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Interactive comment on "A mobile sensor network to map carbon dioxide emissions in urban environments" *by* Joseph K. Lee et al.

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Final author's response to all reviewer and public comments.

Note: The attached 'supplement' contains the manuscript with all changes tracked / highlighted for reference.

Reviewer 1: Erik Velasco

* Lee et al. propose a measuring system based on a mobile network of sensors to validate estimations of carbon dioxide (CO2) emissions at fine spatial resolution (i.e. grid cells of 100 m2) in urban areas. They built and tested an initial network of five sensors as a proof-of-concept. The sensors are basically formed by a commercial CO2 monitor and a Global Positioning System (GPS) connected to a low-cost controlling

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Discussion paper

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board and placed in a special box for being carried on mobile platforms such as cars and bicycles.

The CO2 concentration data collected by the sensors along roads, streets and paths of the city are used to estimate emissions applying an aerodynamic resistance approach and sensible heat flux data obtained from an eddy covariance flux tower located within a sector of the city monitored. As a proxy of the aerodynamic resistance of CO2, they used the aerodynamic resistance of sensible heat under the strong assumption of equivalence between both.

The testing results showed the capability of the mobile network to complement eddy covariance flux measurements and validate emission estimates based on activity data and emission factors. The proposed monitoring system represents a new tool to solve the puzzle of the greenhouse gas emissions at city scale.

As any other approach, it has advantages and limitations. Both are discussed in the manuscript. The description, discussion and validation of the proposed approach fit well within the scope of Atmos. Meas. Tech. This work represents, in general, a valuable contribution to the ongoing efforts to quantify urban emission in a way to support policies for climate change mitigation. The technical issues to be addressed are minor.

- RESPONSE: We appreciate your accurate summary and assessment of the work's impact. Thank you.

However, this reviewer cannot recommend the immediate publication of the manuscript because of severe problems in the writing. The structure of the manuscript is appropriate, but the writing is not good enough for a scientific paper. A number of sentences are repetitive and others confusing. The manuscript needs a comprehensive editorial revision to be considered for publication.

- RESPONSE: We revised the writing in the entire manuscript, removed repetitions and ensured scientific style. All substantial changes are documented below and/or in the

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accompanied document “tracked-changes.pdf”

After the technical comments, a number of editorial suggestions are listed for the first ten pages of the manuscript. This reviewer expects they can provide some insight on how to fix the writing in general.

Technical comments:

* Since the mobile CO2 measurements were conducted along roads and streets, the approach is biased to traffic emissions. How this issue could be addressed, in particular for other trace gases, such as methane, whose origin relies in source emissions other than traffic? Please emphasise this issue even more.

- RESPONSE: Addressed. It is correct that due to the nature of the mobile sensing approach on cars and bicycles, measurements are primarily taken along roads and streets with traffic. However, in the planning of the routes, we also defined many segments along laneways (alley ways behind houses and buildings) - wherever and as often as possible. Laneways have very limited traffic (access to garages, garbage disposal trucks). Measurements in laneways are an attempt to better represent the area. We also drove into cemeteries and parks and used a bicycle to access pedestrian-only pathways in parks. The current approach has been tested only for emissions from vehicles and emissions at roof-level (e.g. emissions from furnaces released though chimneys that then are mixed down). We agree, that this methodology might not be transferrable to emissions whose origin are other than traffic. We therefore added a sentence of caution to the conclusions: “However, due to the assumption that sources are in the canopy layer where sensors operate, the proposed methodology is not necessarily transferable to emissions whose sources are not well represented such as fugitive natural gas emissions (methane) or volatile organic compounds or large industrial sources (tall stacks).”

* Data-driven models in combination with databases of urban parameters, such as land- use, building characteristics, population density, vehicular traffic, etc. at fine spa-

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tial scale may help to identify grid cells of similar characteristics and better estimate their emission... (See Moosavi et al., Atmos. Meas. Tech. 8, 3563-3575, 2015)

- RESPONSE: This is an interesting idea, and could - in the post processing - be further used to achieve more stable emission estimates. We added the a sentence and a reference to Moosavi et al. 2015 to the 'future improvements' section (just before conclusions). We did not apply this approach as it would make our comparison to the emission inventory not independent. The emissions inventory for building emissions depends on detailed urban form information, the emissions inventory for vehicular traffic relies on traffic counts. In the manuscript we independently compare emission inventory and measured data, which would not be possible with the proposed data-fusion approach.

* 10/21-24 Was the stationarity criteria for the eddy covariance flux data used to remove suspicious periods during the mobile measurements? I mean, if a flux measurement period did not meet the stationarity criteria, were the mobile data collected during the same period also discarded?

