Reply to Anonymous Referee #3

We thank the reviewer for their thorough and detailed review of the manuscript text. Highlighted below are changes to the text we have made to address the suggested revisions.

The authors present data and analysis from six mobile measurement surveys in the Montney formation which include methane emission concentration and rate information from 1600 passes near wells. The routes were surveyed 3-6 times each and designated as new wells, old wells, and a control. The authors use the methane and CO2 concentration and meteorology data to calculate emission rates of methane from wells. They analyze the data using online well number, production, age, etc. information to show which types of wells or activities emit most or most often. And finally, they compare their results to available data from recent studies in other formations in U.S. Collection of mobile data, especially when one is at the whim of wind to assure downwind of well measurements, is no easy task. The authors have conducted a great survey of sites in the Montney formation. This study is exactly the type of research that is needed to clarify and quantify the emission rates of methane from different formations and sources. The authors have done a lot of work and the publication of this paper (especially with the availability of the data upon request, as noted at the end of the manuscript) will be a great addition to the current body of knowledge on methane emissions from oil and gas sources. However, there is some more analysis, organization, and sentence structure improvement that is needed for this paper before publication. Please see my General and Specific comments below:

General Comments

1. Various groups have used different approaches to quantifying methane emission rates (e.g., EPA's OTM 33 method, use of different tracers for close or far quantifications using the Tracer Ratio Method, reverse plume modeling, etc.). One of the things that all the methods above have in common is method validation. It seems that the authors of this paper have not conducted any method validation studies. This is a major weakness in the study. I would recommend that a quick methane and CO2 release study and measurement be added to the paper. However, I understand that time and funding may not be available to do this. Instead, I suggest the authors do a detailed uncertainty analysis (maybe even add a section to the paper) where they discuss and calculate a theoretical uncertainty for their measurements and calculations. The authors have a short section on this, but since no method validation has been done, the uncertainty analysis should more exhaustive.

Please see our response to comment *P1 L17* from Anonymous Referee #2 for information on method validation and how our calculations are very similar to results from a recent study at a nearby oil and gas development accessing the same hydrocarbon formation (GreenPath, 2017).

The primary objective of our study was to collect data on emission frequencies and to establish what infrastructure types emitted most frequently. Minimum volumetric estimates were included, but were not the main focus. Calculating emission frequencies for every oil and gas development is important because it determines the number of wells/facilities by which emission factors should be multiplied in order to achieve an accurate emissions inventory estimate.

We have added the following text to section *1 Introduction* of our manuscript to clarify that emission frequency calculations were the main objective of this study.

"In this study we used a multi-gas (CO2, CH4) mobile surveying method that uses ratio-based gas concentration techniques and wind data to detect and attribute on-road CH4-rich plumes to the infrastructural sources of natural gas developments in northeastern British Columbia, Canada. Our primary interest in this study was to determine the frequency of emissions, and the relationship between emissions and specific classes of infrastructure."

2. Another point that is not clarified in this paper is the difference between measurements made from unconventional vs conventional wells. The authors make a distinction between new and old wells. The attribute the increase in the oil and gas activity in the area to the use of unconventional extraction methods. However, when they discuss the wells measured, they do not show any information on the unconventional vs conventional wells. Are all the wells measured unconventional?
The area we surveyed in Northeastern British Columbia mainly produces unconventional natural gas. A large majority of gas wells we surveyed use unconventional techniques of extraction (hydraulic fracturing and/or horizontal drilling). We included one survey route that targeted an area of conventional oil development for comparison (Route 1). The increase in development in the area over the last decade has been from unconventional natural gas infrastructure (discussed in section *1 Introduction*). Information about what type of infrastructure is on each route is included in section *2.1 Field Measurements*. And the difference in emission frequencies from oil and gas infrastructure is shown in Figure 8 (now Figure 9 in the revised manuscript) in the chart titled Well Fluid Type.

