USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No. 179OSUY2.2

# Mobile air quality monitoring for local high-resolution characterization of vehicle-sourced criteria pollutants

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Report Submission Date: June 19, 2017

## ACKNOWLEDGMENTS AND DISCLAIMER

Partial funding for this research was provided by the NEXTRANS Center, Purdue University under Grant No. DTRT12-G-UTC05 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (OST-R), University Transportation Centers Program. Additional funding was provided by The Ohio State University (OSU) including the College of Engineering and Transportation and Traffic Management.

The authors are grateful to OSU's Transportation and Traffic Management for its support of the OSU Campus Transit Lab (CTL) including Beth Kelley-Snoke and Timothy Smith for their efforts in supporting the continued development and maintenance of the CTL, which resulted in the availability of the data used in this study.

Several undergraduate students contributed to this work in various capacities: Olivia Ambuehl, Tyler La-Susa, Maxwell Lisska, Sachinda Liyanaarachchi, Declan McCord, Emma van Dommelen, and Bennett Wildey. Furthermore, we thank Roisin McCord for assistance in data collection via personal automobile. Lastly, we thank Mohammad Hafiz Gulam Mohd Khan and Jakob zumFelde for assistance with the Automatic Vehicle Location (AVL) data.

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

## TABLE OF CONTENTS

## 1. INTRODUCTION AND MOTIVATION

Transportation-related emissions are a major source of air pollution in many urban areas (*1–3*). Human exposure to this pollution is related to their proximity to major roadways (*4*, *5*), yet federal and state Environmental Protection Agencies (EPAs) conduct regulatory air quality monitoring at sparsely-distributed, fixed-site stations. While these distributed stations are useful for inferring the general hourly air pollution exposure of the public located within a broad geographic region, they cannot accurately capture exposure at a finer spatial resolution and adequately capture the spatiotemporal variability in transportation-related air pollution (TRAP). For example, there may be large differences in TRAP near urban highways and suburban collector roads within a geographic region. Furthermore, the temporal variations at each of those locations are likely to be substantially different in light of the differences in the factors that contribute to such variations. For examples, in addition to traffic activity, the built environment (*6*) and terrain (*7*) can also play a role in this variability. Thus, the use of data from the EPA monitoring sites may result in large uncertainties when estimating human exposure in different micro-environments within an urban area.

In lieu of empirical data, models can be used to estimate air quality at locations away from monitoring sites. Dispersion models are used routinely by the EPA, but these models require some knowledge of the pollutant source. For TRAP, US EPA's Motor Vehicle Emission Simulator is used to calculate vehicle emissions in a manner sensitive to roadway traffic conditions. However, the software is designed for spatiotemporal predictions of average conditions resulting in model uncertainties. For example, there is uncertainty in exposure assessments due to the transient nature of traffic activity throughout time (e.g., morning and afternoon commutes, weekday and weekend effects). Alternatively, statistical forecasting models can be used to predict air quality, but these models may reflect even more uncertainty due to the scarcity of data that are available to inform the estimates. In short, model outputs cannot substitute for the high-resolution spatiotemporal detail of air quality or the in-depth understanding of local conditions, which are the primary foci of this research effort.

## 2. AIR QUALITY MONITORING VIA TRANSIT BUSES

To improve air quality monitoring, there are several potential approaches, each with strengths and weaknesses. One approach would simply be the widespread distribution of the traditional, stationary sites currently operated by the EPA. However, this approach is not financially practical due to the large capital, operating, and maintenance costs for these sites. Conversely, the recent technological developments of low-cost air quality sensors offer the possibility to deploy greater numbers. However, these sensors are less accurate than the EPA-grade monitors (*8*), and a large number of sites will still be required to obtain sufficient spatial coverage.

To achieve spatial coverage while maintaining a smaller number of monitors required, a mobile sampling platform can be used. For example, prior research efforts have outfitted mobile laboratories with high-quality instrumentation for on-road air pollution monitoring (*9–12*). Like traditional stationary sites, mobile laboratories can be costly to equip and operate. As a result, some researchers have pursued other mobile platforms using lower-cost equipment such as bicycles (*13*, *14*), taxis (*15*), and pedestrians (i.e., personal monitoring) (*16–19*). However, even if wide spatial coverage is possible, temporal resolution at any given point may be low, given the high potential for randomness in spatial coverage. Moreover, all of these aforementioned mobile platforms may not be viable for long-term monitoring since they can be burdensome for the data collector.

To overcome the challenges outlined previously, the deployment of low-cost air quality sensors using transit buses as a mobile platform is proposed. Transit buses cover extensive sections of the urban roadway network, and although sensors carried by these platforms would only sample a location for a limited time in a single bus pass, the repeated, regular pattern of transit coverage could capture temporal patterns. Thus, the key objective of this study is to investigate the feasibility of low-cost air quality sensors carried on transit buses in monitoring air quality in urban micro-environments.

## 3. Sensor Package Development and Laboratory Evaluation

After conducting a product review and considering potential advantages and disadvantages of available commercial sensors, individual air quality sensors were purchased and an "integrated" sensor package was fabricated for this study. Specifically, a carbon monoxide (CO) sensor (Model CO-A4F), an ozone ($O_3$) + nitrogen dioxide ($NO_2$) sensor (Model OX-A431), and a standalone $NO_2$ sensor (Model NO2-A43F)* are used – all are electrochemical sensors purchased from Alphasense Ltd. (Great Notley, UK). CO is considered because this is an unequivocal tracer for mobile sources in Franklin County, OH (as in most other urban areas). $O_3$ is not directly emitted from mobile sources, but it is formed in the atmosphere due to photochemical reactions between volatile organic compounds (VOCs) and nitrogen oxides ($NO_x$ = nitric oxide NO + $NO_2$), both of which are emitted from mobile sources. Moreover, the US EPA regulates all three pollutants under the National Ambient Air Quality Standards.