- RESPONSE: All fluxes were processed according to the guidelines defined in the "Environmental Prediction in Canadian Cities Network" following Crawford et al. (2011) which included spike removal, tests for statistical behaviour, tests against other systems [Crawford B., Christen, A., Ketler R. (2009): 'Processing and quality control procedures'. EPiCC Technical Report No. 1, 11pp. http://hdl.handle.net/2429/45079]. There was no additional processing or stationarity test run on top of this. Individual values were all 'valid'.

* Table 2 & 3. Are statistically different ($p \leq 0.05$) the concentrations/emissions recorded/estimated between the grid cells of each neighborhood and between neighborhoods?

- RESPONSE: A student's t-test was run on the gridded values for each combination of neighborhood. In the summer campaign, all neighborhoods were significantly differ-

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ent from each other neighborhoods ($p \leq 0.05$), except for the combinations between "Stanley park", "Sunset - Victoria-Fraserview" and "Kensington-Cedar Cottage - Riley Park", and the combination "Stanley Park" vs. "West End" which were not statistically significant. In the winter campaign, the same pattern was found, but in addition, the combination between "Fairview - Mount Pleasant" and "West End" was insignificant, while the combination "Stanley Park" vs. "West End" was significant. The table R1 summarizes the statistical tests.

* 21/4-6 How do you explain that the measured emissions were in average higher in summer than in winter, contrary to the estimated emissions by bottom-up approaches?

- RESPONSE: This is an interesting question, that has different possible answers as discussed in the conclusions. Although we assign March 18, 2016 as "winter", it was really at the end of the season, and home heating sources were certainly less than they would be in the middle of winter. The daily average temperature of 6.1°C, however, is not different from the average of 6.9°C for March (1981-2010). A minor complication is that March 18, 2016 is during school holidays, which might have caused less traffic than during school days, but does not explain the significant mismatch. In the model, traffic counts were used irrespective of whether schools were open or closed (but only mid-week traffic counts were selected). It might also show the sensitivity of the aerodynamic resistance.

* 21/23 Indeed, the approach lead to realistic and consistent results in average when evaluated at neighbourhood scale, but not at fine scale (i.e. grid cells)

- RESPONSE: Agree. The approach lead to realistic and consistent results only in average when evaluated at neighbourhood scale, not at the individual grid-cell. This was already stated in the conclusions, but has been updated.

* 22/10-14 The comparison should be restricted to the same periods of the day on week-days and same climatological seasons

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- RESPONSE: Although the model presented in Christen et al. (2011) separates different months (Table 2 in Christen et al., 2011), it does not separate between weekdays. We replaced the annual comparison with a comparison to the respective months of the year as follows: “Data can be compared to an independent previous study by Christen et al. (2011) that measured and modelled emissions within a 1.9 x 1.9 km study area centered on the “Vancouver-Sunset” tower (see Fig. 1). In the 1.9 x 1.9 km area, emissions were modelled 34.0 kg CO2 ha-1 hr-1 and measured emissions by eddy covariance were 30.8 kg CO2 ha-1 hr-1. The current study estimates emissions for the “Sunset / Victoria-Fraserview” neighborhood (that is larger than the area in Christen et al. (2011), Fig. 1) for March 18 (winter) as only 16.8 kg CO2 ha-1 hr-1. For the month of May, Christen et al. (2011) report modelled emissions of 26.9 kg CO2 ha-1 hr-1 and measured emissions of 26.0 kg CO2 ha-1 hr-1. The current study matches extremely well here, with emissions for “Sunset / Victoria-Fraserview” on May 28 (summer) of 26.5 kg CO2 ha-1 hr-1. Note that not only the spatial extent, but also the time scales of the two studies disagree. Christen et al. (2011) report monthly 24-hr emissions for the years 2008 - 2010, while the current study is restricted to weekdays between 10:00 and 13:30 on the two given dates.”

Editorial suggestions:

* 1/11 Why the use of quotation marks?

- RESPONSE: Done. We removed quotation marks. Also in later instances, the term “measured” is used without quotation marks.

* 1/17 Eighty seven percent (summer) and 94%

- RESPONSE: Done. Changed as proposed. 87% is spelled out as “Eighty seven percent”.

