

Bridging Detection Gaps in Oil and Gas Methane Inventories: Comparison between Aerial-Based and Vehicle-Based Surveys

Martin Lavoie

mlavoie@stfx.ca

St. Francis Xavier University

Robyn Latimer

St. Francis Xavier University

Gilles Perine

St. Francis Xavier University

Afshan Khaleghi

St. Francis Xavier University

David Risk

St. Francis Xavier University

Mackenzie LeVernois

St. Francis Xavier University

Research Article

Keywords: inventories, top-down, bottom-up, methane, measurement systems

Posted Date: June 17th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9348130/v2>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

**Bridging Detection Gaps in Oil and Gas Methane Inventories: Integrating Vehicle-Based to
Screening Surveys**

Martin Lavoie^{1,*}, Robyn Latimer^{1,2}, Gilles Perrine¹, Afshan Khaleghi^{1,2}, Mackenzie LeVernois¹,
David Risk¹

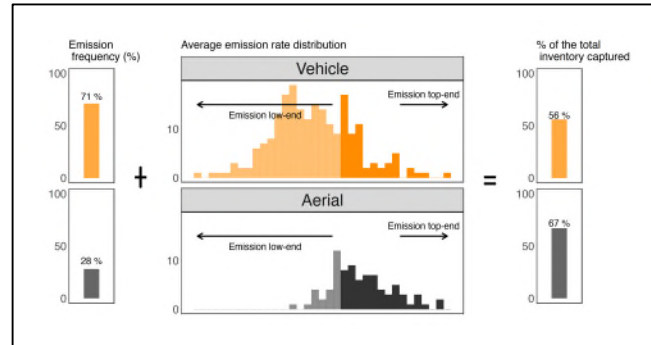
¹Department of Earth and Environmental Sciences, St. Francis Xavier University, Antigonish,
NS, Canada

²Department of Engineering and Applied Sciences, Memorial University of Newfoundland, St.
John's, NL, Canada

*Corresponding author: martin21skifond@gmail.com; mlavoie@stfx.ca

Abstract

Optical gas imaging (OGI) is widely used in regulatory leak-detection and repair (LDAR) programs, yet studies show it misses a substantial share of sites and emissions compared to aerial methods suggesting the two



methods capture complementary emission subsets. In addition, OGI surveys are time-consuming, which creates opportunities for alternative technologies that are equally sensitive but faster and more cost-effective. This study compared vehicle-based and aerial-based technologies at 302 sites in Alberta, Canada. The vehicle-based system had the highest detection frequencies at 71% compared to aerial-based at 28%. The vehicle-based system was also more sensitive than aerial-based, capturing 69% of emissions < 1kg/h, far more than aerial-based, while aerial-based measurements identified higher total site-level emissions, particularly from tall sources. These findings suggest that the vehicle-based system was more effective than the aerial-based at finding emitting sites across a broader emission range. In addition, the vehicle-based method is faster than OGI, positioning it as a strong candidate for bridging the gap between component-level and aerial methane monitoring.

Keywords: inventories, top-down, bottom-up, methane, measurement systems

Synopsis: The vehicle-based system found more emitting sites than the aerial-based technology across a range of facility sub-types. The vehicle-based is also faster and more cost-effective than OGI surveys.

1. Introduction

The oil and gas (O&G) industry is a significant contributor to anthropogenic methane (CH₄) emissions, accounting for roughly 45% of CH₄ emissions in Canada ¹, and 20% worldwide ². Recognition of CH₄ as an important near-term climate forcer has led to increased regulatory efforts aimed at reducing O&G CH₄ emissions, with regulations already implemented in the US and in Canada and recently introduced in the European Union. This focus on CH₄ emission reduction has accelerated the development of new CH₄ measurement technologies that span a range of spatial scales and detection capabilities. Significant challenges have emerged in reconciling emissions measured by different technologies with each other and with reported inventory values; a comprehensive review by Helmig and Caputi ³ found that 86% of the recent literature reported higher top-down emissions than bottom-up estimates. There is an emerging consensus that rather than framing different measurement methods as competing alternatives, their complementary capabilities can be leveraged and combined to better characterize the full distribution of emissions. However, more work is required to understand the strengths and limitations of individual technologies, the implications of relying on any single method, and how different technologies can be integrated within LDAR programs and inventory development.

At one end of the measurement spectrum, optical gas imaging (OGI) cameras have long been an accepted method of detecting and more recently of quantifying (qOGI) component-level CH₄ leaks on O&G sites. They remain the regulatory standard for LDAR programs in many jurisdictions and have also been used to fill in the low-end of emission distributions for inventory applications ^{4,5}. OGI allows operators to visually identify emissions from individual components, enabling targeted repairs. However, OGI surveys are labour intensive and time consuming, limiting the number of facilities that can be inspected within a given period. In addition, controlled release studies have shown that OGI detection sensitivity can vary widely depending surveyor experience, operating conditions, inspection duration, and the background used to view a leak, with reported 90% probability of detection thresholds ranging from 1.55 kg/h ⁶ to 0.013 kg/h ⁷. This wide range of detection sensitivity introduces uncertainty regarding the extent to which low-level emissions are consistently captured by OGI surveys.

On the other end of the spectrum, aerial-based surveys provide efficient coverage of large geographic areas and have emerged as an important emission screening approach. Bridger Photonics' gas mapping LiDAR (GML), for example, has the capability to estimate emission rates at the site level with considerable accuracy, and under certain conditions, identify the specific components responsible for emissions^{8,9}. Previous field studies have shown that aerial LiDAR surveys frequently capture large emission sources that are missed by traditional OGI-based LDAR surveys^{8,10}. Bridger's detection sensitivity is influenced by wind conditions and flight altitude, with detection capability improving at lower wind speeds and flight altitudes¹¹⁻¹³. Conrad et al.¹¹ calculated a 90% detection limit of 2.3 kg/h under reference conditions of 175 m altitude and 3 m/s windspeed. As a result, aerial surveys may fail to consistently identify lower-level emissions that can collectively contribute to overall emissions.