These air quality sensors were integrated with a Raspberry Pi 2 (or simply "Pi") single-board computer, using a solderless breadboard and an analog-to-digital converter. Figure 1 shows a photograph of the sensors integrated with the Pi. In addition to the air quality sensors, a temperature and relative humidity sensor (Model DHT22; Aosong Electronics Co., Guangzhou, China) are connected to the Pi. Data acquisition (including sensor outputs and time stamps) is enabled via an executable written in the Python programming language. In the laboratory, power is supplied via an AC-to-DC converter. However, battery power is the current viable option for measurements outside of the laboratory.

In total, ten integrated sensor units were fabricated and calibrated in the laboratory using EPA-grade monitoring instruments for CO, $NO_x$, and $O_3$ (all from Teledyne API, San Diego, CA). All sensors showed a linear relationship with the EPA-grade monitors, which facilitates the translation of the sensor signals into pollutant concentrations.

*The OX sensor provides the total (sum) of $O_3$ and $NO_2$ since this sensor is not selective towards just $O_3$ (i.e., there is an interference from $NO_2$). Thus, $O_3$ concentrations can be inferred from the difference between the OX and $NO_2$ sensors.

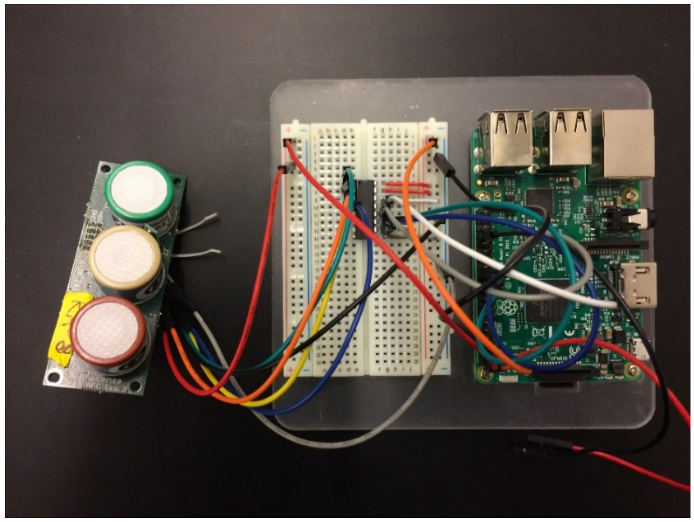

**Figure 1. Photograph of the sensors (left-hand side of image) including CO (green), OX (yellow), and $NO_2$ (red); solderless breadboard; and Raspberry Pi 2 (right-hand side of image).**

## 4. Empirical Study Set-up

***Study Location***

Following design and laboratory testing, the sensors were ready for real-world deployment using OSU's Campus Transit Lab (CTL). The CTL is a living laboratory that supports research, education and outreach (*20*). It is based on OSU's Campus Area Bus Service (CABS), which is owned and operated by OSU and run by Transportation and Traffic Management (TTM). CABS consists of six routes traversing varied land uses consisting of the core academic campus, two park-and-ride facilities, the medical campus, administrative facilities, and surrounding residential and commercial neighborhoods and serving approximately 5 million passengers per year. As such, there are numerous sources of TRAP, including large surface parking lots, parking garages, and areas of high traffic activity. Moreover, OH State Route (SR) 315 passes through the western portion of campus. It is a major highway used by commuters to travel to and from downtown Columbus, OH.

Co-PIs McCord and Mishalani, the co-founders and co-directors of CTL, have a long-standing relationship with TTM, which is a partner in the establishment of CTL. Therefore, the CTL is an attractive setting for initial deployment, whereby the institutional and physical accessibility substantially facilitates and accelerates the deployment, the availability of CTL data (namely transit vehicle locations) readily supports the air quality data analysis, and the setting offers complexities that allow for the generalizations of the results and conclusions.

The deployment is conceived in three stages. The first involves the installation of a sensor unit on a personal automobile to collect data while traversing select CABS routes. The intent is use the experience with physical set-up and collected data to inform any revisions to the installation and data collection during the next stages. The second stage involves the installation of a second sensor unit on a CABS bus and collect data on the routes to which that bus is assigned. The third stage involves the installation of sensor units on multiple CABS buses serving multiple routes. The collection of data from the personal automobile continues during the second and third stages for the purpose of comparing results from both sensor units in light of the differences in the physical conditions of the deployment (e.g., vehicle dimensions and resulting air flow, interactions of sampling vehicles with other vehicles and the infrastructure, etc.). The scope of the present study is confined to the first two stages.

For the first two stages, two routes were selected for data collection: Campus Loop North (CLN) and Buckeye Village (BV). The route maps for these two routes are shown in the Appendix. The CLN route operates on roadways with posted speed limits of 25 MPH and 35 MPH and circumnavigates much of OSU's academic core and includes service to a park-and-ride facility on the western part of campus. The BV route operates on roadways with posted speed limits ranging from 25 MPH and 45 MPH, travels through a small portion of the academic core, and serves the Buckeye Village Apartments at the northern end of the OSU campus. The speeds, roadways, and land-uses are similar to typical urban transit routes.

Naturally, in addition to measurements of air quality using the integrated sensors, some method of relating the sensor data to a given location is essential to study spatiotemporal patterns. As discussed in more detail subsequently, two approaches to obtain location data are used, depending on whether the sensors are deployed on a personal automobile or on a transit bus.

***Sensor Mounting***

In designing a method for mounting the integrated sensors onto a mobile platform, three main design criteria were considered:

- Include features to the case that houses the sensors that allow suitable air to flow into the case such that the sensors are appropriately exposed to the air quality variables of interest.
- Mitigate the effects of potential water intrusion (from rain) into the case.
- Securely mount the case to a vehicle (personal automobile and bus).