3. The authors do not distinguish between short term operations and permeant emission sources in their calculations. This may be difficult to do, but at least a discussion of how these would affect the regional emission calculations should be added.
In this study we look at emission persistence in terms of survey repeats. To be conservative in our method of identifying emitting infrastructure, we only tagged infrastructure as emitting if we detected CH4-enriched plumes within 500 m downwind at least 50% of the times we surveyed it. For many of the pieces of infrastructure we surveyed this means it was associated with a plume downwind on three out of six surveys. We have added text to clarify this in section *3.4 Methane Emission Inventory Estimates*.

"This value is likely a conservative estimate because it is the smallest value detected at our mean detection distance (319 m), and the majority of our emission detections occurred around this value (Fig. 3). It is also conservative because our method of attribution only considers the wells and facilities that were persistently associated with downwind plumes."

4. Some of the writing in the paper is confusing. The sentence structures do not flow well. I have given some specific examples of this in the "Specific Comments" section, but strongly suggest the co-authors who were not directly involved in the writing of the manuscript read the paper and comment on sections. Sometimes it is easy for the authors to unintentionally disregard clarity as they themselves are so familiar with the subject of the study.

We have combed the manuscript with this comment in mind and improved the phrasing as recommended in the "Specific Comments" section of this review.

5. The authors use two different tenses and two different voices (active and passive) throughout the paper. I suggest choosing only one. Two different voices and tenses make it confusing for the reader and require re-reading of sections.

We have made all necessary changes to move from passive to active voice.

Specific Comments

1. Abstract: The writing style of the abstract does not lend itself to clarity. The flow of the sentences is not coherent. I suggest re-writing it for better clarity and flow. For example: "We also observed emissions from facilities of various types that were highly repeatable." is one of the sentences that is unclear and confusing. Or "This value exceed reported bottom-up estimates of 78,000 tonnes for all oil and gas sector sources in British Columbia, of which the Montney represents about 55% of production". The abstract starts very abruptly. I suggest rewording the first sentence.

The following sections of the abstract have been revised for clarity, as well as sections addressed in response to comment from Anonymous Referee #2 *p1 L13-15.*

"In August to September, 2015 we completed almost 8,000 km of vehicle-based survey campaigns on public roads dissecting oil and gas infrastructure such as well pads and processing facilities."

"Emissions from gas processing facilities were also highly repeatable."

"This estimate for the Montney area exceeds reported bottom-up estimates of 78,000 tonnes methane for all oil and gas sector sources in the province. Current bottom-up methods of methane emission estimates do not normally calculate the fraction of emitting infrastructure through thorough on-ground measurements. However, this study demonstrates that mobile surveys could be used to gather a more accurate representation of the number of emission sources in an oil and gas development. This study presents the first mobile collection of methane

emissions from oil and gas infrastructure in British Columbia, and these results can be used to inform policy development in an era of methane emission reduction efforts."

2. Page 1, Line 2: What do the authors mean by "incidence"?
"Incidence" was used interchangeably with "emission frequency". This sentence has been reworded for clarity, and "incidence" has been changed to "emission frequency" throughout the text of the manuscript.

"This study examined the occurrence of methane plumes in an area of unconventional natural gas development in northwestern Canada."

3. Page 1, Line 4: Are authors including all oil and gas locations in "development". I suggest clarifying this or using a different word.
"Development" refers to areas where oil and/or gas is being extracted, and oil and gas infrastructure is dense. It has been changed in the abstract, and defined when it is first used in the manuscript.

"North American leaders recently committed to reducing methane emissions from the oil and gas sector, but information on current emissions from areas of unconventional natural gas extraction in Canada are lacking."

4. Page 1, Line 6: The use of "infrastructural" here has the same problem as the previous comment.
"Infrastructural" refers to oil or natural gas infrastructure, including wells and processing facilities. This has also been reworded in the abstract and defined in the manuscript for clarity.

"To attribute on-road plumes to oil and gas related sources we used gas signatures of residual excess concentrations (anomalies above background) less than 500 m downwind from potential oil and gas emission sources."

5. Page 2, Line 5: What do the authors mean by "a petroleum system".
A petroleum system is a term defining all the necessary geological components and processes required for the formation and accumulation of hydrocarbons.

6. Page 2, Line 14: Please rewrite "Over a 100-year... (ICPP, 2014)" for clarity.
This sentence has been revised for clarity.

"The radiative forcing of CH4 is greater than 30 times that of CO2 over a 100-year timespan."