Vehicle-based methane measurement systems occupy an intermediate position between these two approaches. In a typical configuration, a vehicle equipped with a high-precision methane analyzer measures CH₄ concentrations downwind of O&G sites, and atmospheric modelling is used to estimate site-level emissions. One implementation of this method, originally developed at St. Francis Xavier University (StFX), has been used extensively in upstream O&G emission studies¹⁴⁻¹⁸ and is actively employed by the industry within LDAR programs. The detection sensitivity of these systems depends on the measurement protocol (e.g. on-pad vs off-pad surveys, number of measurement transects) and instrument precision. Controlled release experiments have demonstrated that the range of detectable emission rates overlaps with the lower end of reported OGI sensitivities, with a 90% POD of 0.024 kg/h reported in a recent study¹⁹. Unlike OGI, the StFX vehicle-based method cannot resolve leaks at the component level, instead attributing detected leaks to equipment groups or sites. The StFX method has been shown also to be less effective at quantifying tall emission sources and large sites¹⁶. However, it can survey significantly more facilities over a given period than conventional OGI inspections while detecting emissions below the detection limits of aerial methods.

While vehicle-based measurement systems are widely deployed in O&G emission monitoring, field studies comparing their performance to commonly used aerial-based and OGI approaches are lacking. This study therefore aims to (1) compare site-level emission rates from independent aerial

LiDAR and vehicle-based surveys at 302 operating oil and gas sites in Alberta, (2) compare site-level emission rates from vehicle-based and OGI measurements at 53 oil and gas facilities, and (3) investigate differences in emission rate magnitudes, frequencies and distributions between the measurement technologies. By evaluating the complementary capabilities of these approaches, this study provides insight into how vehicle-based screening can enhance CH₄ monitoring strategies by bridging detection gaps between aerial and component-level surveys.

2. Methods

2.1. Study Area

The study was carried out in the vicinity of Sundre (51.7971° N, 114.6393° W), Alberta Canada, approximately 100 km northwest of Calgary and located within the Red Deer management area overseen by the Alberta Energy Regulator (AER). The Sundre area is predominantly characterized by natural gas extraction activities, representing approximately 62% of the active sites (amounting to 1215 gas-related sites), alongside light and medium oil production, constituting 28% and 10% respectively.

2.2. Sundre Petroleum Operators Group (SPOG) Alt-FEMP pilot program

In 2021, SPOG received approval from the AER to conduct an alt-FEMP pilot program from January 2021-December 2022, designed to systematically evaluate alternative CH₄ measurement technologies (aerial- and vehicle-based) relative to conventional OGI-based methods. Each year of the program included two screening campaigns (one aerial, one vehicle-based), with OGI LDAR follow-up performed at a predetermined percentage of the highest emitting sites on a per-company basis. The screening surveys produced site-level total emission estimates, encompassing both vented and fugitive emissions, while the OGI surveys identified fugitive and vented emissions separately.

The pilot program encompassed 399 facilities across 363 sites operated by 12 producers. In this study, we focus exclusively on Year 2 (2022) data, drawing from a subset of 302 sites surveyed by both the aerial- and vehicle-based methods during that period.

2.3. Vehicle-based surveys

2.3.1 Survey methodology and data processing

Vehicle-based surveys were conducted from September 7 to September 18, 2022, employing a hybrid approach of both on and off-pad measurements. A truck was outfitted with a Cavity Ring-Down Spectrometer (G2210-i, Picarro Inc., USA), operated in concentration mode, enabling the measurement of surface air concentrations of methane ($1\sigma \sim 1$ ppb), carbon dioxide ($1\sigma \sim 1$ ppm), and ethane ($1\sigma \sim 10$ ppb). Air samples were drawn into the analyzer through an inlet situated on a mast at a height of 2.1 m, facilitated by a pump (M42x30/l, Thomas Inc., Germany) maintaining a constant flow rate of 7.1 liters per minute. Additionally, an electronic compass (32500, RM Young, USA), a 2D heated Ultrasonic anemometer (Model 86004, RM Young, USA), and a GPS unit (18x 5 Hz, Garmin, USA) were affixed to the mast to ensure precise georeferencing of the mixing ratio measurements. The survey vehicle maintained an average speed of 60-70 km/h on paved roads, 30-50 km/h on township roads, and under 15 km/h on site/access roads. A gas standard, featuring concentrations of 2.116 ppm for methane and 515.5 ppm for carbon dioxide, was utilized to monitor for analytical drift in the gas analyzer. All data collected were logged at a frequency of 2-Hz, using a datalogger (CR1000X, Campbell Scientific, Canada).

Vehicle-based emission rates presented here do not match those originally published in the alt-FEMP dataset available on the AER website²⁰, as the data has been reprocessed using a new and updated processing framework detailed in Latimer et al.¹⁹. Briefly, methane background concentrations were calculated using an iterative mean suppression method inspired by Liland²¹ and subtracted from the measured methane time series, giving excess methane (eCH₄). Peaks in the eCH₄ time series were flagged using a modified version of the spike detection algorithm described in Daniels et al.²². Detected peaks were traced upwind to their respective infrastructure using a highest-weighted likelihood algorithm that considers both measured wind characteristics and the peak's location relative to the infrastructure. Emission rates were estimated using a conventional point-source Gaussian dispersion algorithm (GDA) factoring in the reflection of the plume on the ground²³. For each anomaly, modeled excess concentrations were calculated using Eq. 1:

$$eCH_{4,model}(x,y,z) = \frac{Q_{ref}}{2\pi\sigma_y(x)\sigma_z(x)\bar{u}} e^{\frac{-y^2}{2\sigma_y^2}} \left[e^{\frac{-(z-h)^2}{2\sigma_z^2(x)}} + e^{\frac{-(z+h)^2}{2\sigma_z^2(x)}} \right] \quad (1)$$

where Q_{ref} is a reference emission rate (1 g/s), $\bar{u}$ is the mean horizontal wind speed (m/s), x and y are downwind and crosswind distance (m), z is inlet height (m), and h is the source height above ground (m). The plume centerline and wind direction were defined by the relative locations of the source and CH_4 peak. The dispersion parameters, σ_z and σ_y , were calculated using the Pasquill-Gifford atmospheric stability classifications, informed by meteorological data from the Red Deer Alberta airport²³. The estimated emission rate Q_{est} (g/s) was determined by taking the ratio of the integral of measured eCH_4 values to the integral of modeled eCH_4 values, multiplied by the reference emission rate^{24–26}.

$$Q_{est} = \frac{\sum eCH_{4,meas}}{\sum eCH_{4,model}} \times Q_{ref} \quad (2)$$

Emission rates were not estimated when the ratio of the horizontal source distance to the relative source-inlet height difference was less than 8:1. This constraint arose from the inability to quantify emission rates with reasonable accuracy in controlled-release testing and reflects the physical limitations of measuring emissions from a tall source. Sources that did not meet these criteria were deemed invalid and were neither classified as non-emitters nor included in our analysis.

