COMPARISON OF LINK-BASED AND SMOKE-PROCESSED MOTOR VEHICLE EMISSIONS OVER THE GREATER TORONTO AREA

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1. INTRODUCTION

Motor vehicle emissions contribute significantly to air pollution, especially in cities, where emissions from motor vehicles are usually the main precursors of smog. Mobile sources also emit some air toxics, which may have serious health effects. It is thus very important to characterize the spatial and temporal distribution of mobile source emissions when modelling local air quality and its effects on public health at a fine grid scale.

Typically, emissions values from an emissions inventory are disaggregated in space and time using spatial surrogates and pre-defined temporal profiles by emission processing software, such as SMOKE (Sparse Matrix Operator Kernel Emissions; http://www.smoke-model.org/index.cfm). However, the spatial surrogates and temporal profiles that are used may not represent the mobile source activities well, especially at high grid resolutions over cities. On the other hand, link-based emissions are estimated from traffic flow characteristics for each road segment and are usually deemed to be more representative of on-road mobile emissions. Significant differences have been found between the emissions processed by the traditional method and link-based method in a number of urban areas (e.g., Cook et al., 2008; Lindhjem et al., 2012; DenBleyker et al., 2012).

In this study, we compared motor vehicle emissions over the Greater Toronto Area (GTA, almost equivalent to the Toronto Census Metropolitan Area (CMA)) estimated from these two methods: (1) SMOKE-processed emissions based on a set of road-type-specific spatial surrogates and temporal profiles; (2) link-based emissions calculated by a traffic flow simulation software package from traffic flows and congested travel speeds on the road network within the study area. Based on the comparisons, issues with both the SMOKE-processed and link-based emissions will be discussed and possible improvements to SMOKE emissions processing will be investigated.

2. METHODOLOGY

2.1 SMOKE Mobile Emissions Processing

SMOKE was used to process on-road mobile emissions in a traditional top-down approach, in which the on-road monthly emissions inventory at a sub-provincial level (4 sub-regions for the province of Ontario) was spatially and temporally disaggregated to each model grid cell. Spatial disaggregation was performed by using a set of 6 gridded spatial surrogate fields generated from: (1) a newly compiled road network consisting of primary and secondary highways to represent emissions on major roads, and (2) population density to account for mobile emissions on small local roads. Temporal disaggregation was done by applying a set of weekly and diurnal temporal profiles developed for different road classes and vehicle types (Zhang et al., 2012). Chemical speciation of inventory pollutants to model species was based on chemical speciation profiles.

2.2 Link-based Mobile Emissions Processing

A link-based on-road mobile emissions inventory for the GTA was processed by a bottom-up method based on link-level activities and other parameters that can affect emissions, such as traffic volumes, road capacities, congested vehicle average speeds, vehicle type, fuel type, meteorology, and emission factors at various conditions. In this study, the emissions were

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generated by the Centre for Spatial Analysis (CSpA), McMaster University, based on an agreement between Environment Canada and McMaster University (Kanaroglou et al., 2009).

Emission factors from MOBILE6.2C, a Canadian version of the U.S. EPA MOBILE6.2 emissions factor model, were used to estimate on-road emissions under various conditions, such as vehicle type and age profile, road type, vehicle speed, fuel type, etc. The emission factors in MOBILE6.2C have been customized for the Canadian vehicle fleet and adjusted for roadway type, temperature, humidity, gasoline volatility, and gasoline and diesel sulfur content.

The traffic flow and congested travel speed on each road segment ("link") were estimated by a software package called "TRAFFIC", developed at CSpA. It requires a road network description with links and nodes and a set of origin-destination (O-D) matrices as inputs for the traffic simulation.

Toronto is the largest city in Canada, with a CMA population of 5.5 million based on Statistics Canada 2011 census data. It is located in southern Ontario on the northwestern shore of Lake Ontario as shown in Fig. 1. The road network in the GTA includes major highways that link to cities in the U.S. and in central and eastern Canada, and a dense arterial network (Fig. 2).

Fig. 1. Location of the GTA (from Google Maps).

The O-D matrices were based on a travel survey conducted within the study area in 2001 (Transportation Tomorrow Survey, http://www.jpint.utoronto.ca/ttshome). The 1,316 traffic assignment zones (TAZs) that were considered are shown in Figure 3. The resulting O-D trips were validated with actual traffic count data obtained from the city.

