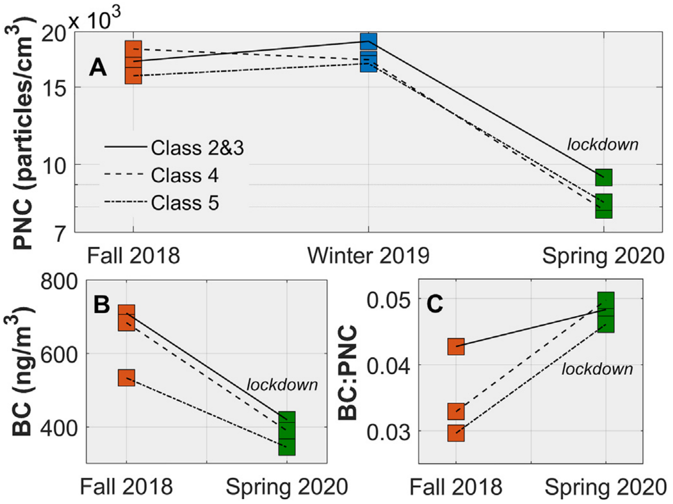


Fig. 3. Seasonal medians for (A) PNC, (B) BC, and (C) concentration ratios (BC [ng/m^3]:PNC [particles/cm^3]) for different roadway classes in the study area. Each colored square represents the seasonal median of the median value of all measurements during a single lap of the monitoring route for each roadway class.

class and monitoring periods were tested using the non-parametric Wilcoxon rank sum test (significance threshold $p = 0.05$) because pollutant concentrations were not normally distributed.

3. Results and discussion

3.1. Reduction in traffic volume

During the lockdown, daily traffic on I-93 was on average 49% and 50% lower on weekdays and weekends, respectively, relative to the same period (March 24 to May 14) from the two most recent, pre-pandemic years with complete data: 2016 and 2018 (Fig. 2(A)). Years 2017 and 2019 are not plotted due to substantial data gaps in traffic counts. The diurnal traffic patterns on I-93 during lockdown were similar to the normal traffic period. Specifically, there were distinct morning and evening rush-hour periods on weekdays, and traffic was lightest between 0200 and 0400 h (Fig. 2(A)). During the lockdown period, peak hourly traffic on I-93 near Somerville was 660 vehicles/h, which was similar to that observed at midnight during pre-pandemic normal traffic conditions. Fleet composition data in Fig. 2(C) highlights the dramatic reduction in gasoline-vehicle traffic (i.e., passenger cars) during the lockdown compared to January–February 2020; daily median car traffic was 71% lower. In contrast, daily median truck (classified as vehicles with ≥6 wheels) traffic was only 46% lower.

3.2. Reduction in PNC and BC on urban roadways

3.2.1. On-road concentrations

Based on 15 days of mobile monitoring during the ~5 week lockdown period, we observed that PNC and BC concentrations on Somerville roadways were substantially lower during the lockdown compared to pre-pandemic, normal traffic conditions (Fig. 3A and B). Depending on road class, median PNC were 44–56% lower and median BC concentrations were 31–42% lower during the lockdown compared to normal traffic conditions in the fall of 2018 ($p < 0.001$ for all road classes for both pollutants) (Table 2).

Differences among road classes during the lockdown were modest. Median PNC during the lockdown were 9300, 7900 and 8200 particles/cm^3 for Class 2 & 3, 4 and 5 roadways, respectively, with no significant differences by class ($p > 0.05$). Median BC concentrations were 420, 390 and 340 ng/m^3 for Class 2 & 3, 4 and 5 roadways, respectively. Class 5 (residential roadways) were statistically-significantly lower than Class 2 & 3 (highways and ramps) ($p = 0.02$) (Fig. 3B; for data histograms see Appendix Section A3). But, as shown in Fig. 3, differences among road classes during normal conditions were also modest. For example, median PNC by road type during fall 2018 were 17,200, 18,300 and 15,900 particles/cm^3 for Class 2 & 3, 4 and 5 roadways, respectively; BC medians were 470, 450 and 440 ng/m^3 for Class 2 & 3, 4 and 5 roadways, respectively.

When data from individual laps of the monitoring route were compared, we observed spatial patterns consistent with the expectation of higher concentrations on busier roadways. Fig. 4 illustrates the spatial patterns for PNC and BC for a spring day during the lockdown and a fall day in 2018 that had comparable meteorology. The spatial patterns in

Table 2

Summary of concentrations during different monitoring campaigns and reduction in concentrations. For distributions see Figs. 5 and A8-A9. The median values of those distributions are summarized in this table except for the mean columns (which are means of means).