2.3.2. Infrastructure characterization and grouping

Polygon shapefiles outlining the sites to be surveyed were provided by SPOG. We identified wells and facilities within each polygon using the Wells Surface Hole and Facilities shapefiles provided by IHS Markit, however, these shapefiles typically represent a single point for an entire facility without capturing the locations of individual pieces of equipment. To address this limitation, we conducted a manual verification and tagging of equipment within each polygon using Google Earth Satellite View. A clustering algorithm was then applied to group equipment on each site into groups with a 15 m radius. This grouping was necessary for the vehicle-based approach due its limitation in differentiating emissions from individual pieces of equipment, with emissions subsequently aggregated at the site level.

Infrastructure within each group was consolidated, maintaining information on well type, production fluid (e.g., oil, gas), facility type, and sub-facility type. The categorization of well

190 statuses adheres to the definitions found in the AER Directive 013 ²⁷ and Directive 020 ²⁸. Groups
191 whose statuses and fluid type were unknown or labelled as other fluids, or those that were
192 unclassifiable due to inconsistencies or lack of reference in the IHS Markit database, the AER well
193 dataset ²⁷, the Petrinex database ²⁹ or SPOG data files, were marked as unknown. To enable cross-
194 method comparison, all sites were cross-referenced by their corresponding AER Facility ID. Any
195 sub-facilities that were primarily satellite wells (as per facility type designation) but lacked a
196 specific sub-facility designation in the IHS Markit database or other datasets were categorized as
197 satellite. This approach ensures consistency in the classification and analysis of infrastructure
198 groups within the study.

200 2.4. Aerial-based surveys

201 The aerial-based surveys referenced in this study were conducted by Bridger Photonics from May
202 22 to May 27, 2022, targeting the same sites as the vehicle-based surveys. A comprehensive
203 description of their methodology can be found on Bridger Photonic website and has also been
204 documented in the literature ^{8,9}, with a summary provided below. Using a single-engine fixed-wing
205 aircraft (Cessna 172) flying at a speed of 160 km/h and at an altitude of 230 m above ground level,
206 Bridger Photonics equipped the aircraft with a continuous wave absorption laser employing
207 wavelength modulation spectrometer, a variant of the LiDAR technique ⁹. The laser, directed
208 downward at an approximate angle of 30 degrees, performs sweeps and reflects back to the aircraft
209 at a wavelength of 1651 nm to derive emission rate estimates with a spatial resolution of 2 m.
210 High-definition RGB imagery was also captured by Bridger, enabling the production of geo-
211 referenced images that identified methane leaks from known oil and gas sites down to the
212 equipment level, which subsequently were aggregated at the site level.

214 2.5. Optical Gas Imaging Surveys

215 Following the vehicle-based surveys, 53 sites were selected for OGI follow-up. OGI surveys were
216 carried out commercial providers using trained OGI operators from October 24, 2022 to November
217 15, 2022. The OGI camera was mounted on a tripod and pointed toward oil and gas equipment
218 against a neutral background, when possible (i.e., clear sky), operating in quantification mode in
219 accordance with the Alberta regulatory prescription ³⁰. Emissions were aggregated at the site level
220 to enable direct comparison with the vehicle-based measurement system.

3. Results and Discussion

3.1. Aerial-based vs vehicle-based measurements

The vehicle-based system had the highest emission frequency at 71% compared to 28% for the aerial-based system (Figure 1- left panel). In contrast, the average emission rate was slightly higher for the aerial-based system at 1.35 kg/h (CI = 0.92 – 1.92), compared to 1.1 kg/h (CI = 0.78 – 1.56) for the vehicle-based technology. These results are in line with previous studies in the Red Deer region that have reported averaged emission estimates between 0.80 kg/h and 1.1 kg/h^{16,31}, although with larger sample sizes (i.e., n=654 and n=2,677 respectively). Missing numerous emitters had a substantial impact on the average emission estimate for the aerial-based system, which dropped from 5 kg/h when non-emitters (zeros) were excluded to 1.35 kg/h when the full population of sites was considered (Figure 1 - right panel).

Figure 1 (middle panel) shows that the vehicle-based technique detected and quantified a higher number of smaller methane emissions than the aerial-based surveys. The vehicle-based system detected emissions as low as 0.011 kg/h– approximately 25 times below the minimum rate detected by aerial-based system (0.28 kg/h). Sixty nine percent of the emitting sites detected by the vehicle-based method had an estimated emission rate below 1 kg/h, and 81% of the sites detected exclusively by the vehicle-based surveys had an average estimated emission rate under 1 kg/h.