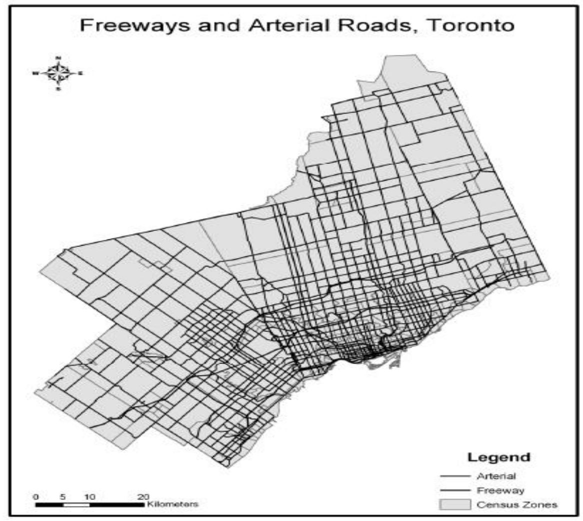


Fig. 2. Highways and arterial roads in the GTA (Fig. 2.1 in Kanaroglou et al., 2009).

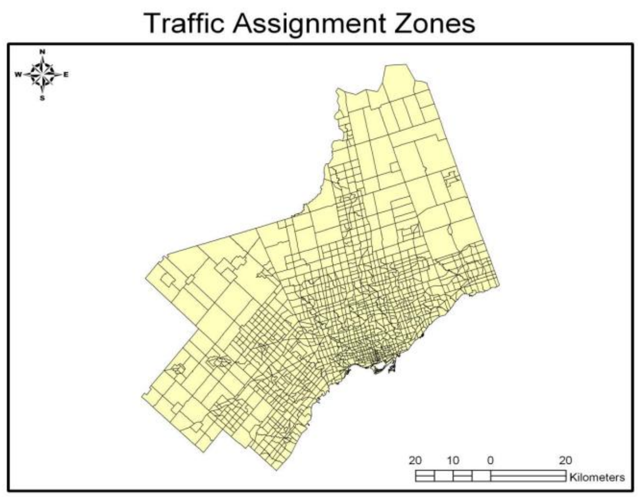


Fig. 3. Traffic Assignment Zones used for the travel survey to build the O-D matrices (Fig. 3.3 in Kanaroglou et al., 2009).

Traffic flows on weekdays and weekends were processed differently because the traffic volume on weekends is usually lower than on weekdays and the morning and afternoon peaks are usually not so obvious on weekends. Based on the estimated traffic flow and emission factors, hourly emissions were estimated for each road-network segments. The link-based emissions were then aggregated to an air quality model domain at 2.5-km resolution (Golder Associates Ltd., 2012) to compare with the emissions processed by SMOKE on the same model domain.

3. COMPARISONS AND DISCUSSION

SMOKE-processed and link-based NO and CO on-road emissions from a week in July 2006 were compared in this study in terms of weekly and diurnal variations and spatial distributions.

3.1 Comparison of Temporal Allocation

Time series of domain total CO and NO emissions from SMOKE- and link-based processing are compared in Figs. 4a and 4b.

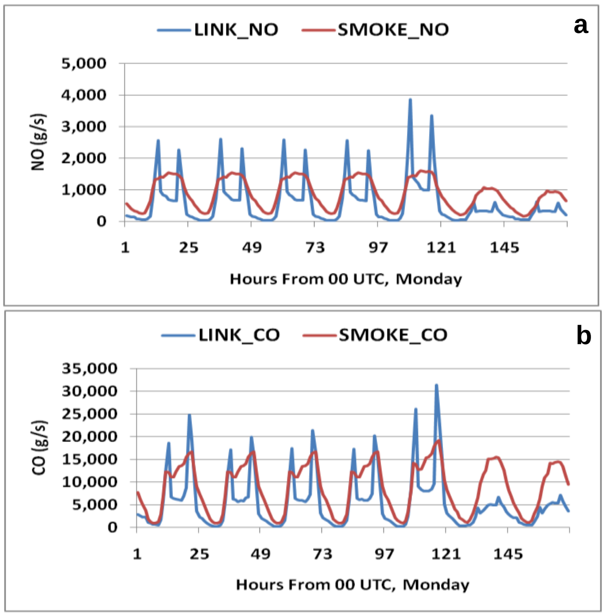


Fig. 4. Time series of domain total (a) NO and (b) CO emissions during a period of one week