Campaign	Season	Road Class	PNC (particles/cm^3)					BC (ng/m^3)				
			Background	Total On-road		Traffic Contribution		Background	Total On-road		Traffic Contribution	
				Median	Mean	Median - Background	Mean - Background		Median	Mean	Median - Background	Mean - Background
Normal Conditions	Fall	2&3	10,200	16,700	25,600	6500	12,000	430	720	1040	280	430
	Fall	4	9900	18,100	26,200	6800	12,100	370	660	1150	260	420
	Fall	5	9600	15,200	20,400	5200	9100	300	490	850	180	320
	Winter	2&3	9700	19,200	29,700	7700	12,800					
	Winter	4	10,600	18,300	25,700	7100	11,900					
	Winter	5	10,400	15,400	22,900	5000	8200					
During Lockdown	Spring	2&3	5400	9300	16,300	2600	6400	190	420	610	210	290
	Spring	4	5700	7900	14,400	2200	5300	190	390	680	140	260
	Spring	5	5700	8200	12,200	2000	4500	190	340	520	140	240

Campaign	Compared to Season	Road Class	Reduction in PNC (particles/cm^3)					Reduction in BC (ng/m^3)				
			Background	Total On-road		Traffic Contribution		Background	Total On-road		Traffic Contribution	
				Median	Mean	Median - Background	Mean - Background		Median	Mean	Median - Background	Mean — Background
During lockdown Compared to Normal Conditions	Fall	2&3	47%	44%	36%	60%	47%	56%	42%	41%	25%	33%
	Fall	4	42%	56%	45%	68%	56%	49%	41%	41%	46%	38%
	Fall	5	41%	46%	40%	62%	51%	37%	31%	39%	22%	25%
	Winter	2&3	44%	52%	45%	66%	50%					
	Winter	4	46%	57%	44%	69%	55%					
	Winter	5	45%	47%	47%	60%	45%					

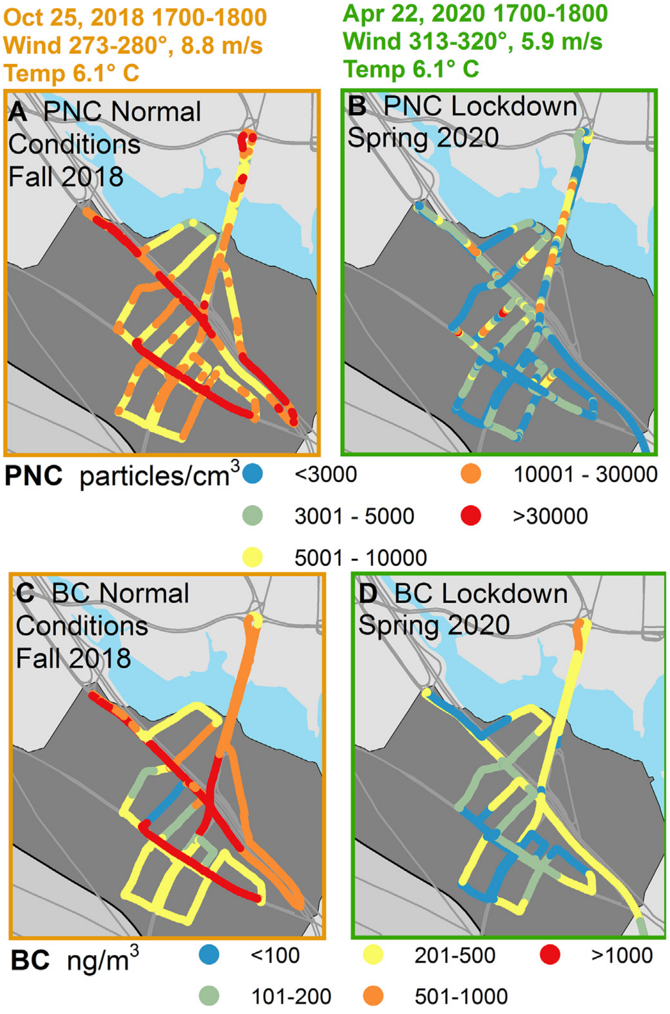


Fig. 4. Spatial distribution of PNC (A and B) and BC (C and D) during evening rush hour (~17:00–18:00) on a fall day during normal traffic conditions (October 25, 2018) and a spring day from the lockdown period (April 22, 2020). Days were selected for similar prevailing wind directions, wind speeds, and ambient temperatures.

pollutant concentrations were similar on both days with higher concentrations on state routes and major arterials than on local roads; however, on the lockdown day the concentrations were as much as an order of magnitude lower for both PNC and BC on these roads compared the pre-pandemic day. This comparison highlights the need to examine pollution gradients at fine spatial and temporal resolution rather than comparing bulk statistics where fine-scale differences are lost (e.g., Fig. 3 compared to Fig. 4).