* 2/3 Define directly and indirectly emissions. Not all readers might be familiar with these

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- RESPONSE: Direct emissions are emission that occur within the area investigated (e.g. administrative unit, grid cell), due to activities within the same area. Indirect emissions are emissions that occur outside the area investigated, but are linked to activities within the area (e.g. local electricity useage links to power plant emissions elsewhere). In the context of cities, the direct emissions refer to emissions that occur within the built-up area, while the indirect ones are the emissions needed to sustain cities or due to transport outside cities. We feel introducing the context of direct and indirect emissions is not essential for the current work, and a detailed definition would unnecessarily complicate the introduction paragraph. Consequently, we rewrote and simplified the sentence without using the terms “directly” and “indirectly” as: ‘On the global scale, urban areas are responsible for up to 80% of the total anthropogenic CO2 emissions footprint (Satterthwaite, 2008)’. At the end of the paragraph, we clarified then ‘..., although a large fraction of the emissions related to the resource chains that sustain cities does not occur within the built-up area, but rather is emitted elsewhere.’

* 2/10 It depends on the latitude (e.g., Velasco et al., Landsc. Urban Plan. 148, 99-107, 2016)

- RESPONSE: Done. Thank you for clarifying this aspect. We edited the as follows and added the reference: “Overall, fossil fuel sources dominate CO2 fluxes in cities. The sequestration of CO2 by urban vegetation in most cities is very limited (Velasco et al., 2016). However, the rate of CO2 uptake by photosynthesis at a given time, can be relevant and is measurable in highly vegetated cities during the daytime in the growing season (Peters et al., 2012, Weissert et al., 2014).”

* 2/15 Avoid acronyms to start a sentence.

- RESPONSE: Done. Changed sentence as follows: “According to IPCC (2014), the urban scale has the highest potential for fast, efficient, and sustained implementation of mitigation efforts.”

* 2/16 Does it sound better quick or fast instead of agile?

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- RESPONSE: Done. Changed to “fast, efficient, and sustained”

* 2/24 The research goal of this study/work is to develop. . .

- RESPONSE: Done. Changed to “The research goal of this study is to develop, . . .”

* 2/25-27 Rewrite. For example: Data from a network of mobile sensors and an eddy covariance flux tower combined with an aerodynamic approach are used to calculate and map. . .

- RESPONSE: Done. Changed as proposed: “Data from a network of mobile sensors and an eddy covariance flux tower combined with an aerodynamic approach are used to calculate and map emissions at fine scales (blocks to neighborhoods) in cities.”

* 2/28 Mobile measurements have been used. . .

- RESPONSE: Done. Changed as proposed to “Mobile measurements have been used. . .”

* 2/30 mobile monitoring methods rely on a. . .

- RESPONSE: Done. Changed as follows “These studies relied on single, . . .”

* 2/31 – 3/2 These two sentences are repetitive, merge them with the previous one.

- RESPONSE: Done. In an effort to reduce redundancy we rewrote as follows: “Because trace gas analyzer systems for greenhouse gases are still bulky (e.g. Tao et al. 2015), past mobile mapping studies utilized specialized research vehicles (Bukowiecki et al., 2002, Elen et al., 2013, Crawford and Christen, 2014). While these vehicles have the advantage that they can be equipped with additional components such as calibration tanks or computers, the complexity of such systems does not allow for easy deployment on standard and flexible modes of transport.”

* 3/3 I would say interest instead of success.

- RESPONSE: Agree. Changed to “There is increasing interest to develop innovative..”

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* 3/4 Top-down data mining?

RESPONSE: Done. We deleted this sentence to remove also confusion with bottom-up approached (see next comment).

* 3/8 Not all readers might be familiar with “bottom-up approaches”.

RESPONSE: Done. We agree that not all readers might be familiar with “bottom up approaches” and have deleted the sentence.

* 3/16 “Autonomous flying vehicles” sounds like science fiction

- RESPONSE: Done. Changed to “drones”.

* 3/3 – 3/17. The whole paragraph needs to be rewritten. This reviewer does not consider necessary the discussion on the use of open-source microcontrollers in combination with cell-phones as a proxy to map environmental parameters. This work proposes the use of instrumentation specifically designed for measuring CO2.

RESPONSE: Agree. We removed the discussion of cell-phones. Due to lack of use of distributed CO2 sensors, we showcase two examples of low-cost networks for air and surface temperature, and then dramatically shortened the paragraph as follows “There is increasing interest to develop innovative methods for monitoring urban climate and air pollution using low-cost distributed sensor networks. For example, Meier et al. (2015) used sensor data from a commercial consumer-grade weather station network to examine fine-scale urban heat island effects in the city of Berlin. In another example, Chapman et al. (2015) developed a road sensor network to monitor road surface temperatures to optimally salt roads during the winter months in Birmingham. Given this growing interest in distributed sensing systems and the advances in related technologies, could there be new opportunities for the fine-scale mapping of CO2 emissions in cities?”

* 3/20 This study investigates the feasibility for mapping greenhouse gas emissions, specifically CO2. . .