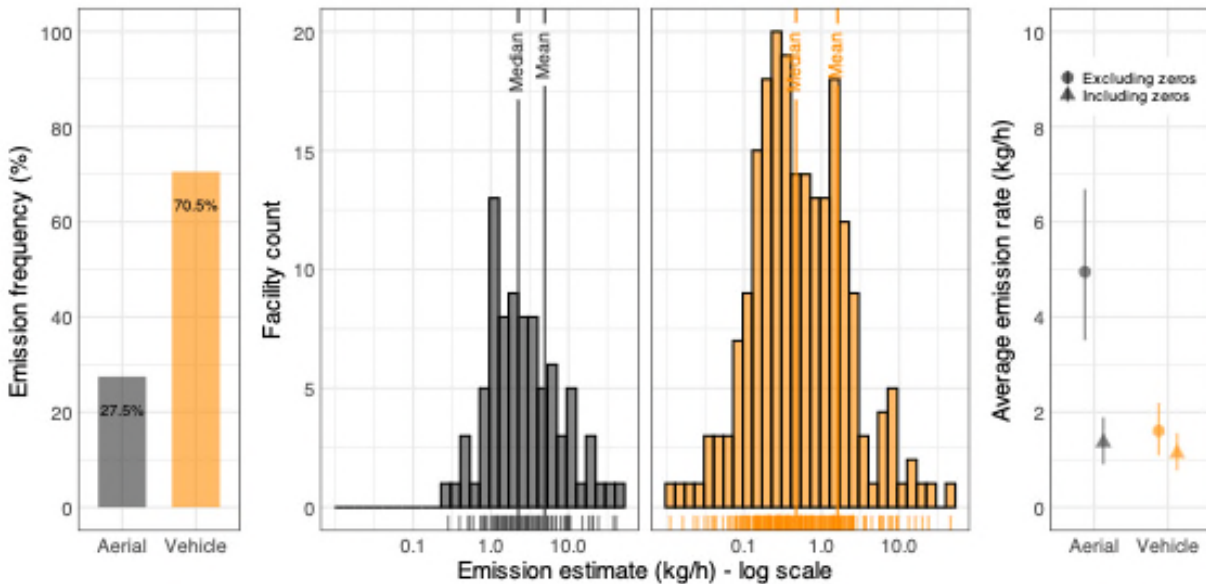


Figure 1. Emission frequency (left panel), emission distribution (middle panel; exclude zeros), and average emission estimates (right panel) for vehicle-based (orange) and aerial-based (grey) technologies (n=302). Each line at the bottom of the plot (middle panel) shows individual measurement estimates.

Across almost all facility sub-types, emission rate estimates from the aerial-based system exceeded those obtained by the vehicle-based surveys, with larger differences observed for facility sub-types with multiple tall emission sources such as multi-well batteries (e.g., 361 = Gas multiwell group battery) which may be more difficult to sample with ground-based methods (Figure 2 - top panel). For example, the aerial-based surveys detected notably higher emission rates from a gas multi-well group battery site (sub-type code 361; 41 kg/h), and two crude oil multi-well proration battery sites (sub-type code 321; 38 kg/h and 24 kg/h). This is further reflected in the overall distribution, with close to 86% of the emitting sites detected by the aerial-based method above an estimated emission rate of 1 kg/h. The ability of the vehicle-based system to detect emissions from tall sources was limited by factors such as road access, site layout, and wind direction¹⁶. Additionally, Scarpelli et al.³² observed that their own estimates were higher, attributing this to the possible exclusion or underestimation of emissions from tall facilities in the Red Deer region by MacKay et al.¹⁶.

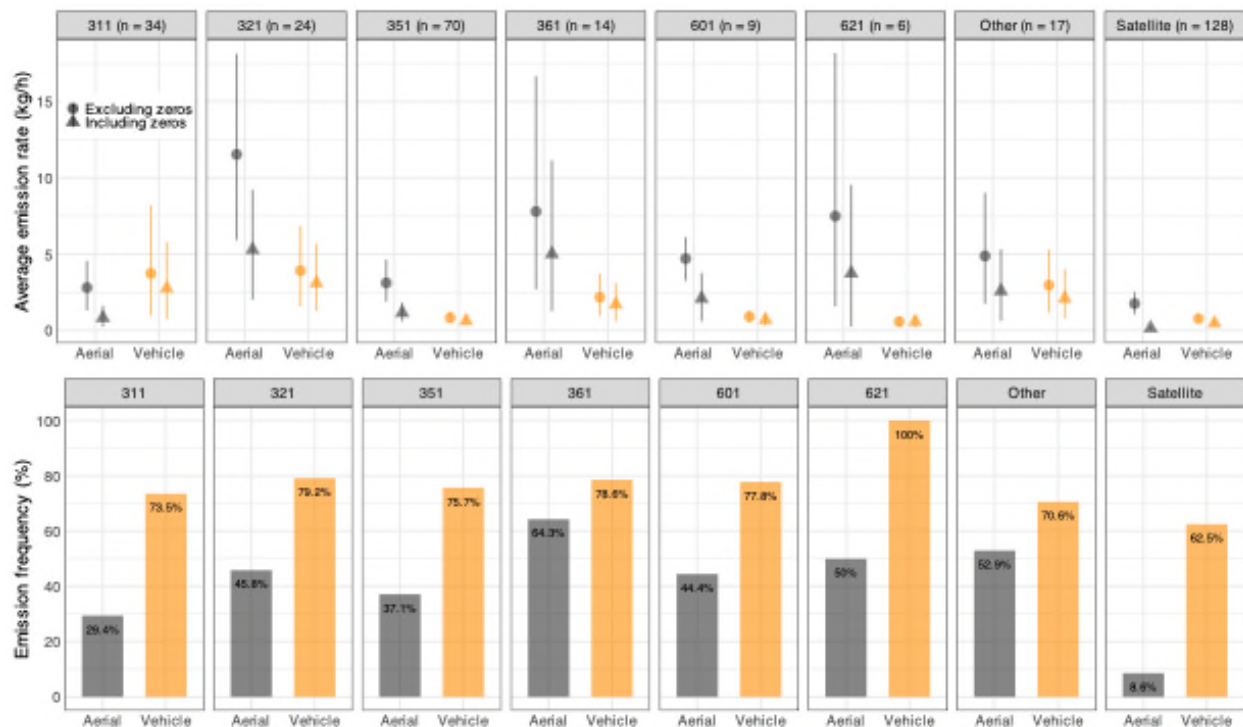


Figure 2. Emission frequency (bottom panel) and average emission estimates (top panel) segmented by facility sub-type for each measurement technology. The other category includes facility sub-type codes (322, 362, 401, 501, 507) with less than 5 facilities. 311 = Crude oil single well battery; 321 = Crude oil multiwell group battery; 351 = Gas single well battery; 361 = Gas multiwell group battery; 601 = Compressor station; 621 = Gas gathering system.