Interestingly, despite the lower concentrations for both BC and PNC during the lockdown, we observed a higher BC:PNC ratio compared to the previous fall (Fig. 3(C)), perhaps indicative of the higher fraction of diesel vehicles in the fleet due to lesser reductions in truck traffic during the lockdown (see Fig. 2). Fleet distribution data on arterial roadways was not available, but field observations indicated a higher fractional presence of diesel-powered vehicles such as pick-up trucks and cargo vans. Further, essential services such as consumable goods deliveries and garbage collection, which use diesel vehicles, were operational during the lockdown. Compared to pre-lockdown conditions, the BC:PNC ratio was 13% higher during the lockdown for Class 2 & 3 roadways where most of the trucking activity typically occurred (Fig. 3(C)), but 56% higher for Class 5 streets during the lockdown (likely due to a steeper reduction in gasoline-powered passenger cars relative to diesel trucks on residential streets). The Class 4 trend was similar to that for Class 5.

3.2.2. Contributions from local traffic

Consistent with the reductions in traffic volume, PNC and BC contributions from traffic were also greatly reduced. Depending on the statistic used for quantification, the magnitude chosen for quantification (Table 2), which is generally in line with the 50–70% reduction in car traffic and 40% reduction in truck traffic observed in the area. Based on Fig. 5, which shows the distributions of traffic contributions during the lockdown period compared to pre-pandemic conditions for three road classes, we make the following observations. First, the traffic contribution to on-road pollutant concentrations were comparable in pre-pandemic (normal traffic conditions) datasets from fall and winter of the preceding years. Second, in comparison to normal traffic conditions, the reductions during the lockdown period were greater for PNC than BC. This is possibly due to lesser reductions in diesel vehicles (which are higher emitters of BC) during the lockdown period relative to gasoline vehicles. Third, in comparison to the scales of pollutant reductions themselves, the reductions by road class were modest for PNC (62–68% and 60–69% lower compared to fall and winter, respectively, for all three road class types), while for BC there was more variance by road class and reductions ranged from 22 to 46%.

It is also worth noting that PNC and BC background concentrations were substantially lower during the lockdown compared to normal conditions. Background concentration distributions are shown in Figs. A8–A9 and medians of those distributions are presented in Table 2. During the lockdown period the local background was at least 40% lower than during the fall of 2018 and winter of 2019. This is partly due to seasonal effects but more significantly because all other sources (e.g., local industry, long-range transport) were lower, which resulted in overall improved regional air quality. The local background was not found to vary by road class types.

3.3. Differences in PNC on Interstate highway (I-93) during lockdown versus normal traffic conditions

We also compared measurements from 196 runs of the 3-km-long, I-93 monitoring route made during the lockdown period with 39 runs of the same route from March to May in 2012 and 2013 to illustrate the contrast between lockdown and pre-pandemic normal traffic conditions. During lockdown, traffic was 41% lower (5200 vs 8800 vehicles/h) on I-93 and the median PNC was 60% lower (16,000 vs 40,000 particles/cm^3) relative to the 2012 and 2013 data (Fig. 6). Although emission factors for vehicles have decreased over the last decade, (BTS, 2018), the scale of difference we observed far exceeds the documented changes in PNC emission factors for vehicles. We also observed that there was substantial scatter in the PNC vs. traffic volume data, indicating that other factors (e.g., wind speed and direction, atmospheric mixing height, fleet composition and speed, proximity of the monitoring platform to super-emitting vehicles) also influenced PNC (Patton et al., 2014b). Due to a lack of traffic congestion on I-93 during the lockdown period, the average highway travel speed was higher. In our previous work in Somerville, we found that PNC was about 10,000 particles/cm^3 lower during low traffic versus congested traffic conditions (Patton et al., 2014b).

3.4. Trends at regulatory sites

Regulatory sites in Boston generally corroborate the on-road pollutant concentration reductions we observed, but the extent of the reductions varied by pollutant and site. At two of the regulatory monitoring sites - the near-I-93 site and the urban background site - BC concentrations were 51% lower, NO$_2$ concentrations were 30% and 47% lower, respectively, but PM$_{2.5}$ concentrations were 9% and 52% lower, respectively, during the lockdown period compared to the previous five-year averages for the same period (March 24–May 15, 2015 to 2019) (Fig. 7 and A10). Both BC and NO$_2$ (but not PM$_{2.5}$) concentrations in urban areas are highly impacted by traffic emissions, and the