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RESPONSE: Done. Changed sentence as follows: “This study investigates whether it is feasible to map greenhouse gas emissions, specifically CO2 at a spatial resolution of neighborhoods / blocks across the city with a portable network of mobile sensors that can be routinely implemented on various mobile platforms.”

* 3/22 Replace “car sharing platforms... or random vehicles” by “mobile platforms”.

- RESPONSE: Done. Changed to: “implemented on various mobile platforms.”

* 3/24-28 These four bullets sound more like the manuscript’s structure rather than the objectives. Rewrite them in one paragraph.

RESPONSE: Not changed. We argue that the organization into four sequential objectives (1-4) is useful to understand the work done, and does not impose a particular manuscript structure. Those are technical objectives that were fulfilled.

* 4/1-2 Never leave titles/subtitles without text. Don’t use uncommon acronyms for a title. All acronyms need to be previously defined in the text.

RESPONSE: Done. We changed the title to “2.1 A mobile measurement system for carbon dioxide”. We deleted the subheading “2.1.1 System requirements” which now becomes the introductory text for 2.1.

* 4/4 This sentence is repetitive.

RESPONSE: Due to the shortening of the section on previous work (Comment on 3/3 – 3/17) this sentence is no longer repetitive.

* 4/5 What about “passenger” instead of “various”?

- RESPONSE: Done. Changed “various cars” to “passenger cars”

* 4/7 Define limited time-scale and fine resolution. One, two five hours? Grid cells of 50, 100, 500 m2?

RESPONSE: Done. We do not specify a typical temporal range (deleted ‘(hours)’)

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because this depends on the size of the area to be measured. But given the density of our transect and typical vehicle speed, our 12.7 km2 area was sampled within 3.5 hours with five sensors. This means for one km2 and one sensor we can cover approximately 0.7 km2 hr-1. We added the following sentence: 'With typical vehicle speed and a characteristic urban street layout / traffic density, one sensor is capable of covering between 0.5 and 1 $\rm{km}ˆ2$ per hour.'

* 4/9-10 ... have been stationary or mounted in specialized vehicles. . .

- RESPONSE: Agree. Changed as proposed.

* 4/13-16. Rewrite the whole paragraph. For example: Carbon dioxide analysers based on infrared detection (Licor...) were coupled with microcontrollers (Arduiono ...), etc.

RESPONSE: Done. The paragraph was rewritten in passive voice and simplified as follows: "We used a commercially available carbon dioxide infrared gas analyser (IRGA) (Li-820, Licor Inc., Lincoln, NE, USA). The Li-820 is a compact (23.23 x 15.25 x 7.62 cm, 1 kg), low maintenance (approx. 2 years of continuous use) and high accuracy (+- 1 ppm) CO2 analyzer. The Li-820 uses a single path infrared light to determine the CO2 mixing ratio within a closed path by detecting the amount of absorption of the light from the path. The gas analyzer was coupled with an Arduino microcontroller (Arduino CC, Ivrea, Italy). The Arduino platform is capable of communicating digitally with the IRGA, a Global Positioning System (GPS) unit (Adafruit Ultimate GPS Logger Shield with GPS Module, Manhattan, New York, USA) unit, and a digital temperature thermometer (Maxim Integrated One Wire Digital Temperature Sensor - DS18B20, San Jose, CA, USA). A custom hardware board was developed to connect all of the components together to distribute the correct amount of power to each of the hardware components and to allow for compact hardware and sensor input. The portable CO2 system was named the "Do-It-Yourself-Sensor-CO2", or "DIYSCO2' system. . ."

* 4/14 12.23 $\times$ 15.25 $\times$ 7.62 cm

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- RESPONSE: Done. Changed to “12.23 × 15.25 × 7.62 cm” as proposed.

* 4/16 No need “...monitoring applications including agriculture.”

- RESPONSE: Done. Removed: “built for various CO2 monitoring applications including agriculture “

* 4/19 Define GPS.

- RESPONSE: Done. Changed to “...Global Positioning System (GPS) unit...”

* 4/27 Material of the tube?

- RESPONSE: Done. Material defined as “Synflex, Polyethylene/Aluminum composite”

* 5/Panel b. Which is the height of the sampling line over the vehicle’s roof?

RESPONSE: Done. Added to text: ‘The sampling line inlet was 70 cm over the vehicle’s roof and 2.2 m above the road surface’.

* 5/Figure 1 legend. It is clear that both panels show photos of the CO2 system. No need of indicating that during operation the system is enclosed in the case neither that the used vehicle was a car-shared one.

RESPONSE: Done. We removed the sentence “During operation, the system is enclosed in the case, while LEDs on the box indicate system state” and also removed “of a car-sharing vehicle” and replaced by “of the vehicle”.

* 6/10 Indicate that in Canada, the driver position is at the left side.