Where there was overlap between aerial-based and vehicle-based systems ($n = 74$) the relationship between the two platforms was poor ($R^2 = 0.043$). This finding suggests that the measurement systems are likely capturing different methane sources due, in part, to differing probabilities of detection, sensitivities, uncertainties inherent to each technique, and methodology set-up. It should be noted that leaks at a small subset of facilities ($\sim 8\%$) had repairs (1 to 8 repairs) between the aerial and vehicle surveys which could explain in part the lower emissions measured by the vehicle-based system, and we also cannot rule out the possibility that temporal variability resulted in variations in site-level emissions between surveys from the two measurement systems.

3.2. Vehicle-based vs OGI measurements

Since the comparison between the vehicle-based and OGI focuses on a subset ($\sim 17\%$) of the highest emitters identified through vehicle-based surveys our analysis was more limited, and we could not determine whether vehicle-based surveys detected more emitters than OGI surveys.

Taking into account that some of the differences in site-level emissions between the two measurement systems may be attributable to temporal variability, our results suggest that OGI surveys (3.9 kg/h; CI = 2.6 – 5.6) measured a higher average methane emission estimate than vehicle-based surveys (2.1 kg/h; CI = 1.4 – 2.9; [Figure 3 - top right panel](#)). Although the median estimates were closer with 1.9 kg/h and 1.1 kg/h respectively for the OGI and vehicle-based systems. Both systems captured similar emission distributions ([Figure 3 - top left panel](#)). However, OGI surveys reported higher emission estimates for multiwell group batteries (sub-types 321 and 361), while estimates for single-well batteries were comparable between the two systems (sub-types 311 and 351; [Figure 3 - bottom panel](#)).

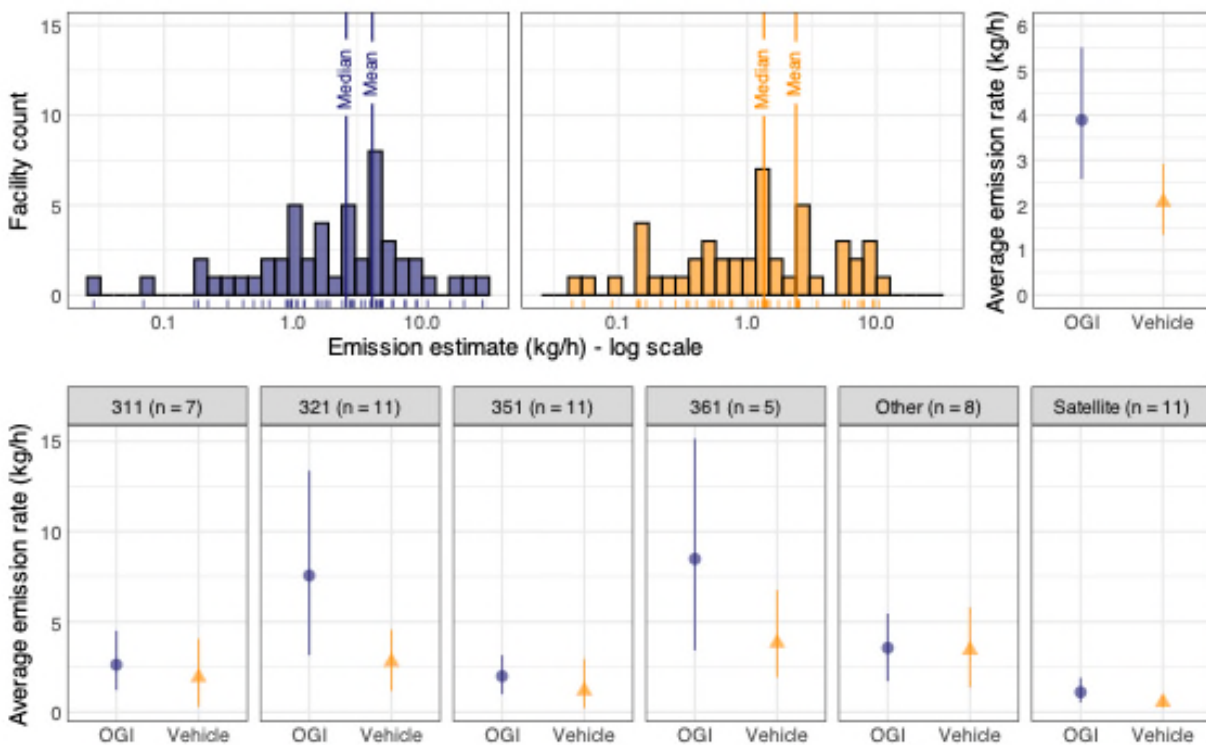


Figure 3. Emission distribution (top left panel; exclude zeros), and average emission estimates (top right corner) for vehicle-based (orange) and OGI (blue) technologies (n=53). Average emission estimates (bottom panel) segmented by facility sub-type for each measurement technology. The other category includes facility sub-type codes (322, 401, 403, 601, 621) with less than 5 facilities. 311 = Crude oil single well battery; 321 = Crude oil multiwell group battery; 351 = Gas single well Battery; 361 = Gas multiwell group battery.

Interestingly, the average emission estimate (including zeros) from the quantification method “visual inspection” was higher than the metered value ([Figure 4 - top left panel](#)). The maximum

value recorded by the visual inspection (13.9 kg/h) was roughly 4x as much as the maximum from the other two categories (2.9 and 3.6 kg/h) with the highest estimates associated to the process block tankage and tankage (controlled) coming from facility sub-type 321 (Crude oil multiwell group battery) and 361 (Gas multiwell group battery). The number of observations included in the comparison was relatively small, but previous studies have shown that OGI imagery used for quantification still has considerable uncertainty and is generally considered more suitable for leak detection than for accurate emission quantification ³³.