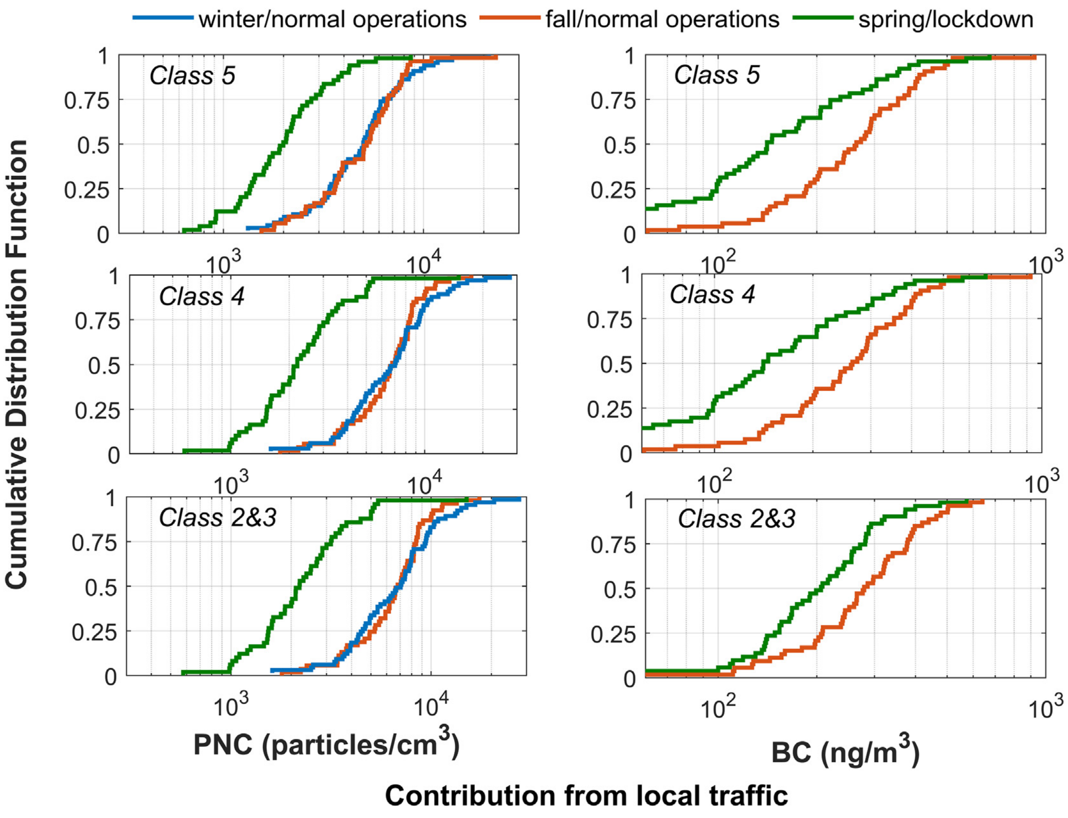


Fig. 5. Empirical cumulative distributions for the contribution of traffic emissions to total on-road concentrations (i.e., 50th - 5th percentile concentrations per road class per monitoring lap) during the lockdown period (spring 2020) compared to normal traffic conditions (fall 2018 and winter 2019) for PNC and BC by road class.

reductions in BC and NO_2 concentrations in Boston were commensurate with the reduction in traffic volumes in the area. These trends are consistent with Bekbulat et al. (2020) who observed that during the lockdown periods in Los Angeles, New York and Seattle reductions in NO_2 were about 30% while changes in $PM_{2.5}$ were inconsistent. Similarly, several other studies around the world have reported that reductions in NO_2 were larger or more consistent than those for $PM_{2.5}$ during lockdown periods (Mahato et al., 2020; Tobías et al., 2020; Department for Environment Food and Rural Affairs, n.d.).

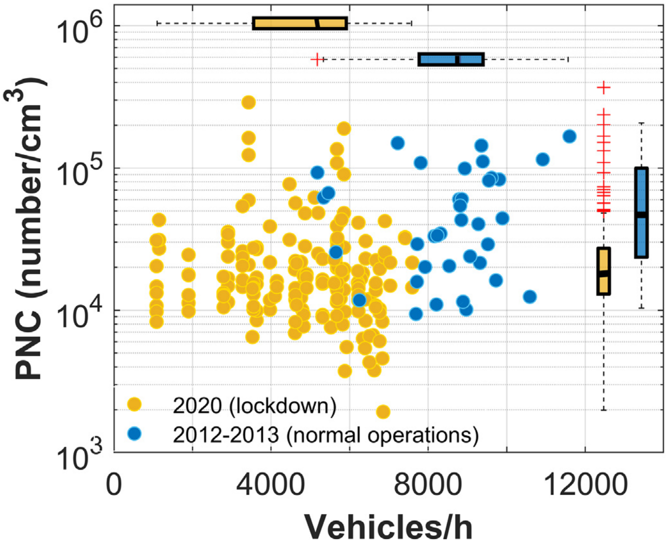


Fig. 6. Traffic volume versus PNC on I-93 before and during the lockdown period. Each data point represents the median of 1-s PNC measurements for a one-way, 3-km run of I-93 plotted against total traffic in both directions during the 1-h period overlapping the run. Boxplots highlight PNC (right) and traffic volume (top) for all data within the 2012–2013 and 2020 comparison groups. The median is shown as a thick black line in each box; the interquartile range (IQR) extends from 25th to 75th percentile; whiskers extend up to 1.5 times the IQR. Values beyond the whiskers are shown with red plus signs.