After several iterations using computer-aided drawing software, clear acrylic sheets were cut using a laser cutter, and the resulting parts were glued together using a waterproof adhesive. This initial prototype was used in the first stage of the study using a personal automobile. While this prototype was sufficient for short-term use on a personal automobile, the design was modified slightly (to reduce direct exposure of the sensors to solar radiation and to implement some additional measures to prevent water intrusion) prior to the second stage deployment on a transit bus.

## 5. Pilot Study via Personal Automobile

In July 2016, a feasibility test of the integrated sensors was conducted using the prototype case mounted on a personal automobile with data acquisition every 3 seconds. Based on this test of relatively short duration (~15 min), some qualitative conclusions were drawn, namely that the prototype case is easily mountable onto a personal automobile, that sensor outputs are highest at locations near high traffic activity (e.g., surface parking lots, intersections), and that a 3-second sampling period appears to be sufficient to capture meaningful patterns.

With these lessons in mind, a systematic plan was designed for conducting air quality measurement, initially along the CLN route and, subsequently, on both CLN and BV routes. Each sampling day, two undergraduate students would conduct one "tour" consisting of two "bus" trips (a circuit completely traversing the route once). One student was responsible for driving, while the passenger was responsible for recording the time at which the vehicle reached pre-specified waypoints (e.g., intersections, transit bus stops) as a means of geo-referencing as a GPS chip since was not installed onto the Pis. The passenger also recorded any events of interest observed throughout the tour (e.g., following a transit bus, passing a construction site, stopping at a red light) that could potentially be used for interpreting the collected data. Tours via personal automobile commenced in Autumn 2016 and remain on-going. In total, 24 trips along CLN (collected between September 2016 and March 2017) and 24 trips along BV (collected between November 2016 and March 2017) are considered in this report. (As noted previously, maps for the two routes are provided in the Appendix.)

One example time series of CO concentration from CLN on September 12, 2016 is provided in Figure 2. Panel (a) shows the raw data from the sensors (converting sensor signal to concentration in parts per million, ppm), and panel (b) shows the smoothed data from the same route and day, calculated as a moving average (window = 60 seconds, step size = 3 seconds). While data for $O_3$ and $NO_2$ are also collected from the integrated sensors, these pollutants are more regional in nature and, therefore, a roughly 1-hour automobile tour is insufficient to capture any meaningful trends. Moreover, the majority of the data were collected outside of $O_3$ "season" (April-October) when the atmosphere is not very photochemically-active.

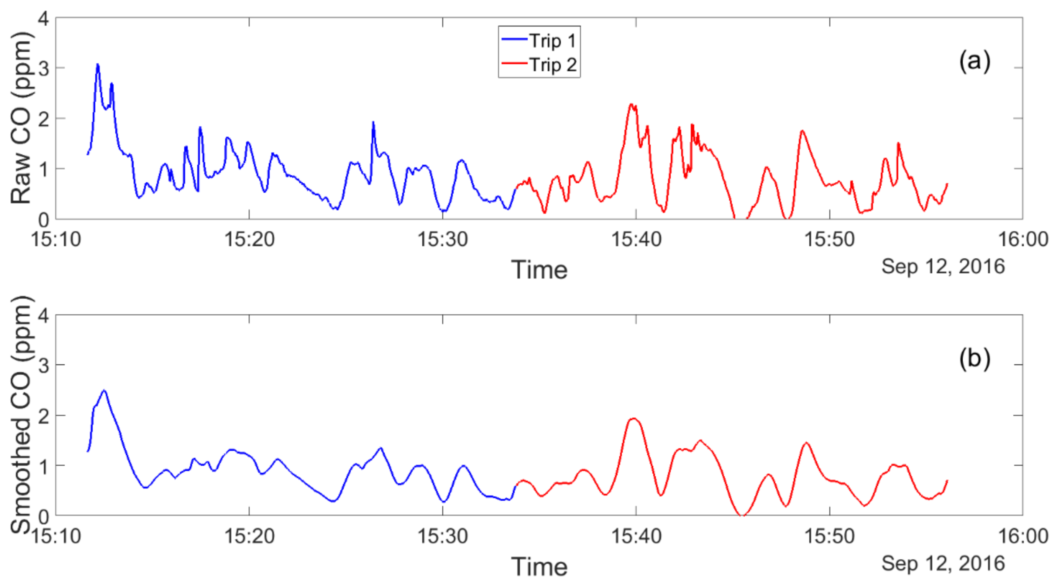


**Figure 2. Time series of (a) raw CO concentration and (b) smoothed CO concentration measured on Campus Loop North during the afternoon of September 12, 2016; the route was traversed twice (referred to as "Trip 1" and "Trip 2").**

Because the tours on each route occurred during different times of the day and because the duration of each tour was variable due to different on-campus traffic patterns, a means of systematically comparing the data by location across tours is desirable. Therefore, each trip was separated into "segments" between waypoints (37 for CLN, 36 for BV) and the time-series data were interpolated at locations forming a grid defined in increments of 0.1 of a segment. These locations are referred to as "sub-segments". Figure 3(a) shows the same data shown in Figure 2(b), except that the smoothed data are gridded onto the sub-segments via interpolation. The remainder of the analyses of the personal automobile data referred to in this report are focused on smoothed and gridded data (unless otherwise noted).

To analyze for spatial patterns, the trip series are normalized by subtracting the median CO concentration from the smoothed, gridded data for the trip. An example of normalized CO concentration is shown in Figure 3(b).