7. Page 2, Line 33: I have noted this in the abstract too. Please describe what you call "infrastructure".
Please see answer to comment *4. Page 1, Line 6* above.

8. Page 3, Line 1,2: Please re-write sentence for correct grammar.

This sentence has been revised for clarity.

"Furthermore, it is important to note that emission frequencies may vary between developments because of operator best practice, or due to the properties of the geological formation that the hydrocarbons are being extracted from."

9. Page 3, Line 13: Please define "super-emitters" and use appropriate references.
This sentence has been changed to include all emission sources.

10. Page 3, Line 26: Do the authors have some estimate of numbers of wells?
We have revised this line discussing the increase in natural gas production to the following:

"These unconventional methods yielded 4-5 times more natural gas from the Montney formation than conventional techniques that were attempted prior to 2005. Since then, production of BC unconventional natural gas has increased significantly, with the Montney play being the largest contributor in the province (BC Oil and Gas Commission, 2012)."

11. Page 4: The authors use the words unconventional and hydraulically fractured interchangeably. These two do not mean the same thing. Unconventional oil and natural gas extraction refers to both hydraulic fracturing and horizontal drilling.
The use of "hydraulically fractured wells" has been changed to "unconventional wells" where appropriate throughout the text of the manuscript.

12. Page 4, Line 8: Is 1Hz frequency the rate of data collection?
Yes, it is the rate of data collection. This sentence has been reworded for clarity.

"In total we surveyed 7,965 km of public roads, with an average route length of 248 km. We collected gas concentrations and wind data at 1 Hz frequency while surveying."

13. Page 4: What were the average distances from wells? If this data is available, can it be used with meteorology data for plume dispersion modeling?
We calculated the average distance from wells and used this value with plume dispersion modeling to calculate our minimum detection limit in section *3 Results and Discussion* of the manuscript.

14. Page 4, Line 14: Please re-write for correct grammar.
This sentence has been reworded to the following:

"We surveyed four of the routes six times throughout the field campaign, and the two remaining routes (including the Control Route) three times each. We repeated surveys on multiple days to account for varying wind directions. Repetitions of each survey route included both morning and afternoon drives to incorporate varying atmospheric conditions. We also used the repeated survey data to obtain statistics on emission persistence."

15. Page 4: Please note which routes the numbers are based on in Figure 1.
We have referenced the route names from Figure 1 in this section.

16. Page 4, Line 19: What do the authors mean by "raw" ?
We used the term "raw" in this section to make clear that no processing was done to the atmospheric gas concentrations at this phase of data collection.

17. Page 4, Line 23: What are wind speed units?
The wind speed was measured in km/h. We have added this information to the manuscript.

18. Page 4, Line 25: Since the authors have given the manufacturer of the other instruments used, why not indicate what type of GPS was used?
The type of GPS used has been included in the manuscript.

19. Page 4, Line 32: Please re-write "However, our surveys. . . unusable." for clarity.
This sentence has been rewritten to the following:

"The survey routes in our study were multiple hours long each and were often routed through various land use types. For this reason, we did not use the traditional methods of calculating background atmospheric gas concentrations."

20. Page 5: Were the same approaches used for both CO2 and CH4 data handling and analysis? Please add a few sentences to clarify this.
Yes, we used the same method of data processing for all gas measurements collected (CO2 and CH4). We have added text to clarify this in the manuscript.

21. Page 5, Line 10-12: Please add some statistical data.
Please see answer to Anonymous Referee #2 *P5 L10-12.* We have added an example plot to explain our method of choosing the RMRI.

22. Page 5, Line 20-21: Please re-write for clarity.
We have rewritten this sentence to the following:

"We identified CH4 plumes from oil and gas infrastructure in areas where there were multiple successive datapoints with depressed eCO2:eCH4 values."

23. Page 5, Line 21: What do the authors mean by "normal air"?
The term "normal air" has been changed to "ambient air" in the manuscript.