3.5. General discussion

Our results demonstrate that significant improvements in neighborhood-scale air quality can be achieved by reducing overall traffic emissions. During the lockdown period, PNC and BC spatial patterns were similar to pre-pandemic spatial patterns (i.e., generally higher on major roadways and lower concentrations in more residential areas), but the concentrations were up to an order of magnitude lower throughout the study area during the lockdown period when comparing individual runs with similar meteorology. Overall, total on-road concentrations, contributions from traffic, and local background concentrations were lower for both PNC and BC. Although we did not have street-level traffic estimates for Somerville, we did see comparable reductions in both the on-road measurements of PNC and BC and traffic volumes estimated at the nearest counters on I-93. Similarly, we also observed substantial reductions in background PNC and BC, which further suggests that these two pollutants were useful markers of traffic emissions, and that traffic was the dominant pollutant source in our study area.

Reductions in the concentrations of BC and NO_2 were also recorded at Boston-area regulatory monitoring sites during the lockdown period. The reductions in BC and NO_2 concentrations (51% and 30–47%, respectively) were consistent with our on-road measurements and were comparable in scale to the reduction in traffic, suggesting that BC and even NO_2 in urban environments could be useful for tracking traffic-related air quality impacts in areas where traffic is a dominant source of pollution. Nonetheless, because BC is unregulated in the US and there are relatively few near-road