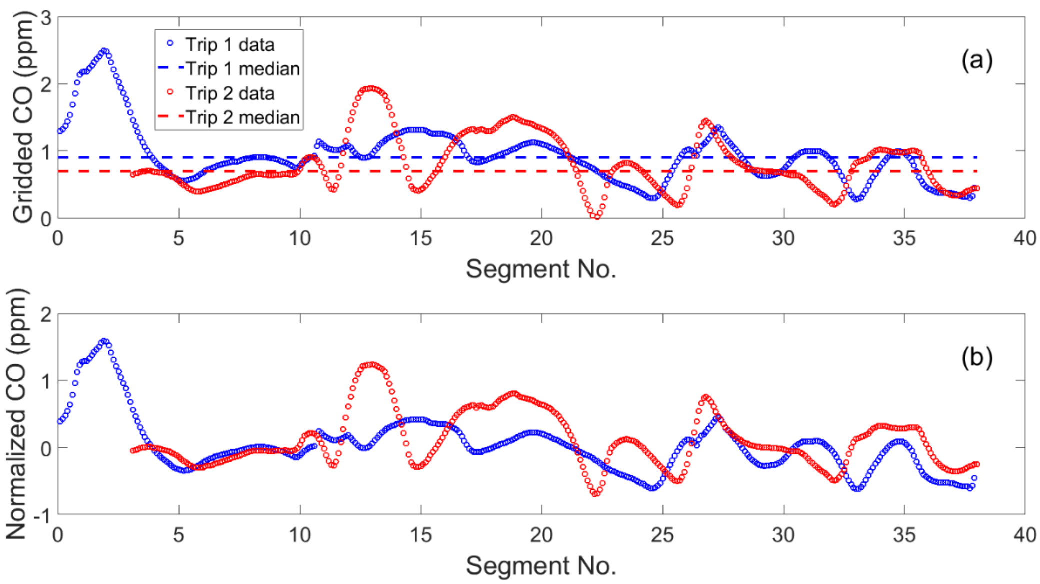


**Figure 3. Data from Figure 2 presented as (a) gridded, smoothed, and interpolated CO concentration and (b) normalized gridded CO concentration; the median values for both trips are presented in panel (a).**

By repeating this median-subtraction process for each trip, some patterns emerge. For example, Figure 4(a) shows the fraction across trips where sub-segments on CLN are positive (i.e., they are greater than the median). This fraction is typically greater than 0.50 roughly between segments 11 and 22, corresponding to a stretch of campus passing the OSU Medical Center and Ohio Stadium, which are adjacent to several large surface parking lots, one parking garage, and an off-ramp for OH SR 315 (i.e., areas with potentially high traffic activity). Conversely, the segments with lower fractions (e.g., segments 5-8, 22-25, and 31-32) are located in areas on campus that are not adjacent to major traffic sources or are located near open space where mixing with cleaner air is likely. Figure 4(b) shows the fractions for the BV route. In this case, the highest fractions occur around the academic core while the lowest fractions occur at the northern end of campus where there is more open space. (It is not appropriate to compare across the two routes due to the differences in land use, which may result in different median CO values even if both routes were sampled at the same time on the same day.)

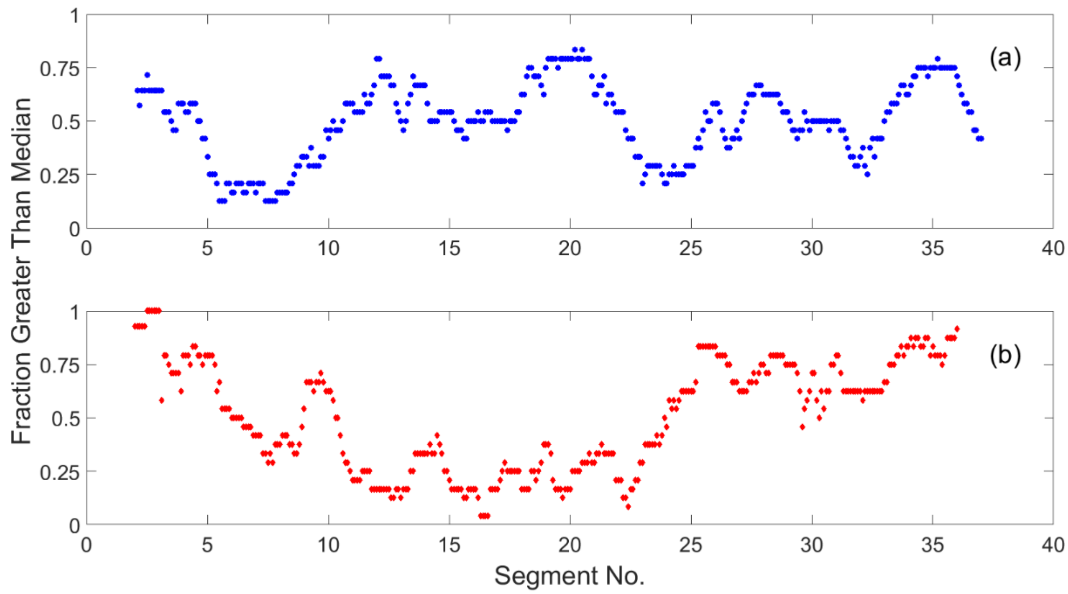


**Figure 4. Fraction of positive normalized sub-segment concentrations (greater than the trip median) across all trips for (a) Campus Loop North and (b) Buckeye Village.**

## 6. Transit Bus Deployment

In March 2017, the second sensor-mounting case with a slightly revised design (see Section 4) was installed onto a CABS bus, and integrated sensors were deployed shortly thereafter for the collection of air quality data using the bus as a mobile platform. CABS buses are equipped with an Automatic Vehicle Location (AVL) system. To interpret data collected via the transit buses, the air quality sensor data are integrated with the AVL data associated with bus on which the sensors are deployed. As with the personal automobile data collection, bus trips have variable duration. As a result, space is used for the purpose of comparing across trips. The spatial variable used is the distance from a reference point derived from the AVL data. The raw data are smoothed and gridded via interpolation using a moving average (window = 1000 ft, step size = 100 ft). Figure 5 shows an example spatial distribution of the median smoothed and gridded CO data across 16 bus trips on March 21, 2017. As is discussed in more detail in Section 7, qualitatively, this spatial pattern agrees reasonably well with the pattern seen in the data collected using the personal automobile as the mobile platform. (The data for CO are the focus of the remainder of this report for the same reasons discussed previously.)