RESPONSE: Done. We added a bracket “passenger window (right side)”

* 6/19-26 Rewrite the whole paragraph.

RESPONSE: Done. Changed and simplified to “The study area is a 12.7 km x 1 km quadrangle within the City of Vancouver, BC, which spans from the northern-most tip of the city in forested “Stanley Park” (49° 18’ 45.17”N, 123° 09’ 29.10” W, WGS-84) to

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the city's south eastern neigborhood "Victoria - Fraserview" (49°,12' 59.00"N, 123° 03' 46.90"W) (Fig. ... "

* 6/20 Provide locations using latitude and longitude in degrees.

RESPONSE: Done. All coordinates in the entire text of the manuscript have been changed to degrees (WGS-84). The geodetic datum (WGS-84) is only defined in the first instance.

* 6/27 Flux tower measurements.

RESPONSE: Done. Change title to "Flux tower measurements" as proposed.

* 6/28 Eddy covariance flux tower . . .

RESPONSE: Done. Changed from "eddy-covariance tower" to "eddy covariance flux tower".

* 6/28 No need to include the Fluxnet ID of the flux tower. The manuscript never makes reference to Fluxnet.

RESPONSE: Disagree. The reference given refers to the Fluxnet database. We kept the Fluxnet ID, because the Fluxnet ID is an official, unique global code, issued by ORNL that identifies the site. Knowing the Fluxnet ID goes along with the global fluxnet database that also hosts all data from this site, see: https://fluxnet.ornl.gov/site/4132.

* 6/28 – 8/9 This paragraph needs to be rewritten. Indicate since then the flux tower has been working. Provide a reference to a comprehensive description of the tower.

RESPONSE: The reference to Crawford and Christen, 2015 is appropriate to describe the tower location. The paragraph has been rewritten as follows: "On the flux tower, a CSAT-3 ultrasonic anemometer-thermometer (Campbell Scientific Inc., Logan, UT, USA) provided continuous measurements of sensible heat flux (H), wind direction, and wind velocity. Further, air temperature (T_tower) was measured with a shielded HMP 45 thermometer / hygrometer (Vaisala Inc., Vanta, Finland). All four radiation compo-

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nents, including long-wave upwelling radiation (L_downarrow), were measured by a CNR-1 net radiometer (Kipp & Zonen, Delft, The Netherlands). Carbon dioxide molar mixing ratios r_tower were measured near tower top (28 m) using a tube that pumps air to a TGA200 closed path analyzer (Campbell Scientific Inc.). In addition, CO2 mixing ratios were measured by a Licor-7500 open path IRGA (Licor Inc., Lincoln, NE, USA) co-located with the ultrasonic anemometer-thermometer."

* 7/Figure 2 legend. Avoid repeating information already given in the text e.g., 12.7 × 1 km). Try to use active sentences as much as possible (e.g., The location of the flux tower is marked by ... instead of Shown are also ...).

RESPONSE: Done. Changed to active sentences. Deleted redundant information, i.e. "a 12.7 km x 1 km" and "(where all five systems were cross-checked before and after the campaign)".

* 7/Figure 2 legend. Crawford and Christen, 2014 is a very good paper, but I do not consider necessary to include it here.

RESPONSE: Done. Removed "and 24 hour measurements of CO2 storage by Crawford and Christen (2014)."

* 8/11-15 Rewrite the whole paragraph. For example: Two fields campaigns took place, the first on ... during the summer and when trees leaves are in full, while the second on ... , covering the heating season. Sampling was conducted from 10:00 – 13:30 h, when vehicular traffic and meteorological conditions are relatively constant.

RESPONSE: Done as proposed, except that we kept the brackets to retain information on heating and leaf state: "Two field campaigns took place, the first on 28 May 2015 (non-heating season, broadleaf vegetation with leaves emerged) and the second on 18 March 2016 (heating season, before leaf emergence). For simplicity, data sets from the two dates will be referred to as "summer" (28 May 2015) and "winter" (18 March 2016). Sampling was conducted from 10:00 - 13:30 h, when vehicular traffic

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and meteorological conditions are relatively constant."

* 8/16. Remove this sentence.

RESPONSE: Done. Removed "In order to ensure that the study area was comprehensively sampled during the duration of the measurement campaign"

* 8/17 Replace predefined by designed.

RESPONSE: Done. Changed to "designed"

* 8/16-19 Rewrite these two sentences.