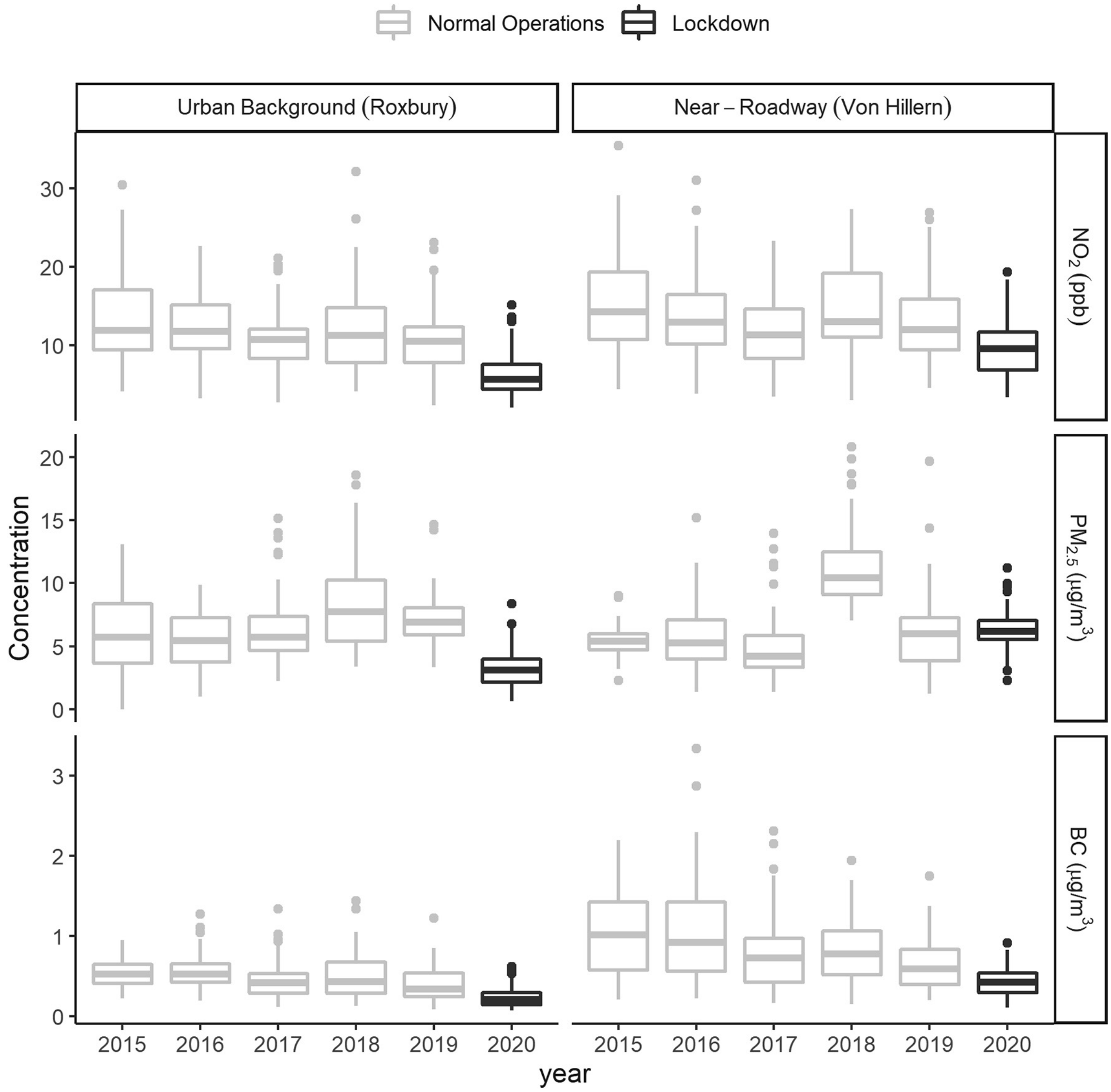


Fig. 7. Tukey box plots of daily measurements (March 24–May 15) of BC, NO_2, and $PM_{2.5}$ for each of six years at two regulatory monitoring sites in Boston. Black boxes represent the lockdown period. All boxes represent the interquartile range from the 25th to 75th percentiles, whiskers represent the 5th and 95th percentiles and outliers are shown as dots beyond the whiskers.

network sites, the regulatory network cannot be a substitute for dedicated campaigns that focus on traffic-related air pollutants (such as BC and UFP) and that provide measurements at spatial scales relevant to traffic emissions tracking. A continuing campaign of measurements and subsequent analysis during the economic ramp-up phase - where traffic increases continually until a return to pre-pandemic volumes - can aid further quantification. It would also be interesting to compare larger on-road measurement datasets to regulatory sites and assess if there is parity in quantification achieved via these different air quality monitoring approaches. Our results – and those of other studies that have examined different regulatory pollutants but have found inconsistent changes across pollutants – suggest that caution is warranted in reporting air quality changes due to traffic reductions based only on regulated pollutants like $PM_{2.5}$ and ozone. Although data for these regulated pollutants are readily available from regulatory networks, $PM_{2.5}$ and ozone are highly influenced by meteorology and long-range transport, and atmospheric transformation processes, and are therefore not an appropriate proxy for local traffic emissions.

Our study had two main limitations. First, as is often the case for natural experiments or opportunistic studies, we were not able to fully match the season during the lockdown period with datasets from the same season predating the lockdown; therefore, we compared spring 2020 data to another transition season (fall). The trends observed in several of our previous measurements campaigns – extending back a decade (Padró-Martínez et al., 2012; Patton et al., 2014a; Perkins et al., 2013; Simon et al., 2017) – provide a basis for this approach. The lower concentrations we observed during lockdown/spring 2020 were in contrast to our previous works (Padró-Martínez et al., 2012; Patton et al., 2014a; Perkins et al., 2013; Simon et al., 2017) in which PNC during the transition seasons, i.e., spring and fall were found to be comparable to each other. Further spring time observations in pre-pandemic years were much higher than those during lockdown or spring 2020 (see Fig. A4a,b). For example, in measurements made in Somerville from 2009 to 2010 on a nearly identical mobile-monitoring route to the one used in the current study, Padró-Martínez et al. reported higher PNC in spring than in fall; further, springtime median PNC ranged from 37,000 particles/cm^3 in Somerville neighborhoods closest to I-93 (<50 m) down to 18,000 particles/cm^3 in neighborhoods 1–2 km from the highway. We controlled for seasonal variation in the background when quantifying the contributions from local traffic, which helped to reduce error possibly introduced by inter-seasonal comparisons. Second, traffic counts were only available for interstate highways and not local streets. Further information on street-level changes in mobility coupled with factors that influence emissions, such as vehicle fleet age distribution and vehicle type prevalence (gasoline vs. diesel vehicles), could have significantly improved air quality data interpretation. Data from I-90 in Boston and our own observations indicates a steeper decline in passenger cars than trucks. In future studies, automated analysis of vehicle class and age (e.g., based on license plates or camera images) could be useful.

Our results can inform air-quality management for near-highway communities. Specifically, these findings document how reductions in the volume of fossil-fuel-burning vehicles leads to improved air quality at the neighborhood scale. Long-term improvements could be achieved by shifts in transportation modes (e.g., more public transportation, more bicycles) or by changes in traffic composition (e.g., more electric or hybrid-engine vehicles (but this would not address non tail-pipe particulate emissions such as brake wear and tire wear). The challenge for air quality managers is to develop policy and incentives to reduce the use of fossil-fuel-burning vehicles in urban areas. In addition, our results could be useful for epidemiological analyses of short-term changes in air pollution exposures and health effects.

4. Conclusions

The steep reductions in traffic emissions during the COVID-19 lockdown period resulted in lower on-road concentrations of traffic-related air pollutants – specifically, black carbon and particle number concentrations, thereby improving air quality in an urban neighborhood highly impacted by traffic emissions.