Unfortunately, the quantification method was not recorded for many observations. Approximately 10% of these observations were classified as fugitive emissions, while the remainder consisted of vent emissions. Only one individual equipment was recorded as non-emitting by the metered method, while pieces of equipment were recorded as non-emitting (e.g. zero) for the visual and unknow category (Figure 4 - bottom left panel). Finally, there was no trend between the four companies registered as vendors to collect OGI measurements since the majority of the observation was recorded by one company only. Overall, missing information impaired our ability to understand the differences between OGI and vehicle-based estimates.

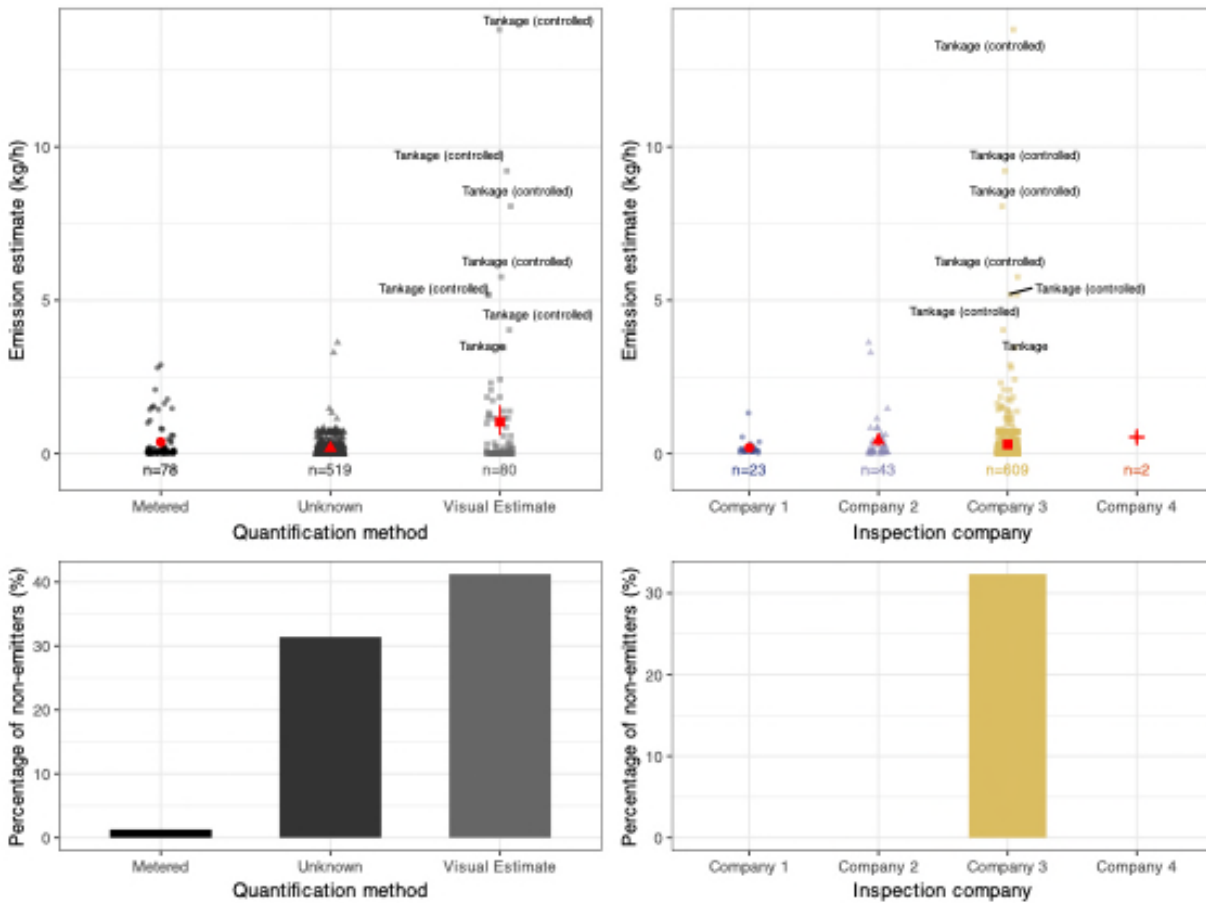


Figure 4. Mean (and confidence interval) emission estimate (includes zeros) indicated in red, and percentage of non-emitters (e.g., zero) recorded by quantification method (left panels) and by inspection technology (right panels) for the OGI surveys. Numbers of observations for each category is also indicated.

4. Implication

Optical Gas Imaging (OGI) is widely used in leak detection and repair programs, often prescribed as the “default” emission screening technology in regulations. It has also been used to improve methane emissions inventories, particularly by capturing smaller, lower-end emissions that are missed by top-down methods (e.g., aerial- or satellite-based). Previous studies showed that OGI can be effective for visually identifying component-level leaks for repair, but relying on it alone for site-level screening and emissions quantification can result in missing a substantial fraction of emitting sites and overall emissions. Vehicle-based surveys, with a comparable detection limit to OGI, seem better suited to address gaps in low-level emission detection, particularly for site-level screening applications. Vehicle-based surveys are also faster than OGI surveys³³.

Our study showed that vehicle-based surveys reported much higher emitting frequencies for the region compared to aerial-based measurements. The average aerial-based emission estimate for the region was 1.2 times higher than the average vehicle-based emission estimate. The vehicle-based system was more sensitive than aerial-based surveys, but in contrast, aerial-based surveys were able to detect larger emissions from taller emitting sources. In contrast, OGI surveys reported higher emission estimates than vehicle-based surveys; however, some of the highest emission estimates were derived from visual assessments.

Ultimately, the fact that each measurement system misses certain emitting sites—whether at the low end or the high end of the emission profile—directly affects the accuracy of methane emission inventories. Employing the vehicle-based survey for initial emissions screening, followed by aerial-based surveys for larger and taller sources, could enhance leak detection and repair and improve methane emission inventories. Replicating reconciliation study across many years, and in regions with different type of operations could provide further insights.

5. Acknowledgement

This research was funded by Sundre Petroleum Operators Group (SPOG).