RESPONSE: Done. Rearranged the paragraph as follows: "Five DIYSCO2 systems were installed on vehicles. Each of the five vehicle was assigned a route to travel approximately 70 km during the study period (achieving an optimal sampling density of about 3.5 km2 hr-1). Each vehicle started and ended at the southeast corner of the transect (49° 13' 15.08" N, 123° 04' 14.11"W, Fig. 2). The routes of the five systems were drawn such that a majority of the streets and lanes in the study area would be sampled at least once in the 3.5 hour time period, but ideally sampled at different times throughout the campaign. The routes were evaluated using an overlaid 100 m $\times$ 100 m grid, confirming that nearly all of the grid cells would be crossed by at least one system if the routes were successfully completed. Furthermore, a bicycle was used to traverse trails in the forested area of "Stanley Park" to sample along pathways in the densely forested ecosystem away from roads. "

* 8/23 Should be bicycle instead of bike?

RESPONSE: Done. Changed all instances of "bike" to "bicycle" in entire manuscript.

* 9/3 Describe briefly such filtering methods.

RESPONSE: Done. They are described in the following sentences, but this was unclear. Updated text reads as follows: "The 1 Hz-data from all five DIYSCO2 systems were filtered according to Crawford and Christen (2014), so that all data were removed

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when the GPS recorded speeds were below . . .”

* 9/20 Data from the eddy covariance tower are. . .

RESPONSE: Done. Changed to “ Data from the eddy covariance tower are”

* 10/Eq. 3 So many conversion factors at the beginning of the equation are * confusing. Merge them in only one factor and explain its meaning in the text.

RESPONSE: Disagree. We argue that readers benefit from knowing how the factor is calculated, which is only possible when separating the individual conversions.

* 10/15 Remove “in the two measurement campaigns”. It is obvious.

RESPONSE: Done. Removed.

* 10/26-30. Make shorter this sentence. For example: This assumption is supported by a previous study in which no storage flux was observed during daytime for this particular site (Crawford and Christen, 2014).

RESPONSE: Done. We changed the sentence as suggested. The following sentence was also rewritten as “However, this assumption is severely violated at night and in the early to mid morning (Crawford and Christen, 2014; Bjorkegren et al., 2015), so the proposed approach does only work midday or afternoon.”

* 11/1-3 Any reference on the Reynolds analogy?

RESPONSE: Done. We added a references to Arya’s textbook (2001) and specify that this is the Reynolds analogy between turbulent heat transfer and passive scalar transfer.

* 11/11 Better indicate the percent of excluded or included readings.

RESPONSE: Done. Included this information as follows: “Grid cells with less than 10 samples were removed from further analysis, which resulted in 30.8% of all cells being removed in the summer campaign and 27.4% in the winter campaign.” * 14/Table 2.

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Indicate which those climate zones are.

RESPONSE: Done. Instead of numbers we now use the LCZ names according to Table 2 in Stewart and Oke (2012).

* 23/17 ... between 9:00 and 19:00 h ... This might be true for office buildings, but not for residential buildings.

RESPONSE: Agreed. We changed the sentence as follows to be more precise: "... studies show that building occupancy (and therefore energy use) varies. For example for office buildings, the major activity is between 9:00 and 19:00 (Martani et al., 2012)"

* 23/30 ... the traffic count data do not indicate . . .

RESPONSE: Done. Changed "does" to "do"

* 24/7-9 Do not list what others have made (you did it already in the introduction), better say that this study was the first in combining ... . to evaluate CO2 emissions at fine scale.

RESPONSE: Done. We changed the text as follows: 'In this study, we proposed and implemented a new approach to determine and map CO2 emissions at fine scale across a city. The approach combines multiple mobile sensors at street level with an eddy covariance flux tower." Also the following sentence was adjusted accordingly: "A portable, mobile sensor system to measure the spatial variability of CO2 mixing ratios called the DIYSCO2 was developed and tested."

* 25/19 Replace six tanks by six standard gases

RESPONSE: Done. Changed from "six tanks" to "six standard gases"

* 27/12 ...to the Open Street Map (OSM)...

RESPONSE: Done. Added acronym in bracket "(OSM)"

Reviewer 2: Anonymous

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Review of Lee at al. “A mobile sensor network to map CO2 emissions in urban environments” The paper presents a detailed methodology for measuring spatial CO2 emission in an urban landscape using low-cost sensor system deployed on vehicles in urban areas. Methodology for the estimation of CO2 fluxes from urban areas is compared with EC approaches measured using a traditional flux tower over Vancouver. This is a very detailed description of the approach and the validation against established methods and one can see the extreme usability of such a system. The paper is well within the remit of amt and the authors have a novel approach. This type of work is needed to address the major challenges of addressing the study of the urban atmosphere, not least its spatial heterogeneity. The authors discuss the various advantages and disadvantages of their approach. I am very happy at the level detail shown by the authors especially with the design and construction of the DIYSCO2 system. I would suggest the authors put the appendix in the supplementary information section of the article.