CRediT authorship contribution statement

Neelakshi Hudda: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition, Project administration. **Matthew C. Simon:** Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **Allison P. Patton:** Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **John L. Durant:** Methodology, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the City of Somerville, MA, USA. NH acknowledges support from NIEHS (R01-ES026980). JLD acknowledges support from the Department of Civil and Environmental Engineering at Tufts University. MCS acknowledges support from the Volpe Center. The contents of this article do not necessarily reflect the views of HEI or Volpe, or its sponsors, nor do they necessarily reflect the views and policies of the EPA or motor vehicle and engine manufacturers. We thank Leslie Collyer at Massachusetts Department of Environmental Protection for providing BC data at regulatory sites and Wig Zamore of Somerville Transportation Equity Partnership for consultations and for the photographs used in graphic abstract. We also thank Jack Bitney, Richard Gilland and Elizabeth White (Tufts CEE-Class of 2019) for assistance with field monitoring, and Liza Samy (Tufts CEE-Class of 2017) and Christopher S Barnett (Senior Geospatial Analyst, Tufts Data Lab) for assistance with processing of 2018-2019 campaign data.

Appendix A. Supplementary data

The Appendix contains the monitoring schedule with summary of meteorological parameters and concentrations for individual monitoring days, a map of traffic monitoring stations, discussion of instruments, data histograms and distributions, and information on and graphics for the trends at regulatory sites. Supplementary data to this article can be found online at doi: https://doi.org/10.1016/j.scitotenv.2020.140931.

References

Bao, R., Zhang, A., 2020. Does lockdown reduce air pollution? Evidence from 44 cities in northern China. Sci. Total Environ. 731, 139052. https://doi.org/10.1016/j.scitotenv.2020.139052.

Bekbulat, B., Apte, J.S., Millet, D.B., Robinson, A.L., Wells, K.C., Marshall, J.D., 2020. PM 2.5 and ozone air pollution levels have not dropped consistently across the US following societal covid response https://doi.org/https://chemrxiv.org/s/3299fafedd485e00c885.

Bureau of Transportation Statistics (BTS), 2018. Estimated U.S. Average Vehicle Emissions Rates per Vehicle by Vehicle Type Using Gasoline and Diesel [WWW Document]. Natl. Transp. Stathttps://www.bts.gov/content/estimated-national-average-vehicle-emissions-rates-vehicle-vehicle-type-using-gasoline-and. (Accessed 19 June 2020).

City of Somerville Office of Strategic Planning and Community Development (OSPCD), 2011. Trends in Somerville: Land Use Technical Report [WWW Document]. somervision2040.com. http://www.somervision2040.com/wp-content/uploads/sites/3/2018/11/LandUseTrendsReportFinalMay2011.pdf. (Accessed 31 May 2020).

Dantas, G., Siciliano, B., França, B.B., da Silva, C.M., Arbilla, G., 2020. The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. Sci. Total Environ. 729, 139085. https://doi.org/10.1016/j.scitotenv.2020.139085.

Department for Environment Food & Rural Affairs, 2020. Report: Estimation of changes in air pollution emissions, concentrations and exposure during the COVID-19 outbreak in the UK - Defra, UK [WWW Document]. https://uk-air.defra.gov.uk/library/reports.php?report_id=1005. (Accessed 4 July 2020).

Governor Charlie Baker Orders All Non-Essential Businesses To Cease In Person Operation, 2020. Directs the Department of Public Health to Issue Stay at Home Advisory For Two Weeks [WWW Document]. mass.govhttps://www.mass.gov/news/governor-charlie-baker-orders-all-non-essential-businesses-to-cease-in-person-operation. (Accessed 1 June 2020).

Hudda, N., Fruin, S., Delfino, R.J., Sioutas, C., 2013. Efficient determination of vehicle emission factors by fuel use category using on-road measurements: Downward trends on Los Angeles freight corridor I-710. Atmos. Chem. Phys. 13, 347–357. https://doi.org/10.5194/acp-13-347-2013.

Hudda, N., Gould, T., Hartin, K., Larson, T.V., Fruin, S.A., 2014. Emissions from an international airport increase particle number concentrations 4-fold at 10 km downwind. Environ. Sci. Technol. 48, 6628–6635. https://doi.org/10.1021/es5001566.

Kerimray, A., Baimatova, N., Ibragimova, O.P., Bukenov, B., Kenessov, B., Plotitsyn, P., Karaca, F., 2020. Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in Almaty, Kazakhstan. Sci. Total Environ. 730. https://doi.org/10.1016/j.scitotenv.2020.139179.

Mahato, S., Pal, S., Ghosh, K.G., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Sci. Total Environ. 730, 139086. https://doi.org/10.1016/j.scitotenv.2020.139086.