6. References

- (1) Environment and Climate Change Canada. *National inventory report 1990 - 2023: greenhouse gas sources and sinks in Canada*.
<https://publications.gc.ca/site/eng/9.506002/publication.html> (accessed 2026-04-30).
- (2) Saunio, M.; Martinez, A.; Poulter, B.; Zhang, Z.; Raymond, P. A.; Regnier, P.; Canadell, J. G.; Jackson, R. B.; Patra, P. K.; Bousquet, P.; Ciais, P.; Dlugokencky, E. J.; Lan, X.; Allen, G. H.; Bastviken, D.; Beerling, D. J.; Belikov, D. A.; Blake, D. R.; Castaldi, S.; Crippa, M.; Deemer, B. R.; Dennison, F.; Etiope, G.; Gedney, N.; Höglund-Isaksson, L.; Holgerson, M. A.; Hopcroft, P. O.; Hugelius, G.; Ito, A.; Jain, A. K.; Janardanan, R.; Johnson, M. S.; Kleinen, T.; Krummel, P. B.; Lauerwald, R.; Li, T.; Liu, X.; McDonald, K. C.; Melton, J. R.; Mühle, J.; Müller, J.; Murguia-Flores, F.; Niwa, Y.; Noce, S.; Pan, S.; Parker, R. J.; Peng, C.; Ramonet, M.; Riley, W. J.; Rocher-Ros, G.; Rosentreter, J. A.; Sasakawa, M.; Segers, A.; Smith, S. J.; Stanley, E. H.; Thanwerdas, J.; Tian, H.; Tsuruta, A.; Tubiello, F. N.; Weber, T. S.; van der Werf, G. R.; Worthy, D. E. J.; Xi, Y.; Yoshida, Y.; Zhang, W.; Zheng, B.; Zhu, Q.; Zhu, Q.; Zhuang, Q. Global Methane Budget 2000–2020. *Earth Syst. Sci. Data* **2025**, *17* (5), 1873–1958. <https://doi.org/10.5194/essd-17-1873-2025>.
- (3) Helmig, D.; Caputi, D. Top-Down Versus Bottom-Up Atmospheric Emission Estimates From Oil and Natural Gas Operations. *Earths Future* **2025**, *13* (11), e2025EF006534. <https://doi.org/10.1029/2025EF006534>.
- (4) Johnson, M. R.; Conrad, B. M.; Tyner, D. R. Creating Measurement-Based Oil and Gas Sector Methane Inventories Using Source-Resolved Aerial Surveys. *Commun. Earth Environ.* **2023**, *4* (1), 1–9. <https://doi.org/10.1038/s43247-023-00769-7>.
- (5) Conrad, B. M.; Tyner, D. R.; Li, H. Z.; Xie, D.; Johnson, M. R. A Measurement-Based Upstream Oil and Gas Methane Inventory for Alberta, Canada Reveals Higher Emissions and Different Sources than Official Estimates. *Commun. Earth Environ.* **2023**, *4* (1), 1–10. <https://doi.org/10.1038/s43247-023-01081-0>.
- (6) Zimmerle, D.; Vaughn, T.; Bell, C.; Bennett, K.; Deshmukh, P.; Thoma, E. Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions. *Environ. Sci. Technol.* **2020**, *54* (18), 11506–11514. <https://doi.org/10.1021/acs.est.0c01285>.
- (7) Ravikumar, A. P.; Singh, D.; Barlow, B.; Robinson, C.; Funk, W. Alberta Methane Field Challenge, Final Report, 2020.
- (8) Tyner, D. R.; Johnson, M. R. Where the Methane Is—Insights from Novel Airborne LiDAR Measurements Combined with Ground Survey Data. *Environ. Sci. Technol.* **2021**, *55* (14), 9773–9783. <https://doi.org/10.1021/acs.est.1c01572>.
- (9) Johnson, M. R.; Tyner, D. R.; Szekeres, A. J. Blinded Evaluation of Airborne Methane Source Detection Using Bridger Photonics LiDAR. *Remote Sens. Environ.* **2021**, *259*, 112418.
- (10) Wilde, S. E.; Tyner, D. R.; Johnson, M. R. The Efficacy of Methane Leak Detection and Repair (LDAR) Programs in Practice. *ACS EST Air* **2025**. <https://doi.org/10.1021/acsestair.5c00195>.
- (11) Conrad, B. M.; Tyner, D. R.; Johnson, M. R. Robust Probabilities of Detection and Quantification Uncertainty for Aerial Methane Detection: Examples for Three Airborne Technologies. *Remote Sens. Environ.* **2023**, *288*, 113499.
- (12) Bell, C.; Rutherford, J.; Brandt, A.; Sherwin, E.; Vaughn, T.; Zimmerle, D. Single-Blind Determination of Methane Detection Limits and Quantification Accuracy Using Aircraft-

