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QUANTIFYING THE IMPACT OF COVID-19 RESTRICTIONS ON EMISSIONS USING INVERSE MODELLING AND MEASUREMENTS

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Abstract: An inversion system that uses a Bayesian approach to combine measurements and ADMS-Urban modelled data by adjusting individual source emissions, subject to estimated uncertainty in the measurements and emissions, has previously been applied to optimising road traffic emissions in Cambridge. In this study the system has been applied specifically to the impact of interventions, in particular the impact of COVID-19 lockdowns on NO_X emissions from road traffic and other sources in London.

The ADMS-Urban model was used to calculate *a priori* hourly NO_X concentrations at 195 receptors in London representing 115 reference monitors and 80 Breathe London Network AQMesh sensors. Input data included hourly meteorological measurements from Heathrow Airport, hourly NO_X concentrations from 4 rural background monitoring sites and buildings road centreline data from Ordnance Survey. *A priori* emissions were obtained from the London Atmospheric Emissions Inventory (LAEI) for 35 point sources, approximately 70,000 major road sources and 2,500 1km grid cells representing minor road, heating and other sources. The analysis period was 1 January 2020 to 30 April 2021. Estimated uncertainties of 4 and 12 $\mu g/m^3$ were applied to reference and sensor measurements respectively, while emissions uncertainties of 100%, 50%, 20% were applied to road traffic, fuels and other emissions respectively. Road traffic emissions were assumed to have error covariance of 40% of their emissions uncertainty.

Measured NO_X concentrations in London reduced significantly during lockdown, with the greatest reduction (around 60%) at kerbside and roadside sites in Central London. However, poor dispersal conditions led to increased concentrations at times when restrictions were tightest. In contrast, inversion system results demonstrate that NO_X emissions from road traffic dropped by around 60% in London compared with pre-lockdown levels and that this reduction occurred when the strictest lockdown measures were in force. The results also show that NO_X road traffic emissions were still approximately 30% lower than pre-lockdown levels at the end of April 2021. This analysis demonstrates that lower cost sensors such as AQMesh can provide valuable insight into the effects of policy measures (in this case lockdown restrictions), if their increased uncertainty compared with reference monitors is accounted for.

Key words: *COVID-19, ADMS-Urban, lockdown,* NO_X*, inversion*

INTRODUCTION

Dramatic changes in transport patterns occurred in London during March 2020 caused by movement restrictions (known as "lockdowns") imposed by the UK Government to limit the spread of the COVID-19 virus (DfT, 2021). These changes caused unprecedented changes in road traffic emissions compared with standard emissions inventories. Emissions inventories based on road traffic activity data take time to collate, but estimates of lockdown-induced emissions changes were needed on shorter timescales, for example for air quality forecasting. This presents a unique and valuable opportunity to analyse and understand the effects on emissions and air quality of a massive step-change in transport activity.

BACKGROUND

The first lockdown restrictions in London were implemented on 17 March 2020: people were asked to socially distance from others and avoid unnecessary travel. The first full lockdown came into force on 24 March: people were only allowed to leave their homes for limited reasons and schools were closed except for the children of keyworkers. From 10 May, people were allowed outside for unlimited exercise. From 15 June all shops were allowed to open, but restrictions on social gatherings remained. On 17 October additional measures were implemented in London: different households were not allowed to mix indoors. On 5 November a second national lockdown was enforced: people were asked to stay at home wherever possible but schools remained open. That lockdown ended on 6 December 2020, but on 6 January 2021 England entered its third full lockdown, with schools again closed for most children. Schools re-opened on 8 March 2021 and restrictions gradually eased through the spring and summer of 2021.

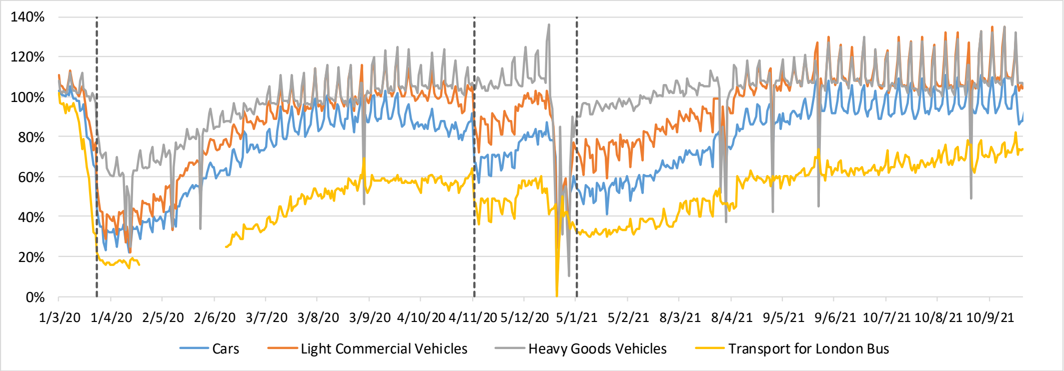

Figure 1. UK Government data (DfT, 2021) on the use of different transport modes in England, Scotland and Wales, as a percentage change compared with the equivalent day in the first week of February 2020. Transport for London (TfL) bus data is London-specific and compared with the equivalent day in 2019. Large discontinuities in HGV activity are due to bank holidays, smaller discontinuities are weekday/weekend differences. TfL bus data from April to June 2020 is missing because no payment was required; no payment means no data.