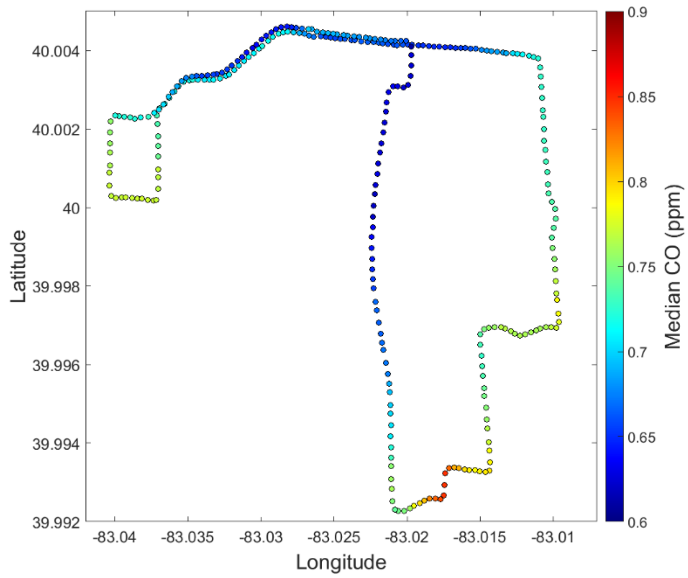


**Figure 5. Spatial distribution of median CO concentration across 16 bus trips on March 21, 2017.**

Temporal trends are also investigated as part of this study. Figure 6 presents the median CO concentrations for each trip om March 21, 2017 organized by the time at the beginning of the trip (at the route's reference point). Although there are some exceptions, the CO concentration generally decreases throughout the day. This decrease is postulated to possibly be, in part, due to atmospheric dispersion caused by local meteorology (e.g., temperature increased from ~ 40 $^{o}$F in the morning to ~55 $^{o}$F in the afternoon, wind speed was 5 MPH greater in the afternoon). In addition, this generally decreasing trend over time is consistent with trends seen from most of the CLN data collected using a personal automobile (not presented in this report). Furthermore, interestingly, local maxima in plot of Figure 6 roughly correspond to the morning commute, lunchtime, and the afternoon commute.

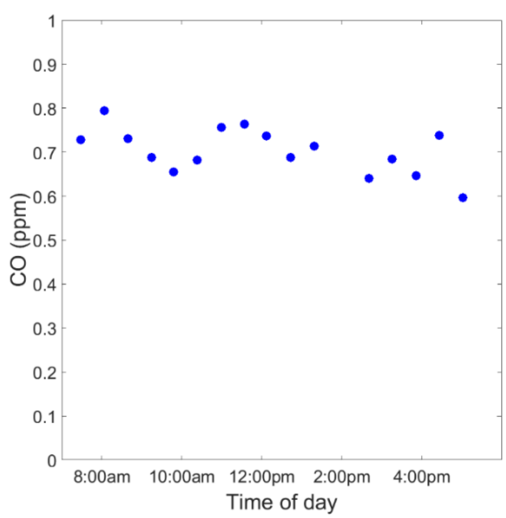


**Figure 6. Median trip CO concentration collected on March 21, 2017; the x-axis represents time of day (the first trip begins around 7am).**

In Figure 7, both spatial and temporal variability are simultaneously considered using a box-and-whisker plot. CO concentration data are grouped into contiguous 1000 ft long intervals – the beginning of the first of which is positioned at the route's reference location – whereby the boxes and whiskers capture the temporal variability within a section across the bus trips of the day. The median values for each interval (the horizontal lines through the boxes) fall between 0.6 ppm and 0.8 ppm, while the interquartile ranges vary from roughly 0.1 ppm to 0.3 ppm, suggesting that temporal variability is greater at some locations than others. Interestingly, the intervals with the smallest interquartile ranges are mostly located along roadways between academic buildings (i.e., "urban canyons"), while larger interquartile ranges are (anecdotally) associated with locations having higher traffic activity or proximity to open space.

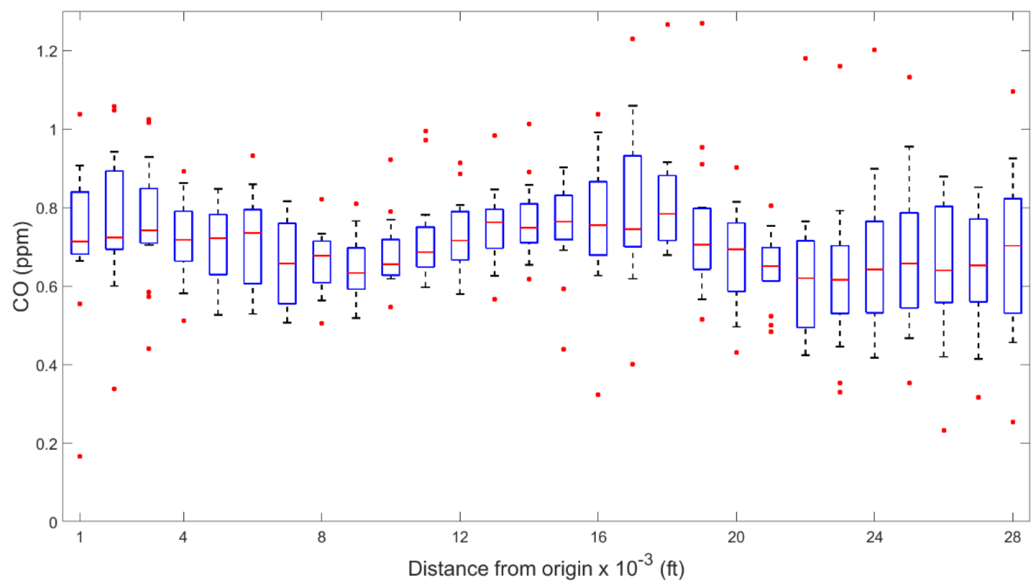


**Figure 7. Box plot of CO concentration across trips on March 21, 2017 separated into contiguous 1000 ft intervals; boxes are the 25th – 75th percentiles, whiskers are the 10th and 90th percentiles, and markers are outliers.**

