



Hager Environmental & Atmospheric Technologies

Paris Project with ICCT

7th December 2018

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1 Acknowledgements

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2 Project Overview

2.1 Introduction

Hager Environmental & Atmospheric Technologies (HEAT) performed an on-road remote sensing project to collect real world emissions data from vehicles in Paris, France using the unmanned, unobtrusive Emissions Detection and Reporting (EDAR) emissions camera in partnership with the International Council on Clean Transportation (ICCT) as part of the Air'Volution Campaign and The Real Urban Emissions (TRUE) Initiative. The TRUE Initiative was established by the FIA Foundation, Global NCAP, Transport and Environment, and C40 Cities in order to supply cities with real world data regarding their vehicle fleet to aid in critical policy decisions. During this project, EDAR was deployed in three (3) different locations in Paris over the course of 20 days while accurately and precisely detecting and quantifying CO, CO₂, NO, NO₂, (NO_x), HC and PM being emitted from more than 200,000 vehicles. **The goal was to collect 110,000 valid emissions readings from light duty vehicles and HEAT was able to accomplish this in less than two weeks.**

This report will illustrate a detailed sampling plan that was developed (outlining each phase of the project), along with a description of the measurement locations, a description of the EDAR equipment, information on EDAR's unique spectroscopic methods that allows the unit to run unmanned without calibration, a summary of the data collection campaign, as well as details of the data processing and validation approach.

2.2 Partners Involved in Project

- Hager Environmental and Atmospheric Technologies (HEAT)
- The International Council on Clean Transportation (ICCT)
- City of Paris Mayor's Office

2.3 HEAT's Role in the Project

- Installation and handling of measurement equipment
- Data collection including gas data and license plate records
- Guarantee and maintain confidentiality of all information collected throughout the project and only allow authorized personnel to handle the data; while following strict security measures
- Data processing carried out in Paris
- Report detailing the project phases

3 Detailed Sampling Plan

3.1 Phase 1

Hager Environmental & Atmospheric Technologies (HEAT) leveraged years of experience in remote sensing to detect exhaust emissions from in use vehicles on-road in order to accomplish this project successfully through a detailed sampling plan. During the development of the sampling plan HEAT worked closely with ICCT, the Paris Department for Transportation and the City of Paris to determine the best and most preferred locations for data collection. After a careful site selection was conducted over the course of several days both physically and through correspondence among the project partners, the locations were narrowed down to four (4) optimal sites. Although, one (1) of the sites was not able to be deployed due to construction and the shutting down of lanes around the site; therefore, a permit was not issued for the fourth site.

The site selection was based on the following criteria:

- High traffic counts on selected roadways
- Roadways with appropriate grades (slight uphill, never downhill) to achieve acceptable Vehicle Specific Power (VSP) by having the car under load
- Continuous traffic flow to minimize stopped or slowing traffic
- Appropriate speeds of vehicles are up to 65mph or 110km/hr
- EDAR can be deployed on multi-lane or single lane roadways (roadway configurations that allow for high traffic counts are preferred)

Traffic scenarios where EDAR may be utilized:

- State highway shoulder
- Intersection/right-hand turn
- Right after a red-light at intersections
- Entrance or exits to tunnels
- Under a bridge
- Roundabouts
- Entrance ramp to interstates or highways

Additional considerations while choosing the sites included:

- Examining the traffic flow and trends of each location
- Determining the lane that EDAR will be detecting emissions
- Feasibility for equipment installation
- An observation of the primary vehicle type

Once the sites were selected, the permitting process began and the timeline for sampling could begin to be more concretely developed and defined. A large component for determining the duration of the data collection was established based on the traffic volume of the selected roads for testing. The traffic volume information in addition to knowledge from previous experiences with projects in Europe, HEAT determined that 2 to 3 weeks would be more than an adequate amount time to collect the data needed to meet the contract goal of 110,000 valid emissions measurements of light duty vehicles and to also potentially provide the project partners with an even larger dataset than originally requested.

HEAT developed a meticulous schedule from preparation and deployment to data processing and analysis in order to efficiently accomplish all required tasks for this project on time. HEAT was prepared to deploy the emissions testing equipment shortly after the award of the contract in August 2017. Due to unforeseen circumstances, the project took longer than expected to start due to obtaining all of the proper contract signatures needed from the City Mayor's office in order to begin with the testing. These signatures could only be acquired during certain times of the year at a meeting with city officials. Once this was accomplished in May 2018, the project schedule was back on track and from that point forward moved rapidly. All equipment was then shipped from the United States to Paris on the second week of June.