RESPONSE: We are thankful and appreciative of the comments provided. We recognize the feedback to move the appendix to the supplementary materials however given the feedback of the community (see comment by L. Golston below) and to emphasize the nature of AMT on measurement systems, we would like to keep the Appendix in the main, peer-reviewed part of the text.

Community comment by L. Golston

I would like to add some comments to help strengthen the description of the DIYSCO2 system:

* Appendix A1 is titled ‘sensor precision’, the first paragraph says accuracy is ensured by calibration but precision and linearity need to be tested, then the second paragraph says accuracy and linearity are tested, and the final paragraph concludes about linearity – please sort out the usage of each of these terms.

RESPONSE: Agreed. Corrected. In this section we have changed the title of the

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section to, “A1: Sensor accuracy and linearity” and changed the text to, “The accuracy of the Li-820 is ensured using a two-point calibration, performed in the lab using a zero-gas and a standard span gas in the range of assumed measurement. In the current study, all standard tanks have been calibrated against primary CDML / NOAA WMO traceable tanks with a typical error between standard and primary tanks in r < 0.15 ppm.” The observed data shown below in Table R2 indicates a strong linearity (R2 of 0.9999) and a root mean square error (RMSE) of 0.233 ppm for the six different CO2 mixing ratios. Note that sensor drift of the system are described in the following section, now renamed to “Sensor drift”.

* 6/5 and Appendix A1: This at first glance suggests impressive linearity, however there is not enough information to evaluate this claim. As an extreme example, if five of the six tanks had a mixing ratio of 399.08 ppm and the sixth was at 503.77 ppm you could get a linear R2 of 0.9999 even with a nonlinear sensor - please state the values of each tank. It would also be helpful to know how the standard tanks were calibrated against CDML / NOAA traceable tanks as was stated:

RESPONSE: Agree. Done. It is important to clarify which tanks we used. that although we used 6 tanks, only four were different. The accuracy of the CDML/NOAA tanks were tested against the TGA200. The table R2 shows each of the tank’s mixing ratios, its uncertainty, and the observed values from one of the Li-820. The text has been changed as follows. To test the linearity in the range 400 to 500 ppm, a test was performed using six standard gases of known r at 400 (2 tanks), 413 (1 tank), 457 (2 tanks) and 504 ppm (1 tank).

* Appendix A3 states a time response of 2.2 seconds for a 50% step change within the IRGA. This indicates that the effective number of samples is less than the 1 Hz that is stated, and could have an implication for the effective sampling density of measurements in the city. Please include a statement about whether the time response of the sensor being > 1 s affects the results.

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RESPONSE: Done. The 50% response time of the IRGA to a step change is 2.2 seconds, so the time constant is 3.2 s. So effectively, the resolution is less than 1 s as correctly pointed out. We changed the description in the main text and wrote a “nominal sampling rate” of 1 Hz and added a note that the sensor’s physical time constant is however 3.2 s. Further in APpendix A2 we stated the positional error, assuming the typical vehicle speed “However, as the time constant with 3.2 s was higher than the nominal sampling frequency of 1 Hz, the actual sampling frequency was less than one second, leading to a positional standard deviation of the signal of 10 m, not 5 m (at typical speed of 20 km $\rm{hr}ˆ{-1}$).” Note that there was also an overall delay of the system (which includes the 3m long sample inlet tube) of 18.2 seconds. We correct our measurements during post-processing from data gathered from field campaigns in order to shift the GPS and the timestamps of observed CO2 mixing ratios to properly attribute the measurements spatially and temporally.

* Appendix A4 This is an interesting test, but the second paragraph is somewhat difficult to read and several things need to be clarified: What exactly is the difference between the tests in p26/L30 where good agreement was seen between the grouped inlets, and p27/L1 where the grouped inlets had relatively large spread? By higher CO2 mixing ratios, does this mean this second results were for an area with direct traffic emissions?

RESPONSE: Done. Your understanding is correct. In areas without direct traffic emissions, there is good agreement between the sensors (+/- 0.5ppm), but in areas with direct traffic emissions, the varibility increases to the percentages listed. We rephrased accordingly. We also added a concluding statement “In summary, the sampling location is a source of much greater uncertainty than instrument accuracy, drift, or linearity in the context of this work.”

* What about the results of the ungrouped test?

RESPONSE: Done. We added the following information “The results of the ungrouped inlet test showed that 54.98%, 79.08%, and 87.49% of the data have a variability within

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5, 15, and 25 ppm, respectively for the data collected at 1s. When aggregated to 1 min, the data showed 66.67%, 91.66%, and 94.44% of the data are within 5, 15, and 25 ppm, respectively."