## 7. Comparing Personal Automobile and Transit Bus Data

Figure 8 shows the median values of normalized CO concentration for CLN: (a) is based on data collected via personal automobile mobile platform across 24 trips, and (b) is based on data collected via the bus mobile platform across 16 trips on March 21, 2017. Although the definitions of location along the x-axes are not identical due to the manner in which geo-referencing is conducted for the two platforms, both panels (a) and (b) in Figure 8 show similar spatial patterns. For example, the campus "Oval" consisting of a large open green space – roughly segments 6-7 in Figure 8(a) and distances of 11,500 to 12,500 ft in Figure 8(b) – is a local minimum in both plots. Furthermore, the OSU Medical Center area with several surface parking lots and garages and relatively high traffic activity – roughly segments 13-16 in Figure 8(a) and distances of 16,000 to 18,000 ft in Figure 8(b) – is a local maximum in both plots. While additional comparisons are necessary, these preliminary results suggest similar patterns from both mobile platforms.

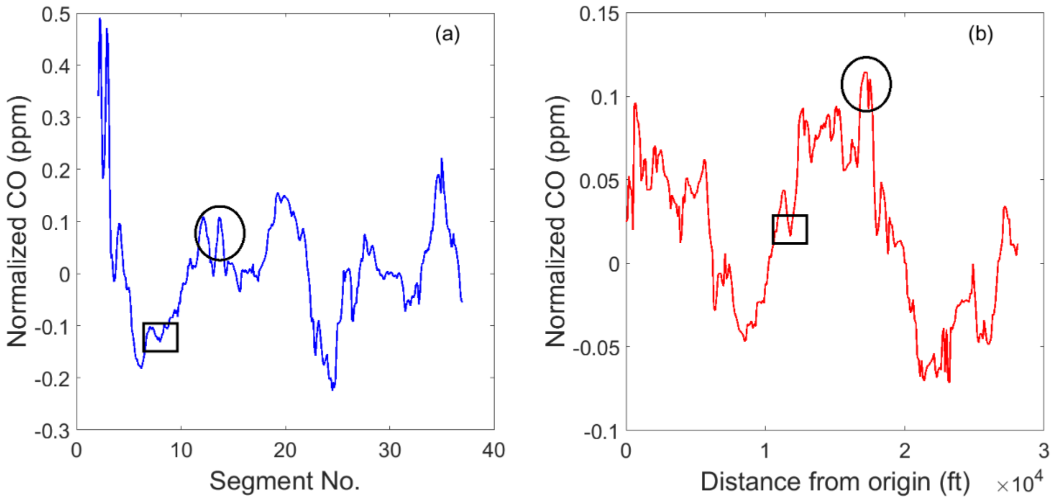


**Figure 8. Comparison of median values across trips on Campus Loop North from (a) 24 trips using the personal automobile mobile platform and (b) 16 trips using a transit bus as a mobile. The rectangles highlight samples collected near an open space on campus; circles highlight samples collected near the OSU Medical Center.**

## 8. Summary and Future Research

The results indicate that sufficiently similar spatial patterns are observed using different sensors on multiple mobile platforms between September 2016 and March 2017. Moreover, some aspects of the patterns could be explained by various possible exogenous factors relating to traffic activities, urban environment, and local meteorology. Therefore, there is sufficient evidence demonstrating that it is feasible to conduct mobile air quality monitoring using low-cost sensors mounted on transit vehicles.

Next steps include the implementation of the third stage of the study where multiple buses will be deployed with air quality sensors and operated simultaneously. Doing so will enhance the temporal resolution of the collected air quality data (especially if multiple buses are traversing the same route).

There are two key technical challenges that have yet to be addressed related to power for the integrated sensors and to data transmission. Currently, the power is supplied by a small battery, so the sensors can only collect data for roughly 1.5 days before the battery must be changed. Moreover, although the Pis have Wi-Fi capability, they have not been configured to automatically transmit data to the CTL file server. Both of these challenges result in required manual efforts and will be addressed in future work.

Moreover, stationary sensors will be deployed at fixed locations along the bus routes for several weeks. Doing so will provide continuous "ground-truth" data at these locations and will allow for comparisons to the lower-temporal-resolution data collected by the sensors on the mobile platforms. Stationary sites will be selected such that they represent different land-uses and have different proximities to traffic activities associated with roadway and parking facilities. Thus, the associations of the built environment and traffic activity with the spatial variability of air pollution can be simultaneously investigated. In addition, to further explore the role of traffic activity, direct measurements of such activities will be considered. Furthermore, to quantify the value of the mobile platform in capturing micro-conditions, measurements conducted on the mobile platform will be compared to those conducted on the local EPA monitoring sites.

Lastly, data for both $O_3$ and $NO_2$ (in addition to CO), will also be considered. For example, in doing so, diurnal trends in these regional pollutants will be investigated (e.g., a daily maximum is expected between around 3pm and 4pm during $O_3$ season).