24. Page 5: What are some sources of CO2 in the area? As this can be a major concern in your calculations, please add a few sentences to address this.
As detailed in Hurry et al. (2016), the ratio technique helps identify (and remove) measurements that are enriched with respect to CO2. We have included the following text in section *2.2 Identification of Natural Gas Emissions* to describe possible sources of CO2 emissions in the area:

"Variation of CO2 within the survey area was likely primarily a function of oilfield processes (emissions, engines, flares) because there was little industrial activity on the survey routes that was not related to oil and gas development."

25. Page 6, Lines 1-2: Please re-write for clarity.
We have rewritten this sentence to clarify.

"Otherwise, all in-place oil and gas infrastructure were considered possible emission sources."

26. Page 6, Line 2: What do the authors mean by "developmental"?
The term "developmental" meant that the well was under development. This term has been removed and this sentence has been reworded to the following:

"The infrastructure database included the well and facility locations, as well as various attribute data such as infrastructure types, statuses, and spud dates (drilling dates)."

27. Page 6: Are there any large dairy operations in the area?
We did not encounter any large feeding operations while surveying. We only encountered smaller farms for which a database of locations could not be obtained.

28. Page 6, Line 15: Please re-write sentence for clarity.
We have rewritten this sentence for clarification.

"We collected atmospheric gas concentration data along 30 surveys of six different routes. The routes ranged in length from 200 - 550 km, and the oil and gas infrastructure located on these routes was managed by more than 50 different operators at the time of surveying."

29. Page 6, Line 16: I thought the authors used one route as control. Did they actually make measurements from oil and gas structures on this route and include them in the analysis? If yes, then should the designation not be changed?
The route we used as a control had significantly less infrastructure. This allowed us to visually compare sections of the surveys near infrastructure, and sections far away from infrastructure. We only used the Control route datapoints > 5 km from any infrastructure to calculate the fraction of false positives.

30. Page 6, Line 19: Following up on the previous comment, please give numbers of the differences in the oil and gas densities.
The amount of infrastructure on each route (sampled and emitting) is listed in Table 1.

31. Page 6, Line 30: What was the speed of the car during these measurements? This is important as it can have an impact based on the width of the plumes.
The vehicle speed was variable due to the speed limits on the public roads we

were surveying. Plume width was not incorporated into any of our measurements, including our estimate of leakage rate. For this reason we have not included vehicle speed in the manuscript.

32. Page 6, Lines 31-32: What is the difference between 314 and 319 meter designations? Also, should this not be in the methods section instead of the results section?

We calculated average distances between the survey route and infrastructure for two scenarios: the first being datapoints when we were sampling infrastructure (314 m), and the second being when we were detecting emissions from infrastructure (319 m). We have reworded these lines in the manuscript to clarify this point. These values are not in the methods section because they were calculated from the collected data and the locations within the infrastructure database.

33. Page 7, Line 1: What do the authors mean by " In each, we see a peak of signatures near ~215 which is representative of natural"?

This sentence has been reworded in the manuscript to the following:

"In each density plot, there is a peak where eCO2:eCH4 = ~220, which is representative of the ratio between ambient CO2 and CH4."

34. Page 7, Line 5: relative to what?

For clarity, we have reworded this sentence to the following:

"The kernel density plots in Figure 1 show that, in all of the survey routes except the Control, we see a population of CH4-enriched anomalies (less than the natural ratio of 220), that are the result of localized plumes from natural gas development."

35. Page 7, Line 25: What are the other methods?

"Other" was a typographical error that has been revised.

36. Page 7, Line 27: Should this be associated?

We have removed the word "associate" from this sentence.

37. Page 7, Line 30: Please define what you mean by ". . . a piece of infrastructure. . ."

The use of the term "infrastructure" in this manuscript refers to oil and gas related infrastructure such as well pads and processing facilities. This is described earlier in the manuscript in response to comment *4. Page 1, Line 6.*

38. Page 7, Line 32-34: Please re-write for clarity.

We have reworded this in the manuscript to make this point more clear.

"Our technique of background subtraction is tuned to resolve small, localized plumes, but it should be noted that atmospheric conditions have a significant…"

39. Page 7: I suggest adding clarifying sentences like, Well pads were the most common oil and gas structures encountered/sampled during our survey (%# of total sites).
We have added the following lines to help refine this section of the manuscript.