* p27/L1 implies that slightly less than half of the 1-s data is within 5 ppm, contradicting the next sentence. I also disagree with the use of 'accuracy' and 'error' here, since there is no standard to compare against other than the mean value, and would recommend spread or variability instead.

RESPONSE: Thank you. Noted. We have corrected the wording to "This indicates that slightly less than half of the 1-s data measured by the sensors are within 5 ppm of each other and that we can expect a majority of the data (>88.85%) to have variabilities up to 15 ppm depending on where on the car the inlet is mounted.

* If the authors move the appendices to a supplement per reviewer 2's comment, I would suggest retaining Appendix A since this would give a disproportionately large amount of space to the field results and comparison to inventory, in comparison to description of DIYSCO2 and the emission calculation methodology.

RESPONSE: We agree and would also ensure an equal treatment of sensor system design and testing and subsequent validation. Also we prefer to retain all appendices to keep them in the peer-reviewed part of the contribution.

* 2/15: This says accuracy, but the value given in parentheses is the 1-s noise specified in the instrument datasheet, not its accuracy. The Li-820 manual gives accuracy specifications, based on mixing ratio range and cell pressure, as a percentage (%) of reading

RESPONSE: Done. Corrected. Thank you for flagging this. It has been corrected in the text.

* 8/29: "In-situ calibration". This is a good thing to do, but should be called a comparison not a calibration since there is no standard used to calibrate against. Can also a

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comment also be made about whether this provided useful information? If this means parking five vehicles adjacent to one another, and given the variability described in

RESPONSE: Done. Well appreciated. Changed “calibration” to “comparison”. During the lab tests, the maximum drift over a 3.5 hour period was 0.82 ppm. We added the following text “During the field experiments however, we observed a maximum drift of +0.95 ppm relative to the mean of all sensors, which was greater than what was found in the lab test.”

* Appendix A4, I imagine it might be difficult to detect drifts this way both for individual sensors and for the ensemble of sensors.

RESPONSE: True, it is difficult to assess drifts for individual and ensemble sensors, especially in the field and could be an interesting future approach to pursue. In this study, our method was to to compare the the individual measurements against the mean. No absolute reference was available other than the manual calibration against standard tanks.

* 12/5: What is the meaning of "sample" in this section. Does one sample correspond to one 1 Hz measurement? If so, there should be some discussion about vehicle speed since that will affect the spacing of measurements.

RESPONSE: Done. Correct, the sample corresponds to one 1hz measurement. We added a claifying bracket: “(1 sample equals one 1 Hz measurement)”. We discuss the delay time and the method for correctly attributing the measurements in our discussion of the response time of the sensor system in Appendix A3. Here we added “At the average vehicle speed of 20 km hr-1 this corresponds to a spatial spacing of 5.5 m.”

* Spell out IRGA at first use

RESPONSE: Done. IRGA is defined as “infrared gas analyzer”.

* p2/L14 and p8/L5: NB -> NE

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RESPONSE: Done. Changed to “NE” for Nebraska.

* p9/L2: gridding

RESPONSE: Done. Changed all instances of “griding” to “gridding”.

Please also note the supplement to this comment:
http://www.atmos-meas-tech-discuss.net/amt-2016-200/amt-2016-200-AC1-supplement.pdf

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Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-200, 2016.

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Table R1 - Student's t-test for pairs of neighborhoods (on 100 x 100 m grid cells). W = populations are statistically significantly different in winter; S = populations are statistically significantly different in summer campaign.

	SP	**WE**	**DT**	**FM**	**KR**	**SV**
Stanley Park (**SP**)		W	W / S	W / S		
West End (**WE**)	W		W / S	S	W / S	W
Downtown (**DT**)	W / S	W / S		W / S	W / S	W / S
Fairview - Mount Pleasant (**FM**)	W / S	S	W / S		W / S	W / S
Kensington-C. Cot. - Riley Park (**KR**)		W / S	W / S	W / S		
Sunset - Victoria-Fraserview (**SV**)			W / S	W / S		

Fig. 1. Table R1

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Table R2 - Comparison between standard tanks and Li-820 observed CO2 mixing ratios.

Tank ID	Standard tank mixing ratio (ppm)	Tank uncertainty relative to primary reference (ppm)	Li-820 observed (ppm)
UBC CO2-007	399.079	±0.047	400.38
UBC CO2-010	400.340	±0.042	401.84
UBC BIOMET-73	412.714	±0.112	413.99
UBC CO2-011	456.912	±0.107	458.38
UBC CO2-008	457.756	±0.131	458.67
UBC CO2-001	503.767	±0.025	504.13

Fig. 2. Table R2

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