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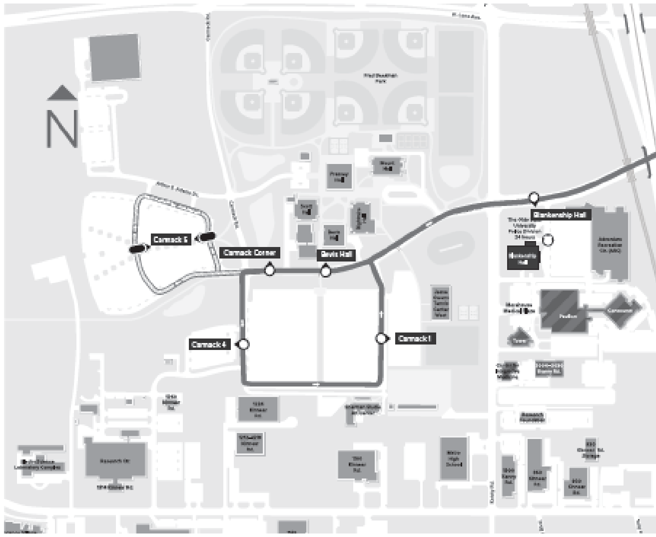
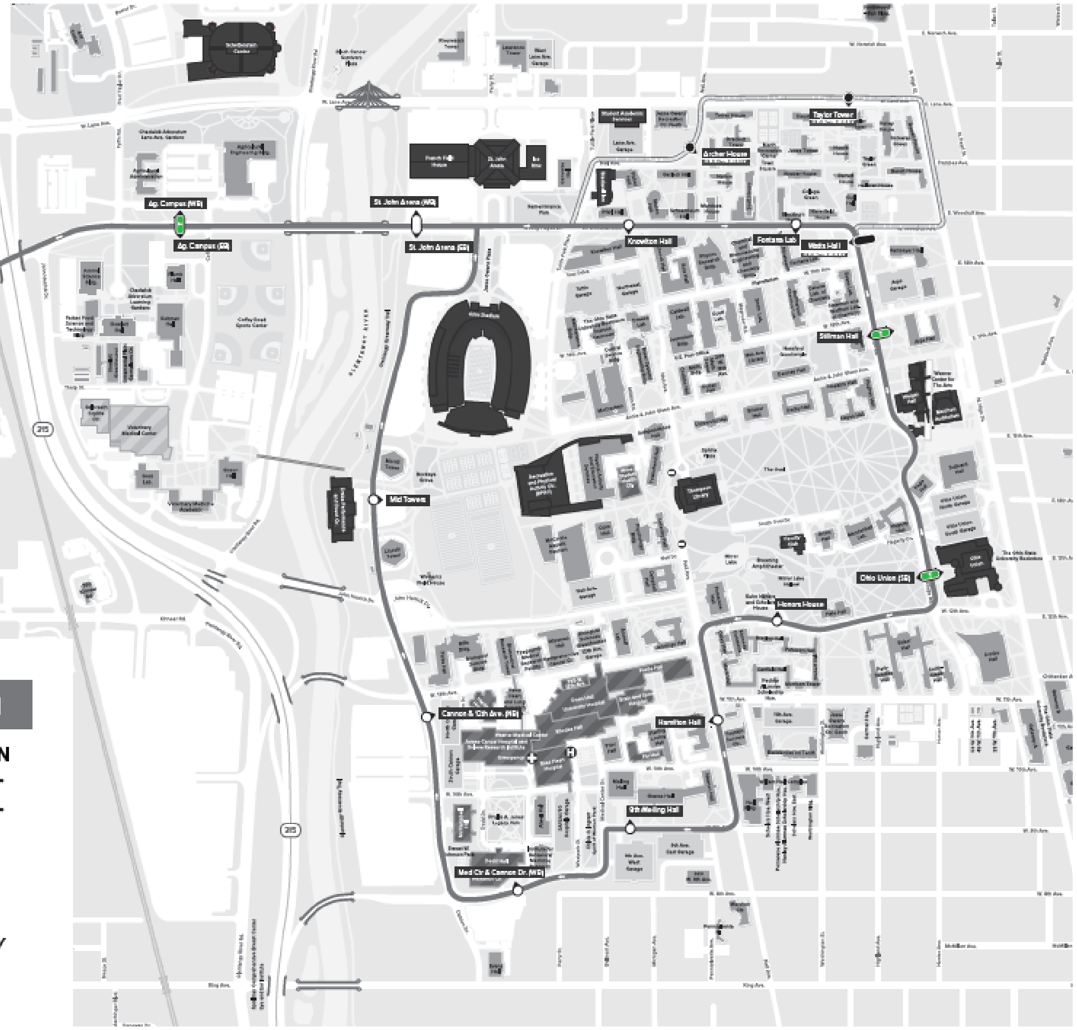
## APPENDIX

What follows are the route maps for Campus Loop North (CLN) and Buckeye Village (BV) (available at http://ttm.osu.edu/cabs).

## REAL-TIME ARRIVAL INFORMATION

Obtain real-time bus arrival information via the **Ohio State app** for iOS or Android.




| CLN | CAMPUS LOOP NORTH | | | | | |
|---|---|---|---|---|---|---|
| **HOURS OF OPERATION** | | **AM** | **MID** | **PM** | **LATE** | **OVN** |
| WEEKDAY | ALL TIMES | 30 | 07 | 11 | 15 | 30*** |
| WEEKEND** | ALL TIMES | 30 | 30 | 15 | 15 | 30*** |
| BREAK | 7 a.m. - 7 p.m. | — | 15 | — | — | — |
| SUMMER* | 7 a.m. - 7 p.m. | — | 11 | — | — | — |

(FREQUENCY)

Campus Area Bus Service will not operate during the following 2016-2017 observed holidays: Thanksgiving (November 24-25, 2016), Christmas (December 23-26, 2016), New Year's Day (January 2, 2017), Memorial Day (May 29, 2017), and Independence Day (July 4, 2017). CABS will run weekend service on all other holidays.

Information current as of 8/05/16. Subject to change without notice. Updates posted at **ttm.osu.edu**.

### FREQUENCY KEY

| | | |
|---|---|---|
| **AM** | = | 5:30 a.m. – 7 a.m. |
| **MID** | = | 7 a.m. – 7 p.m. |
| **PM** | = | 7 p.m. – 10 p.m. |
| **LATE** | = | 10 p.m. – Midnight |
| **OVN** | = | Midnight – 5:30 a.m. |

Please Note: *Campus Area Bus Service will not operate weekend service during the summer.