Fig. 4 shows that, during weekdays, the link based emissions for the morning and afternoon rush hours are significantly larger than the rest of the day. At midday, both NO and CO emissions are only about one-third of the emissions during the rush hours. During weekends a rush-hour signature is still evident even though the total emissions are only about one-third of the weekday emissions. As well, NO emissions during the morning peak hours are slightly larger than the afternoon peak hours and NO emissions on Friday are larger than other weekdays. On the other hand, CO emissions during the morning peak hours are smaller than the afternoon peak hours and emissions on Friday are also larger than other weekdays.

There are some similarities between the SMOKE-processed and link-based emissions: the former also have larger weekday than weekend emissions (although the differences between weekdays and weekends are smaller), the CO emissions have peaks at the morning and afternoon rush hours, and the CO emissions during the afternoon rush hours are larger than the emissions in the morning rush hours. However, there are also significant differences between them. The largest difference is that the mid-day minimum does not exist in the SMOKE-processed emissions and therefore SMOKE-processed emissions are higher than the link-based emissions during the middle of the day. SMOKE-processed NO emissions also do not show higher emissions during the rush hours. On average, SMOKE-processed NO and CO emissions over the GTA are ~50% higher than the link-based emissions.

These differences may be due to a number of causes. One may be that the link-based inventory only considers traffic originating and terminating within the GTA (Kanaroglou et al., 2009), whereas a large fraction of emissions are from vehicles traveling to the GTA from outside or passing through the GTA en route to other cities. Such trips are more likely to happen during the middle of the day to avoid rush hour. Many out-of-city vehicles also traverse the GTA during the night, especially heavy-duty trucks. This is an important source of emissions that was not considered in the link-based inventory and that can help to explain the very low NO and CO emissions during the night.

3.2 Comparison of Spatial Allocation

Link-based emissions were processed for 3 types of roadways: highways; arterial roads; and pseudo links (which connect the major roads to the zoning system). SMOKE-processed emissions were also based on 3 spatial surrogates representing 3 road types: urban primary roads; urban secondary roads; and urban local roads. Total daily NO emissions on a weekday over the GTA area at 2.5-km model grid spacing were calculated for individual road types from both link-based and SMOKE-processed emissions. The spatial distribution of the total NO emissions on different road types are compared between 3 paired link-based and SMOKE road types (Highway vs. Primary Road; Arterial Road vs. Secondary Road; Pseudo Link vs. Local Road) as shown in Figs. 5, 6, and 7, respectively. Time series of the GTA total link-based and SMOKE-processed NO emissions for the 3 types of road are compared in Figs. 8a-c.

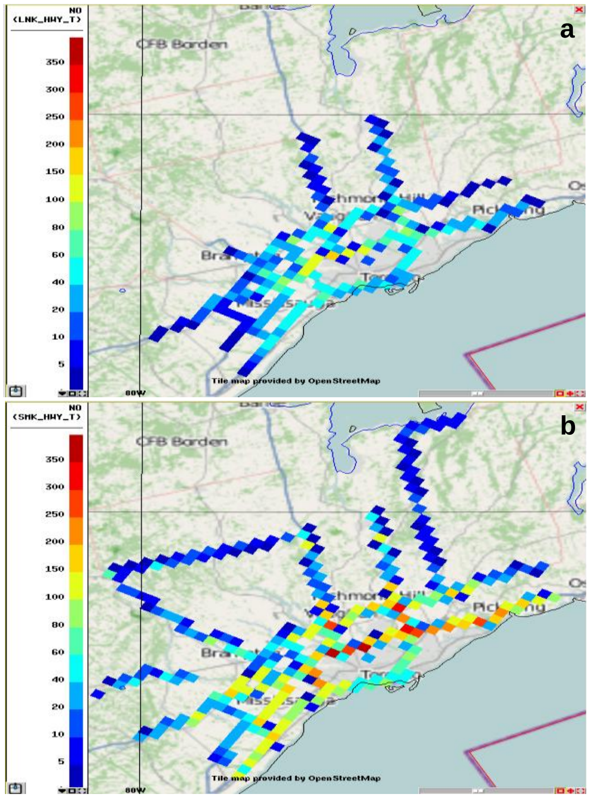


Fig. 5. Daily total NO emissions on (a) link-based Highways and (b) SMOKE Primary Roads.