- Based LiDAR. *Elem. Sci. Anthr.* **2022**, *10* (1), 00080.
<https://doi.org/10.1525/elementa.2022.00080>.
- (13) Thorpe, M. J.; Kreitinger, A.; Altamura, D. T.; Dudiak, C. D.; Conrad, B. M.; Tyner, D. R.; Johnson, M. R.; Brasseur, J. K.; Roos, P. A.; Kunkel, W. M.; Carre-Burritt, A.; Abate, J.; Price, T.; Yaralian, D.; Kennedy, B.; Newton, E.; Rodriguez, E.; Elfar, O. I.; Zimmerle, D. J. Deployment-Invariant Probability of Detection Characterization for Aerial LiDAR Methane Detection. *Remote Sens. Environ.* **2024**, *315*, 114435.
<https://doi.org/10.1016/j.rse.2024.114435>.
 - (14) Atherton, E.; Risk, D.; Fougère, C.; Lavoie, M.; Marshall, A.; Werring, J.; Williams, J. P.; Minions, C. Mobile Measurement of Methane Emissions from Natural Gas Developments in Northeastern British Columbia, Canada. *Atmospheric Chem. Phys.* **2017**, *17* (20), 12405–12420. <https://doi.org/10.5194/acp-17-12405-2017>.
 - (15) O’Connell, E.; Risk, D.; Atherton, E.; Bourlon, E.; Fougère, C.; Baillie, J.; Lowry, D.; Johnson, J. Methane Emissions from Contrasting Production Regions within Alberta, Canada: Implications under Incoming Federal Methane Regulations. *Elem. Sci. Anthr.* **2019**, *7*, 3. <https://doi.org/10.1525/elementa.341>.
 - (16) MacKay, K.; Lavoie, M.; Bourlon, E.; Atherton, E.; O’Connell, E.; Baillie, J.; Fougère, C.; Risk, D. Methane Emissions from Upstream Oil and Gas Production in Canada Are Underestimated. *Sci. Rep.* **2021**, *11* (1), 1–8.
 - (17) Vogt, J.; Laforest, J.; Argento, M.; Kennedy, S.; Bourlon, E.; Lavoie, M.; Risk, D. Active and Inactive Oil and Gas Sites Contribute to Methane Emissions in Western Saskatchewan, Canada. *Elem. Sci. Anthr.* **2022**, *10* (1).
 - (18) Lavoie, M.; Baillie, J.; Bourlon, E.; O’Connell, E.; MacKay, K.; Boelens, I.; Risk, D. Sweet and Sour: A Quantitative Analysis of Methane Emissions in Contrasting Alberta, Canada, Heavy Oil Developments. *Sci. Total Environ.* **2022**, *807*, 150836.
 - (19) Latimer, R.; Bourlon, E.; Hachem, K. E.; Johnson, J.; Nwokoye, C.; Risk, D. Vehicle-Based Methane Detection, Attribution, and Quantification in the Upstream Oil and Gas Sector: Method Overview and Controlled Release Validation. **2026**.
 - (20) AER. *Alternative Fugitive Emission Management Program (alt-FEMP) Approvals*. Alberta Energy Regulator. <https://www.aer.ca/data-and-performance-reports/industry-performance/methane-performance/alternative-fugitive-emission-management-program-alt-femp-approvals> (accessed 2026-04-30).
 - (21) Liland, K. H. 4S Peak Filling – Baseline Estimation by Iterative Mean Suppression. *MethodsX* **2015**, *2*, 135–140. <https://doi.org/10.1016/j.mex.2015.02.009>.
 - (22) Daniels, W. S.; Jia, M.; Hammerling, D. M. Detection, Localization, and Quantification of Single-Source Methane Emissions on Oil and Gas Production Sites Using Point-in-Space Continuous Monitoring Systems. *Elem. Sci. Anthr.* **2024**, *12* (1), 00110.
<https://doi.org/10.1525/elementa.2023.00110>.
 - (23) Turner, D.B. *Workbook of Atmospheric Dispersion Estimates*; U.S. Department of Health, Education, and Welfare, National Center for Air Pollution Control., 1970.
 - (24) Caulton, D. R.; Li, Q.; Bou-Zeid, E.; Fitts, J. P.; Golston, L. M.; Pan, D.; Lu, J.; Lane, H. M.; Buchholz, B.; Guo, X.; McSpirt, J.; Wendt, L.; Zondlo, M. A. Quantifying Uncertainties from Mobile-Laboratory-Derived Emissions of Well Pads Using Inverse Gaussian Methods. *Atmospheric Chem. Phys.* **2018**, *18* (20), 15145–15168.
<https://doi.org/10.5194/acp-18-15145-2018>.

- (25) Korbeń, P.; Jagoda, P.; Maazallahi, H.; Kammerer, J.; Nęcki, J. M.; Wietzel, J. B.; Bartyzel, J.; Radovici, A.; Zavala-Araiza, D.; Röckmann, T.; Schmidt, M. Quantification of Methane Emission Rate from Oil and Gas Wells in Romania Using Ground-Based Measurement Techniques. *Elem. Sci. Anthr.* **2022**, *10* (1), 00070. <https://doi.org/10.1525/elementa.2022.00070>.
- (26) Wietzel, J. B.; Korben, P.; Hoheisel, A.; Schmidt, M. Best Practices and Uncertainties in CH₄ Emission Quantification: Employing Mobile Measurements and Gaussian Plume Modelling at a Biogas Plant. *Atmospheric Meas. Tech.* **2025**, *18* (18), 4631–4645. <https://doi.org/10.5194/amt-18-4631-2025>.
- (27) AER. *Directive 013: Suspension requirements for wells. Oil and Gas Conservation Rules*. Alberta Energy Regulator. <https://www.aer.ca/regulations-and-compliance-enforcement/rules-and-regulations/directives/directive-013> (accessed 2025-05-02).
- (28) AER. *Directive 020: Well Abandonment*. Alberta Energy Regulator. <https://www.aer.ca/regulations-and-compliance-enforcement/rules-and-regulations/directives/directive-020> (accessed 2025-05-02).
- (29) Petrinex. *Petrinex: Public Data Access*. <https://www.petrinex.ca/PD/Pages/default.aspx> (accessed 2025-05-02).
- (30) AER. *Directive 060: Upstream Petroleum Industry Flaring, Incinerating, and Venting*. Alberta Energy Regulator. <https://www.aer.ca/regulations-and-compliance-enforcement/rules-and-regulations/directives/directive-060> (accessed 2025-05-02).
- (31) Johnson, M. R.; Tyner, D. R.; Conley, S.; Schwietzke, S.; Zavala-Araiza, D. Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector. *Environ. Sci. Technol.* **2017**, *51* (21), 13008–13017. <https://doi.org/10.1021/acs.est.7b03525>.
- (32) Scarpelli, T. R.; Jacob, D. J.; Moran, M.; Reuland, F.; Gordon, D. A Gridded Inventory of Canada’s Anthropogenic Methane Emissions. *Environ. Res. Lett.* **2021**, *17* (1), 014007. <https://doi.org/10.1088/1748-9326/ac40b1>.
- (33) Fox, T. A.; Barchyn, T. E.; Risk, D.; Ravikumar, A. P.; Hugenholtz, C. H. A Review of Close-Range and Screening Technologies for Mitigating Fugitive Methane Emissions in Upstream Oil and Gas. *Environ. Res. Lett.* **2019**, *14* (5), 053002.