**CLN provides 30 minute service from midnight to noon and 15 minute service from noon until midnight.

***Due to a driver break, service will deviate from advertised intervals between 1 - 2 a.m. and between 4 - 5 a.m.

### MAP LEGEND

- RPAC Plaza — **Bus Stop Name**
- **Bus Stop Location** (points to side of street that bus stop is located on)
- **Bus Stop Serviced on Both Sides of the Street**
- **Bus Stop with Limited Service**
- **CABS/COTA Transfer Stops**
- **Bus Route Direction**
- **Bus Route**
- **Part-Time Alignment**

## REAL-TIME ARRIVAL INFORMATION

Obtain real-time bus arrival information via the **Ohio State app** for iOS or Android.

## BV — BUCKEYE VILLAGE

### HOURS OF OPERATION

| | | AM | MID | PM | LATE | OVN |
|---|---|---|---|---|---|---|
| WEEKDAY | 7 a.m. - 10 p.m. | – | 18 | 30 | – | – |
| WEEKEND | 8 a.m. - 8 p.m. | – | 30 | – | – | – |
| BREAK | 7 a.m. - 7 p.m. | – | 30 | – | – | – |
| SUMMER* | 7 a.m. - 7 p.m. | – | 30 | – | – | – |

FREQUENCY

Campus Area Bus Service will not operate during the following 2016-2017 observed holidays: Thanksgiving (November 24-25, 2016), Christmas (December 23-26, 2016), New Year's Day (January 2, 2017), Memorial Day (May 29, 2017), and Independence Day (July 4, 2017). CABS will run weekend service on all other holidays.

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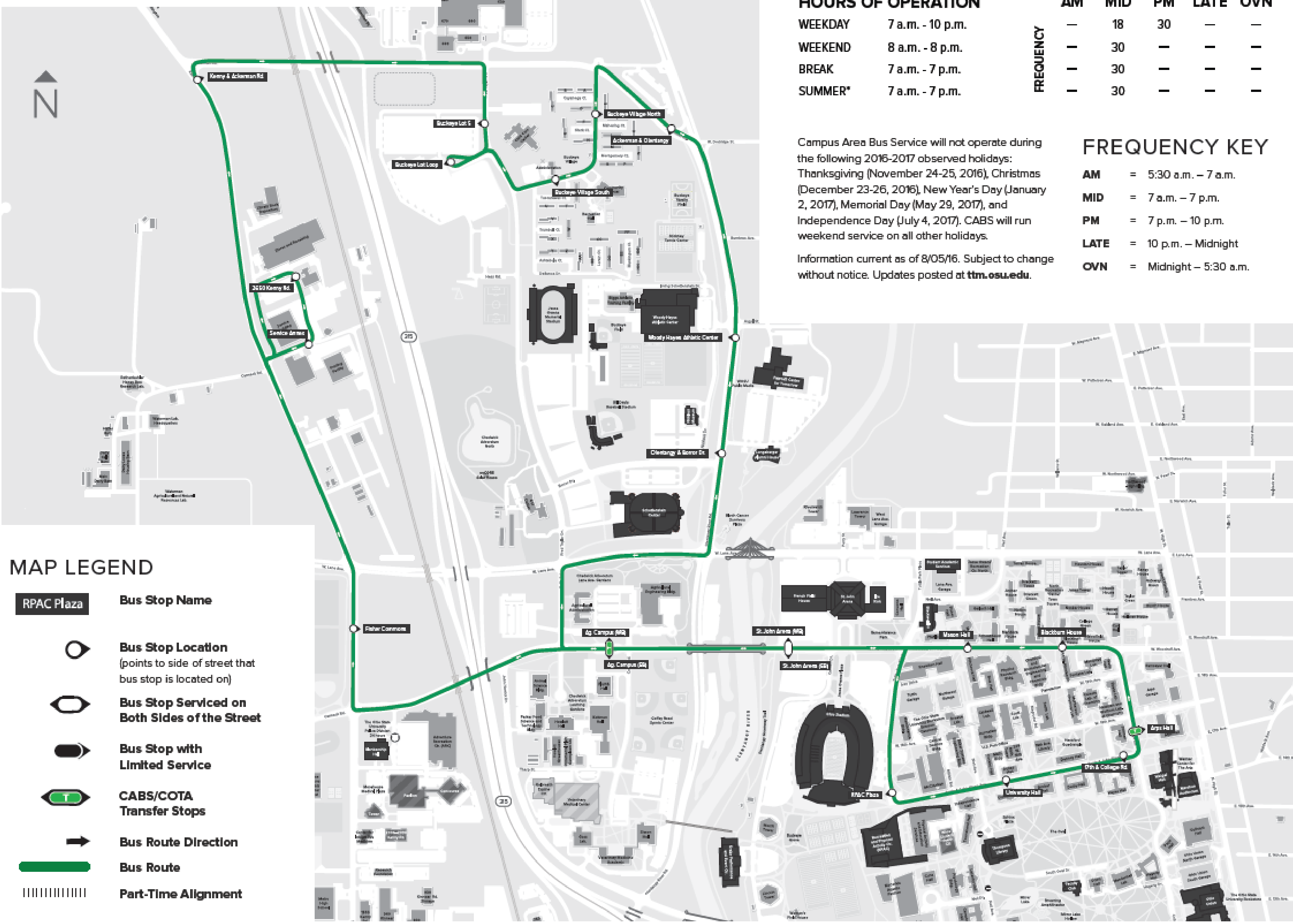


### MAP LEGEND

RPAC Plaza — **Bus Stop Name**

**Bus Stop Location** (points to side of street that bus stop is located on)

**Bus Stop Serviced on Both Sides of the Street**

**Bus Stop with Limited Service**

**CABS/COTA Transfer Stops**

**Bus Route Direction**

**Bus Route**

**Part-Time Alignment**

## CONTACTS


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