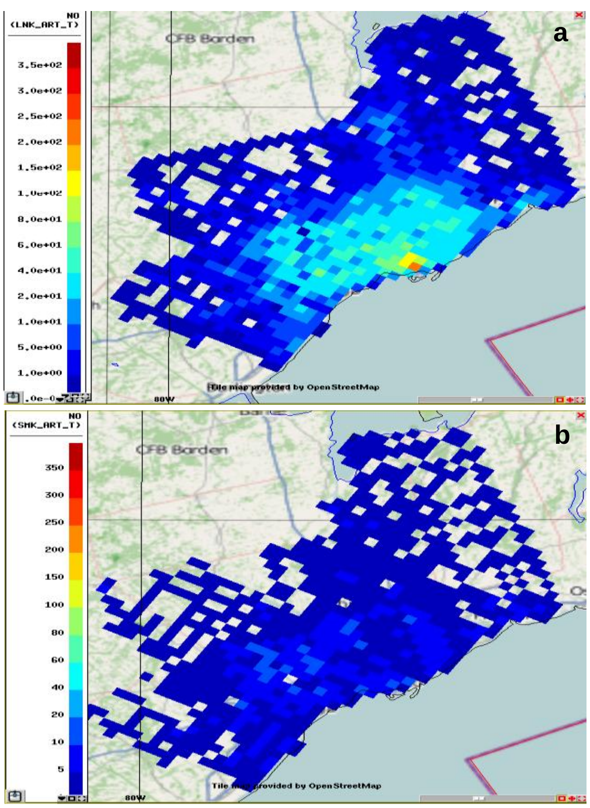


Fig. 6. Daily total NO emissions on (a) link-based Arterial Roads and (b) SMOKE Secondary Roads.

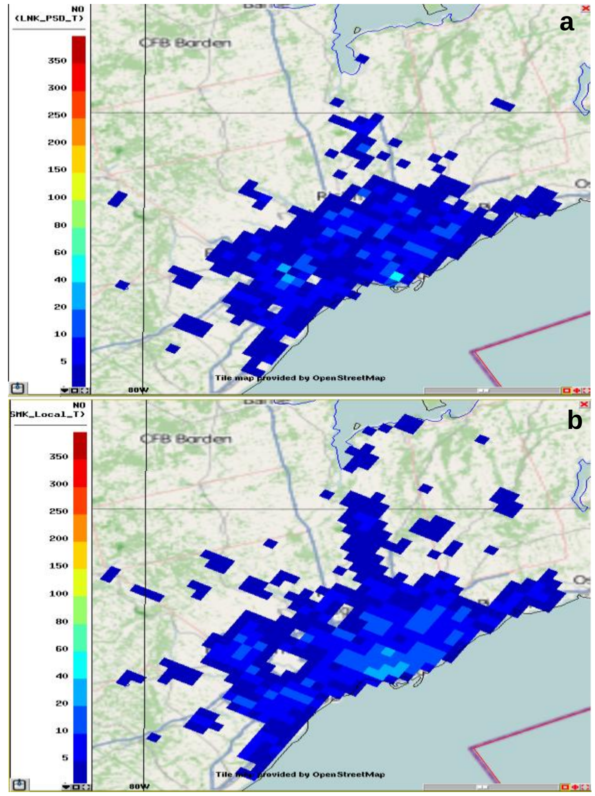
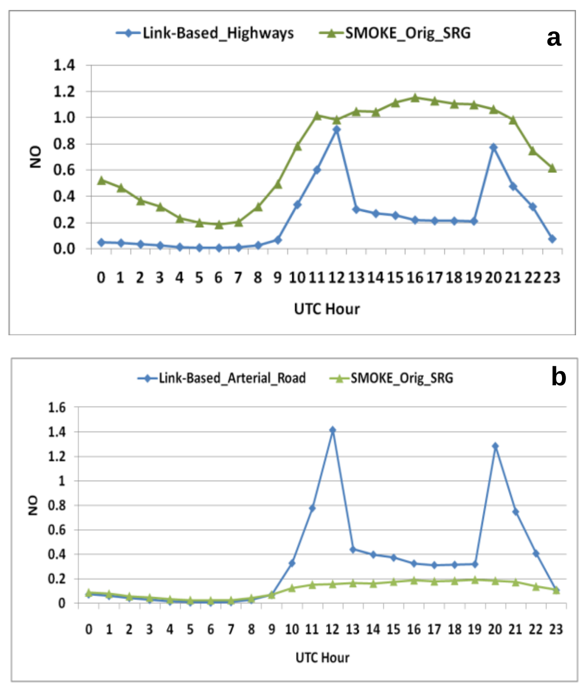