MassDEP, 2019. MassDEP Ambient Air Quality Monitoring Network & Annual Plan | Mass.gov.

MassGIS, 2018a. MassGIS Data: Massachusetts Department of Transportation (MassDOT) Roads [WWW Document]. https://docs.digital.mass.gov/dataset/massgis-data-massachusetts-department-transportation-massdot-roads#Attributes.

MassGIS, 2018b. Massachusetts Document Repository [WWW Document]. https://docs.digital.mass.gov/dataset/massgis-data-massachusetts-department-transportation-massdot-roads. (Accessed 4 June 2020).

Nakada, L.Y.K., Urban, R.C., 2020. COVID-19 pandemic: Impacts on the air quality during the partial lockdown in São Paulo state, Brazil. Sci. Total Environ. 730, 139087. https://doi.org/10.1016/j.scitotenv.2020.139087.

NOAA NCEI, 2020. Automated Surface Observing System (ASOS) [WWW Document]. https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/automated-surface-observing-system-asos. (Accessed 30 September 2019).

Padró-Martínez, L.T., Patton, A.P., Trull, J.B., Zamore, W., Brugge, D., Durant, J.L., 2012. Mobile monitoring of particle number concentration and other traffic-related air pollutants in a near-highway neighborhood over the course of a year. Atmos. Chem. Phys. 61, 253–264.

Patton, A.P., Collins, C., Naumova, E.N., Zamore, W., Brugge, D., Durant, J.L., 2014. An Hourly Regression Model for Ultra fi ne Particles in a Near- Highway Urban Area. Environ. Sci. Technol. 48, 1–16. https://doi.org/10.1021/es404838k.

Patton, A.P., Perkins, J., Zamore, W., Levy, J.I., Brugge, D., Durant, J.L., 2014. Spatial and temporal differences in traffic-related air pollution in three urban neighborhoods near an interstate highway. Atmos. Environ. 99, 309–321. https://doi.org/10.1016/j.atmosenv.2014.09.072.

Perkins, J.L., Padró-Martínez, L.T., Durant, J.L., 2013. Particle number emission factors for an urban highway tunnel. Atmos. Environ. 74, 326–337. https://doi.org/10.1016/j.atmosenv.2013.03.046.

Sharma, S., Zhang, M., Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions during COVID-19 on air quality in India. Sci. Total Environ. 728, 138878. https://doi.org/10.1016/j.scitotenv.2020.138878.

Simon, M.C., Hudda, N., Naumova, E.N., Levy, J.I., Brugge, D., Durant, J.L., 2017. Comparisons of traffic-related ultrafine particle number concentrations measured in two urban areas by central, residential, and mobile monitoring. Atmos. Environ. 169. https://doi.org/10.1016/j.atmosenv.2017.09.003.

Simon, M.C., Naumova, E.N., Levy, J.I., Brugge, D., Durant, J.L., 2020. Ultrafine Particle Number Concentration Model for Estimating Retrospective and Prospective Long-Term Ambient Exposures in Urban Neighborhoods. Environ. Sci. Technol. 54, 1677–1686. https://doi.org/10.1021/acs.est.9b03369.

Simon, M.C., Patton, A.P., Naumova, E.N., Levy, J.I., Kumar, P., Brugge, D., Durant, J.L., 2018. Combining Measurements from Mobile Monitoring and a Reference Site To Develop Models of Ambient Ultrafine Particle Number Concentration at Residences. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.8b00292.

Tobías, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M.C., Alastuey, A., Querol, X., 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci. Total Environ. 726, 138540. https://doi.org/10.1016/j.scitotenv.2020.138540.

Transportation Data Management System, 2020. [WWW Document]. https://mhd.ms2soft.com/tcds/tsearch.asp?loc=Mhd&mod=TCDS. (Accessed 1 June 2020).

U.S. Census Bureau, 2019. QuickFacts: Massachusetts [WWW Document]. https://www.census.gov/quickfacts/fact/table/somervillecitymassachusetts,MA/PST045219. (Accessed 15 June 2020).

US EPA, 2014. National Emissions Inventory Report [WWW Document]. https://gispub.epa.gov/neireport/2014/. (Accessed 25 May 2020).

US EPA OECA, 2019. EJSCREEN: Environmental Justice Screening and Mapping Tool [WWW Document]. https://www.epa.gov/ejscreen. (Accessed 25 May 2020).

Wang, Pengfei, Chen, K., Zhu, S., Wang, Peng, Zhang, H., 2020. Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak. Resour. Conserv. Recycl. 158, 104814. https://doi.org/10.1016/j.resconrec.2020.104814.

William Kuttner, C., 2020. Traffic Volumes | Boston Region MPO [WWW Document]. https://www.ctps.org/subjects/traffic-volumes. (Accessed 10 March 2020).