"Well pads were the most common type of oil and gas infrastructure sampled during our surveys (58% of total infrastructural emission sources)."

"Emitting infrastructure includes wells and facilities where at least half the transits past the well were associated with a CH4 plume in the downwind direction (50% persistence)."

40. Page 8, Lines 5-8: Please re-write for clarity.
We have reworded this in the manuscript to the following:

"Many previous fugitive emission detection studies do not replicate surveys, but repeated emission detections help build both confidence in detection, as well as statistics about emission severity and persistence through time."

41. Page 8, Lines 14-17: Please use a consistent theme for capitalization.
We have made changes throughout the manuscript so that all well/facility status and types are capitalized.

42. Page 8, Line 20: Please replace the term "probably" with one with a more scientific connotation or even some statistics.
This was a typographical error. "Probably" was mean to be "probable", and we have made this change in the manuscript in response to comment from Anonymous Referee #1 *p.8, 1.20.*

43. Page 8: Please explain, clearly, what each category of wells encompasses. For example, does authorization mean that permit was granted? Was work on the pad started? Was temporary drilling part of the study or as noted previously was it excluded?
We have added the following text to the manuscript to clarify the definitions of these terms where possible. Please also see our reply to Tony Wakelin's comment below concerning certain well statuses.

"The infrastructure inventory we obtained from the provincial regulator identified several statuses of wells including Active, Abandoned, Cancelled, Completed, and Well Authorization Granted (WAG). It should be noted that Cancelled means that the permit for the well has been cancelled, usually before drilling has begun. Similarly, wells with the status of WAG may not have commenced drilling at the time we completed our surveys. However, based on discrepancies noted in the field about abandoned infrastructure, the accuracy of the status information in the inventory database could not always be relied upon. Furthermore, we assumed that test drilling and nearby infrastructure in these locations might serve as potential emission sources as well, so we chose to include wells with these status types in our analysis. A well with a Completed status means that the well drilling was complete, and it was being prepped for production."

44. Page 9, Line 27: 60 out of how many?

The total number of active wells we sampled is listed in Table 2. However, we have added the total (676) to this line in the manuscript.

45. Page 10, Line 2: Please reword ". . . less emission prone. . ."

We have reworded this line in the manuscript for clarity.

"Infrastructure type is a potential driver of emission patterns, which supports studies that have found large discrepancies in emission factors between valves used in different regions of the US (Allen et al., 2013)."

46. Page 10, Line 20-32: This paragraph does not belong in this section. I suggest either deleting it or moving it to a more appropriate location.

We have left the first line of this paragraph in this section of the manuscript. The rest of the paragraph has been integrated with the final paragraph in section *4 Conclusion*, and now reads as follows:

"Methane emission reduction strategies for large natural gas developments such as the Montney should focus on first locating super-emitting sites, and then follow up with site-specific emission techniques such as FLIR cameras. This strategy would support LDAR already in place, in a way that would minimize cost to individual operators. It would also focus the attention on the problematic infrastructure and operators, and does not share the cost burden across companies that have already invested heavily in emission reduction technology and leading best practice. It is feasible to detect super-emitters through exhaustive survey campaigns, even …"

47. Page 12: Please give a more detailed (method definition, details, and statistics) of the setup of your calculations.

Where possible, we have added further details to this section of the manuscript. However, we feel that the calculations are made clear in Table 2. We did notice a typographical error in the Emission Volume column of Table 2, which has since been amended.

Table 2. Emission volume calculations for all surveyed infrastructure, and also extrapolated to account for all wells and facilities within the BC portion of the Montney formation. Our minimum detection limit (MDL) of 0.59 g/s was used as the emission factor for wells. Facility emission volumes are from Omara et al. (2016) because our sampling from facilities was probabilistic due to emission height variance.