Government data on the use of different transport modes (Figure 1) shows some reduction across all modes in advance of the March lockdown; a dramatic reduction on 24 March; gradual increases to near-normal levels for HGVs and LGVs by mid-July 2020; and car use did not reach pre-pandemic levels until June 2021. Car use was less than 40% of pre-lockdown levels in lockdown 1, 70% in lockdown 2 and 50% in lockdown 3. TfL bus trips were still at 70% of pre-pandemic levels at the end of September 2021.

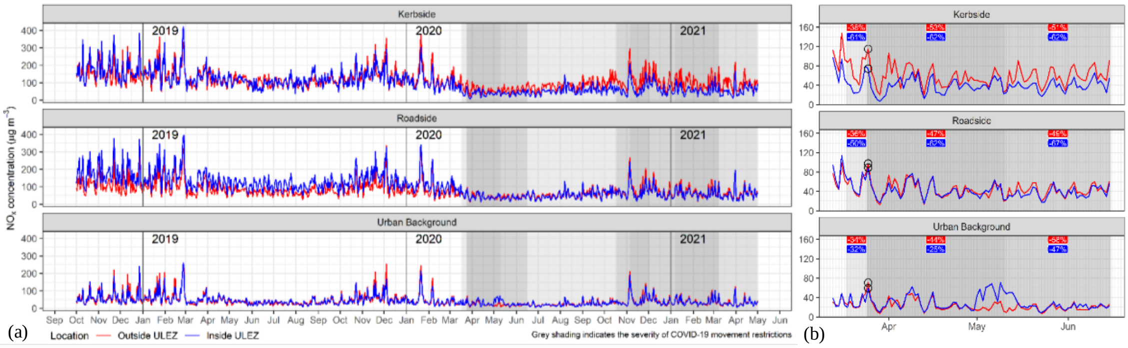

Figure 2. Mean daily mean NO$_X$ concentration over 151 reference monitors, by site type and location with respect to the central London Ultra Low Emissions Zone (ULEZ). The darkness of the grey shading indicates the severity of the lockdown restrictions. (a) 1 October 2018 to 30 April 2021; (b) 12 March to 15 June 2020. The labels give the mean concentration for that period as a percentage change from the mean concentration for 1 January to 16 March 2020.

Measured NO$_X$ concentrations in London reduced significantly during lockdown, with the greatest reduction (around 60%) at kerbside / roadside sites in Central London (Figure 2). However, poor dispersal conditions led to increased concentrations at times when restrictions were tightest. At roadside and urban background sites during lockdown 1 (Figure 2b), measured concentrations were highest on 25 March. For these sites, the reduction in concentration was greater *after* the restrictions began to be lifted from 10 May than when London was under the most severe restrictions (24 March to 9 May).

METHODOLOGY

CERC have developed a data assimilation scheme that applies a Bayesian inversion technique to a high resolution (street-level) atmospheric dispersion model to modify pollution emission rates based on local measurements (Carruthers *et al*., 2020). This scheme has been applied to investigate changes in NO_X emissions from traffic in London during the period from 1 January 2020 to 30 April 2021, as part of the Breathe London Pilot Project. This project installed 100 AQMesh sensors at sites across London to measure NO_X, NO_2, $PM_{2.5}$ and CO_2; two Google cars collected reference-standard mobile measurements at 1-second resolution for one year; and CERC carried out high resolution dispersion modelling and source apportionment modelling using the ADMS-Urban model (Stocker *et. al*., 2012). The 2-year pilot project concluded in November 2020; the static sensors were maintained until the end of April 2021 to capture what was expected to be the 'covid-recovery period'.

ADMS-Urban is a comprehensive system (Stocker *et. al*., 2012) that is widely used for modelling air quality in large urban areas, cities and towns. It is a practical urban air quality model which explicitly represents the full range of source types occurring in an urban area, takes account of complex urban morphology including street canyons, and provides output of short and long term average pollutant concentrations from street-scale to urban-scale. ADMS-Urban was used to calculate *a priori* hourly NO_X concentrations at 195 receptors in London representing 115 reference monitors and 80 Breathe London Network AQMesh sensors. Input data included hourly meteorological measurements from Heathrow Airport, hourly NO_X concentrations from 4 rural background monitoring sites and buildings road centreline data from Ordnance Survey. *A priori* emissions were obtained from the 2013 edition of the London Atmospheric Emissions Inventory (LAEI) (published in 2016) interpolated to 2019 and road traffic emissions calculated using emission factors for 2019 from EFT version 8.0, including adjustments for real-world conditions (Carslaw and Rhys-Tyler, 2013). Modelled sources include 35 point sources, approximately 70,000 major road sources and 2,500 1km grid cells representing minor road, heating and other sources.