Fig. 7. Daily total NO emissions on (a) link-based Pseudo Links and (b) SMOKE Local Roads.



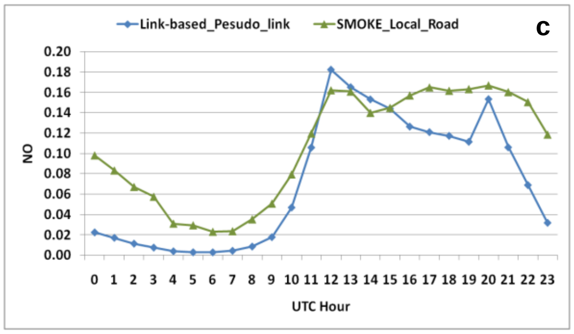


Fig. 8. Time series of GTA total link-based and SMOKE-processed NO emissions on (a) link-based Highways and SMOKE Primary Roads, (b) link-based Arterial Roads and SMOKE Secondary Roads, and (c) link-based Pseudo Links and SMOKE Local Roads.

Figs. 5 to 7 show that overall the distribution of NO emissions for the 3 types of link-based road types correspond well with the 3 types of roads in SMOKE, especially in the downtown areas. However, some road segments in the suburban areas were defined as primary roads in SMOKE but as arterial roads in the link-based processing system. Figs. 5 and 8a show that, compared with the link-based emissions, SMOKE placed a significantly larger amount of NO emissions on the major highways whereas a smaller amount of NO emissions was allocated to the arterial (secondary) roads, as shown in Figs. 6 and 8b. On the other hand, NO emissions on the minor local roads are comparable between these two sets of emissions as shown in Figs. 7 and 8c.

Fig. 6 also shows that link-based NO emissions over the downtown core area are much higher than the SMOKE-processed emissions. It is reasonable that NO emissions in the downtown area are higher due to higher traffic volume and lower speeds. The reason that the SMOKE-processed emissions are spread almost evenly over the whole GTA is that the SMOKE secondary-road surrogate was generated as the product of road length and number of lanes, and the arterial roads in the downtown area usually do not have more lanes than those outside the core.

3.3 Possible Improvements to SMOKE Spatial Allocation

As discussed in Section 3.2, SMOKE allocated a higher amount of emissions to major highways and a smaller amount of emissions to secondary highways. In SMOKE, emissions from urban interstate highways, urban freeways, urban principal arterial roads, and urban minor arterial roads are spatially distributed using the primary-road surrogates. Only emissions from the urban collectors use the urban secondary-road surrogate. Based on the comparison of Fig. 5 and Fig. 6, it looks as if emissions from urban arterial roads should also use the secondary-road surrogate. As a sensitivity test, emissions from urban minor arterial roads were allocated using the secondary-road surrogate, and agreement between link-based and SMOKE-processed NO emissions was improved as shown in Fig. 9.