Type	Infrastructure n	Emission Freq (%)	Emission Volume (tonnes/year)	Emission Total (tonnes/year)
Surveyed Wells				
Active	676	47	18.6	5910
Abandoned	228	26	18.6	1103
Cancelled	130	35	18.6	846
Completed	64	30	18.6	357
Surveyed Facilities	265	32	70	5936
Total CH_4 volume				14152
Montney Wells				
Active	5294	47	18.6	46,280
Abandoned	2149	26	18.6	10,392
Cancelled	1989	35	18.6	12,948
Completed	582	30	18.6	3248
Montney Facilities	1742	32	70	39021
Total CH_4 volume				111,889

48. Page 13, Line 5: Have the number of wells changed since 2012? Would this affect the calculations in this paper, especially when dealing with the comparison to other sites/studies?

Yes, there was most likely a change in the number of active wells between 2012 and the time these surveys took place in 2015. Unfortunately, the most recent regional CH4 emission estimate we could find for the area was from 2012. We have added the following text to section *3.4 Methane Emission Inventory Estimate* of the manuscript to clarify this discrepancy and how it affects our comparison to the provincial estimate.

"It should be noted that the most recent available CH4 emissions inventory from the province was from 2012, and that increased development and production from the Montney since then may have increased what the regulator would expect to see from this development. However, the 2012 estimate was the most recent applicable emissions estimate we could locate to compare our estimate to."

49. Page 13: Please add a discussion of possible reasons for the differences in this study and others noted here. Uncertainty range? Different basins? Different measurement approaches?

We have added the following text to explain the differences in measurement approaches:

"Although airborne measurement techniques are not ideal for locating exact emission sources, they are well-suited to calculate total emission volumes for

entire regions so long as other emission sources (such as agriculture) can be accounted for, which they were in the studies listed above. The top-down nature of mobile surveying large amounts of infrastructure allows for a comparison between our CH4 volume estimate and those of Peischl (2016) and Karion (2015)."

50. Page 13, Line 29: Please give numbers.

We have included the emission frequencies here. This line has been revised to:

"Abandoned wells were also associated with emissions at 26% of the 228 sites we sampled, and we located a group of aging infrastructure (> 50 years old) that was emitting every time we sampled downwind."

51. Please revise the Conclusion. It needs more specific numbers and information. Also, the addition of super-emitters at the end does not make sense as this paper was not directly making measurements from such sites based on the previously discussed statistics.

To maintain the brevity of the paper we have decided to not include more specific results in the Conclusion. As discussed in response to comment *P14 L9* from Anonymous Referee #2, the mobile survey method is ideal for detecting super-emitters. However, our results were not indicative of the presence of super-emitting sites in the BC Montney, and our results mirror the results found in an independent study by GreenPath Energy (2017).

52. Figure 1: Is it possible to add the location of the wells here as a light gray background? It would be helpful in visualizing the type of routes. Also, please make sure that your designations of routes in this figure and the paper are the same. After reading through, I found TABLE 1 in Tables. Do authors mention this table in the text of the manuscript?

The map scale does not allow for the infrastructure locations to appear as individual points. The routes designations in Figure 1 are correct, and Table 1 is now referred to in the text of the manuscript in the following sections: *2.1 Field Measurements*, and *3 Results and Discussion*.

53. Figure 2: What are 88 industry- defined areas?

We have revised this figure to show the detection distances on each route. Please see response to Anonymous Referee #1 *Figure 2.*

54. Figure 3: This is not a comment on this figure, but in looking at this and other figures, having a table with route numbers, names, and characteristics would be very helpful. Something like Table 1.

This information is included in Table 1.

55. Figure 4: Please revise caption to explain graph better. What are the gray lines?

The gray lines are surveyed roads. This is now explained in the caption.

56. Figure 5: Please re-write caption for clarity. Also, the addition of the uncertainty

discussion as noted before, will help this figure.

57. Figure 7: Why are there zero-zero points in this graph? Although physically a zero-zero point makes sense, I do not think the addition of the points is statistically sound.

We have re-plotted the regression plots as bar graphs. Please see response to comment from Anonymous Referee #2 *Fig.5,6,7.*

58. Figure 9: Please add numbers in the increasing sample size legend. Were any of the wells in this area re-worked? This will change the definition of well age in this discussion.

We have not added numbers to the increasing sample size legend because each graph in the figure has a slightly different scale. However, one legend for sample size without numbers is sufficient because it is only meant to show the relative number of times we sampled infrastructure in each category.

We did not have information on whether or not wells were re-worked.