The CERC Inversion System (Figure 3) optimises modelled concentrations in relation to monitored data by adjusting the emissions data that are used to calculate the modelled concentrations, taking into account the known (or estimated) uncertainty in both the *a priori* emissions data and the monitored data. The results are adjusted modelled concentrations for every modelled receptor and associated adjusted emissions for every source, for every hour modelled. Estimated uncertainties of 4 and 12 $\mu g/m^3$ were applied to reference and sensor measurements respectively, while emissions uncertainties of 100%, 50%, 20% were applied to road traffic, fuels and other emissions respectively. Road traffic emissions were assumed to have error covariance of 40% of their emissions uncertainty related, for example, to common emission factors.

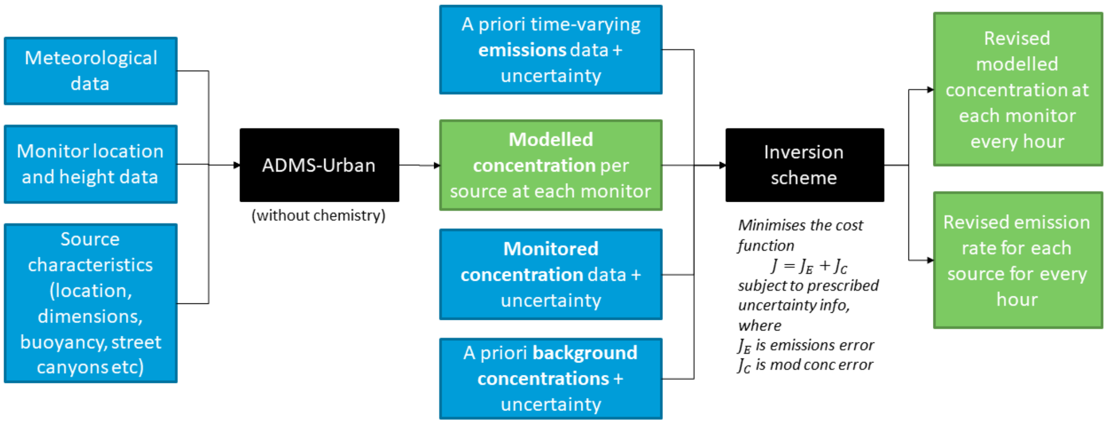

Figure 3. Schematic of the CERC Inversion System. Blue represents a non-calculated dataset, green represents a calculated dataset and black represents a process.

RESULTS

Figure 4 compares modelled and observed NO_X concentration results from January 2020 to April 2021. The *a posteriori* modelled values and observed values for reference sites are almost indistinguishable, confirming that the Inversion System is working as expected; it has, to a large extent, corrected the *a priori* model error. Higher measurement uncertainty was attributed to AQMesh measurements, so, as expected, there are greater differences between *a posteriori* modelled values and observed values at AQMesh sites. On 24 March the impact of the lockdown is clear: until 24 March, the *a priori* modelled values agreed well with measured values; a few days before 24 March the *a priori* modelled values began to diverge from the observed and *a posteriori* modelled values, meaning that emissions were beginning to diverge from the emissions inventory; and the peak on 25 March can be seen in both the *a priori* and *a posteriori* modelled values, suggesting that this was caused by poor dispersal conditions. The gap between *a priori* modelled values and observed values is greatest on 24 March, it reduces towards the end of the analysis period, but remains significant even in April 2021.