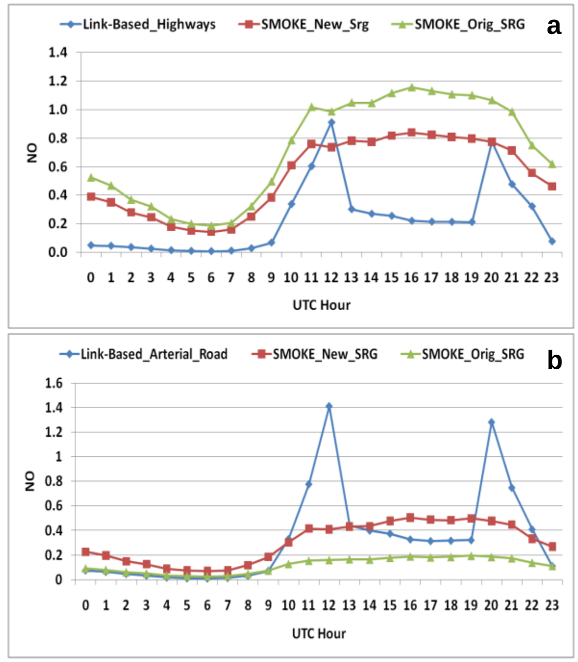
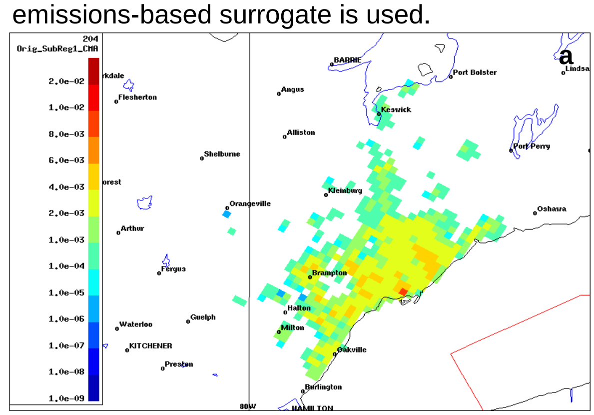


Fig. 9. Time series of total GTA link-based and SMOKE-processed emissions before (green lines) and after emissions from minor arterial roads were allocated to secondary roads (red lines): (a) link-based highways and SMOKE primary roads; (b) link-based arterial roads and SMOKE secondary roads.

Another possible improvement is to generate the secondary-road surrogate based on the link-based arterial road emissions. Fig. 10 compares the original SMOKE secondary-road surrogate with a new surrogate generated from the weekly total link-based NO emissions from the arterial roads. It shows that more emissions will be allocated to the downtown areas if the new emissions-based surrogate is used.



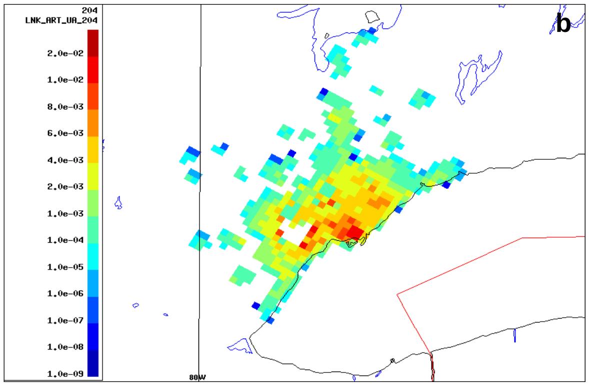


Fig. 10. Original urban secondary road surrogate (a) and the one built from link-based weekly total NO emissions (b).

4. CONCLUSIONS

Results in this study show that there are significant differences, both temporal and spatial, between SMOKE-processed and link-based on-road mobile emissions in the Greater Toronto Area. During weekdays, the link-base emissions have significant peaks during the morning and afternoon rush hours and the mid-day emissions are significantly lower, whereas the rush-hour peaks are not so evident and mid-day emissions are higher for the SMOKE-processed emissions. Although the link-based emissions were estimated with detailed local conditions and relatively realistic traffic-flow data, they might underestimate the emissions during mid-day due to under-representation of vehicles coming from outside the study area and stopping in or passing through the city. On the other hand, the link-based emissions likely have a better representation of the spatial distribution of the emissions. For SMOKE-processed emissions, it is important to make sure that the road-type definitions in the inventory are consistent with the definitions for the surrogates. Otherwise, emissions will be allocated incorrectly to certain components of the road network.

To further evaluate the quality of the estimated emissions, a few more sets of emissions, including (i) swapping the SMOKE-processed emissions with the link-based emissions in the GTA area and (ii) using the Secondary Road surrogate built from link-based NO emissions in SMOKE, have been generated to support sensitivity studies of air quality modeling for the GTA and surrounding area. The results of these AQ modeling sensitivity studies will be investigated in future studies.

5. ACKNOWLEDGEMENTS

The authors would like to thank the project team at the Centre for Spatial Analysis (CSpA), McMaster University, Hamilton, ON for processing the link-based emissions used in this study and our colleagues in Environment Canada for helpful discussions.

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