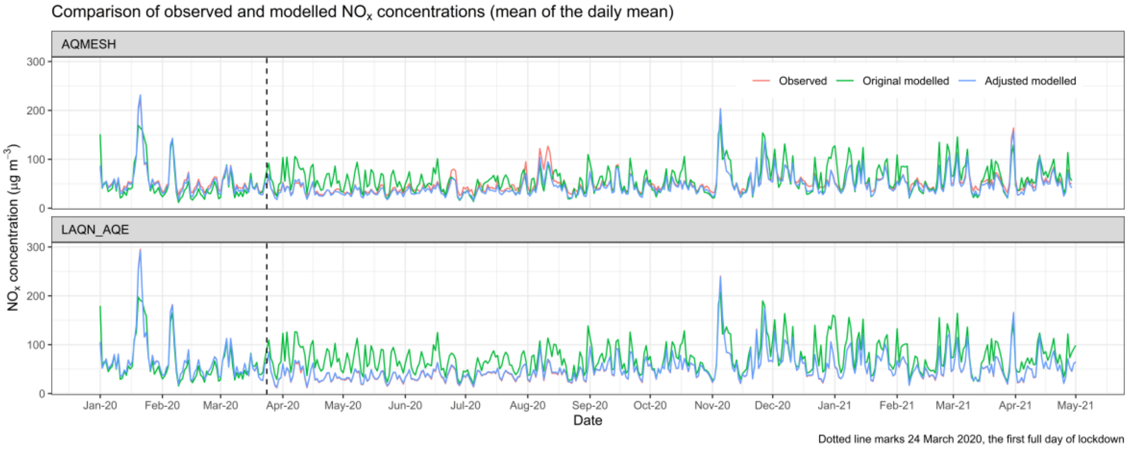

Figure 4. Comparison of observed and modelled NO_X concentrations, averaged over all stations and showsn as the mean of the daily mean values. Observed values are shown in orange; *a priori* ('original') modelled values in green; and *a posteriori* ('adjusted') modelled values in blue. The vertical dotted line marks 24 March 2020, the first full day of COVID-19 lockdown in London. The upper panel shows the results for AQMesh locations; the lower panel shows the results for reference-standard monitoring sites.

The Inversion System results (Figure 5) show that emissions changed more dramatically than concentrations on 24 March 2020, with approximately 60% emissions reduction in the first lockdown phase compared with pre-lockdown levels. Emissions gradually increased during summer and early autumn 2020 as restrictions were relaxed but by the end of April 2021 had not yet returned to normal. During the second full lockdown in November 2020 emissions were 30% lower than pre-lockdown levels, and in the third full lockdown in early 2021 emissions were around 40% lower than normal, according to these estimates.

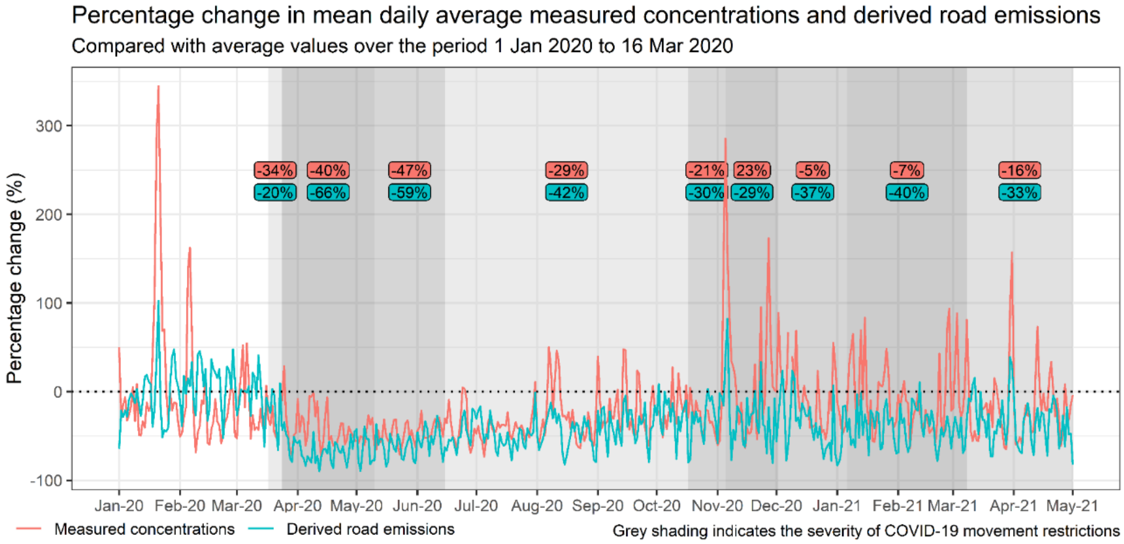

Figure 5. Comparison of the percentage change in emissions (blue) with the percentage change in measured concentrations, both in relation to pre-lockdown levels. The darkness of the grey shading indicates the severity of the lockdown restrictions. The labels give the average value over the relevant lockdown phase.

CONCLUSIONS

Bayesian-based inversion techniques combining high resolution modelling with measurements from reference-grade monitors and lower cost sensors suggest that London road traffic NO_X emissions reduced by around 60% compared with pre-lockdown levels immediately following the imposition of the COVID-19 lockdown on 24 March. The same analysis suggests that road traffic NO_X emissions remained around 30% lower than pre-lockdown levels at the end of the analysis period (30 April 2021). This demonstrates that lower cost sensors such as AQMesh can provide valuable insight into the effects of policy measures (in this case lockdown restrictions), if their increased uncertainty compared with reference monitors is accounted for.

ACKNOWLEDGMENTS

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