3.2 Phase 2

The HEAT team began data collection on June 20th, 2018 at Rue de Tolbiac and Rue de Diderot. In order to obtain an even more diversified sample, on the 2nd of July 2018 the Tolbiac site was moved to Rue de Choisy.

3.2.1 Key Criteria for Sampling

The following represents the details and criteria of the project outlined:

- Detection of 110,000 light duty vehicles
- Readings of CO, CO₂, NO, NO₂, (NO_x), HC, and PM (Particulate Number) for each vehicle detected
- Diversified sample (multiple locations)
- Range of vehicle operating conditions (different times of day and locations)
- Vehicle Specific Power (VSP)
- Ambient weather conditions recorded concurrently with the emissions measurements
- Number Plate
- Provide regular status updates to ICCT

Even though EDAR collected the emissions data of the 110,000 valid light-duty vehicles needed in about two weeks of testing, HEAT decided to continue collecting data for an additional week resulting in under three (3) weeks of total testing time. This extended time period provided the project partners with a statistically significant data set of over 200,000 light and heavy-duty vehicles.

Additionally, in order to accomplish this installation of the EDAR equipment for data collection the steps outlined below were followed:

3.2.2 System Deployment Steps

1. Transport truss to deployment location
2. Install truss system
3. Mount EDAR and its components including rangefinder, weather sensor, and license plate camera on arm
4. Connect power and check all connections
5. Raise truss
6. Install retroreflector
7. Align EDAR
8. EDAR operates unmanned 24/7 with daily local data downloads by engineers
9. All data stored on local computer in Paris

3.2.3 System Takedown Steps

1. Lower truss
2. Disconnect power
3. Remove all EDAR components
4. Remove retroreflector from road
5. Remove truss from site

3.3 Phases 3 & 4

During this phase, the collected data was processed through HEAT's initial algorithms for license plate transcription, the determination of vehicle type (e.g. light-duty), and for valid gas and license plate reads. During this process an anonymized number was also generated to associate with each license plate, in order to comply with all of the required privacy laws which required all license plate data to be deleted from HEAT's records prior to the team's departure from Paris. This anonymized number is used to tie the vehicle technical data to the emissions reading once returned from the vehicle registration authority. Within a few days after testing was completed, HEAT provided the city of Paris with a list of license plates to be submitted for vehicle technical information retrieval.

3.3.1 Deliverables (What EDAR Collected)

After the retrieval of the technical data from the Paris authorities on November 8, 2018 the emissions and technical data was then combined and provided to ICCT in an excel spreadsheet containing one row per vehicle with the following information:

- Anonymized ID Number
- [NO]/[NO₂]
- [NO]/ [CO₂]
- [NO₂]/ [CO₂]
- [CO]/ [CO₂]
- [PM]/ [CO₂]
- [HC]/ [CO₂]
- Concentration CO [ppm]
- Concentration NO [ppm]
- Concentration NO₂ [ppm]
- Concentration HC [ppm]
- Particulate Number
- Emission rate CO [g/kg fuel]
- Emission rate NO [g/kg fuel]
- Emission rate NO₂ [g/kg fuel]
- Emission rate NO_x [g/kg fuel as NO₂]
- Emission rate HC [g/kg fuel]
- Ambient temperature [°C]
- Ambient relative humidity [%]
- Ambient pressure [mbar]
- Longitude
- Latitude
- Altitude
- Name of corresponding scene camera image
- Temperature of the exhaust
- Vehicle passage date
- Vehicle speed (km/h)
- Vehicle acceleration (km/h/s)
- Vehicle specific power (kW/tonne)
- Wind speed [m/s]
- Wind direction [°]
- UTC offset

3.3.2 Vehicle Technical Information Requested

The following list are the categories of vehicle information requested from the vehicle registration entity in order to perform the emissions analysis. The combined data spreadsheet contains this information for each record if provided:

- Vehicle Model
- Model Year
- Make
- Body Style
- Vehicle Type/Category
- Date of Registration
- Fuel type
- Engine displacement
- Maximum power output
- Emission control technology
- Vehicle curb weight
- Vehicle mileage
- Euro class

The headings that were provided to HEAT from the Vehicle Registration System (SIV) at the Ministry of the Interior (DSCR) are as follows:

- id_technique (*Technical ID*)
- b4.marque (*Vehicle Make*)
- b4.denomination_comm (*Trade Name*)
- b4.date_prem_immat (*Date of First Registration of the Vehicle*)
- b4.date_immat_siv (*Date of Registration in the SIV*)
- b4.usages (*Use/Purpose [Excluding Military, Diplomat, or ACE]*)
- b4.mentions (*Specific Information Relating to the Specific Technical Characteristics of the Vehicle*)
- b5.tvv (*Type, Version, or Variant of the Car Model*)
- b5.type_recep (*Type Approval*)
- b5.vin (*Vehicle Identification Number*)
- b5.cnit (*National Type Identification Code*)
- b5.masse_f1 (*Technically Permissible Maximum Laden Mass [Gross Weight]*)
- b5.masse_f2 (*Technically Permissible Maximum Laden Mass [Gross Weight] Except for Motorcycles*)
- b5.masse_f3 (*Maximum Permissible Laden Mass [Gross Weight] of the Assembly in Service in the Member State of Registration*)
- b5.masse_f4 (*Mass of the Vehicle in Service with Bodywork and Coupling Device in the Case of Towing Vehicle Category other than M1*)
- b5.poids_a_vide (*National Empty Weight*)
- b5.categorie (*Vehicle Category*)
- b5.genre (*National Type*)
- b5.carrosserie_ce (*Bodywork*)
- b5.carrosserie (*National Designation of Bodywork*)
- b5.num_reception (*Type-approval Number*)
- b5.cylindree (*Cylinder Capacity in cm³*)
- b5.puissance_net_maxi (*Maximum Net Power*)
- b5.energie (*Fuel Type or Energy Source*)
- b5.puissance_admin (*National Administrative/Regulatory Power*)
- b5.rapport_puiss_masse (*Power-to-mass ratio [Only for Motorcycles]*)
- b5.nb_places_assises (*Number of Seating Positions Including Driver's Seat*)
- b5.nb_places_debout (*Number of Standing Places*)
- b5.niv_sonore (*Noise Level at Standstill*)
- b5.vitesse_moteur (*Motor Speed*)
- b5.co2 (*CO₂ [g/km]*)
- b5.classe_env (*Environmental Class*)
- b5.couleur (*Color*)

4 Description of Measurement Locations

A careful site selection process took place in October 2017 that narrowed the sites down to four optimal locations based on speed, acceleration, vehicle specific power (VSP), grade, traffic flow, and ideal placement. Due to the fact that EDAR can be deployed on multi-lane roads there were a multitude of locations that were possible deployment sites. HEAT along with the cooperation and guidance of ICCT, the Paris Department for Transportation, and the City of Paris the locations were narrowed down to the following:

1. Rue de Tolbiac at Rue Charles Fourier

- a. This location consists of three lanes of traffic flowing both east and west with a 5-way intersection nearby, a bus stop right in front of EDAR and a parking lane. The speed limit of Rue de Tolbiac is 50km/hr. This site had consistent traffic flow throughout the day allowing for a constant stream of data.



2. Boulevard Diderot at Rue de Picpus

- a. This location consists of 2 lanes of traffic flowing both east and west with parking lanes on either side. The location of the EDAR was approximately 30 meters east of the Rue de Picpus 4-way intersection. The speed limit of Boulevard Diderot is 50km/hr. The EDAR system remained at this location for the entire duration of the data collection.

3. Avenue de Choisy at Rue Georges Eastman

- a. This location consists of 3 lanes of traffic flowing both north and south with parking lanes on both sides of the road. The speed limit of Avenue de Choisy is 50km/hr. The EDAR system was situated just south of Rue George Eastman.

4. Avenue de l'Amiral Mouchez at Rue de Rungis

- a. No permit was issued for this location. Due to construction and lane closures this site was not deployed.

Images of each location with coordinates and duration are on the following pages.



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4.1 Location 1: Rue de Tolbiac at Rue Charles Fourier

- ☀ Duration: 20th June – 2nd July
- ☀ Coordinates: 48.825768, 2.350861
- ☀ District: 13th arrondissement

Figure 1: Rue de Tolbiac Site Images





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4.2 Location 2: Boulevard Diderot at Rue de Picpus

- ✳ Duration: 20th June – 12th July
- ✳ Coordinates: 48.848028, 2.393398
- ✳ District: 12th arrondissement

Figure 2: Boulevard Diderot Site Images





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4.3 Location 3: Avenue de Choisy at Rue Georges Eastman

- Duration: 2nd July – 12th July
- Coordinates: 48.828472, 2.358146
- District: 13th arrondissement

Figure 3: Avenue de Choisy Site Images





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4.4 Location 4: Avenue de l'Amiral Mouchez at Rue de Rungis

- ✱ Duration: Not deployed due to area construction and lane closures
- ✱ Coordinates: 48.821260, 2.342757
- ✱ District: 13th arrondissement

Figure 4: Avenue de L'Admiral Mouchez Site Images



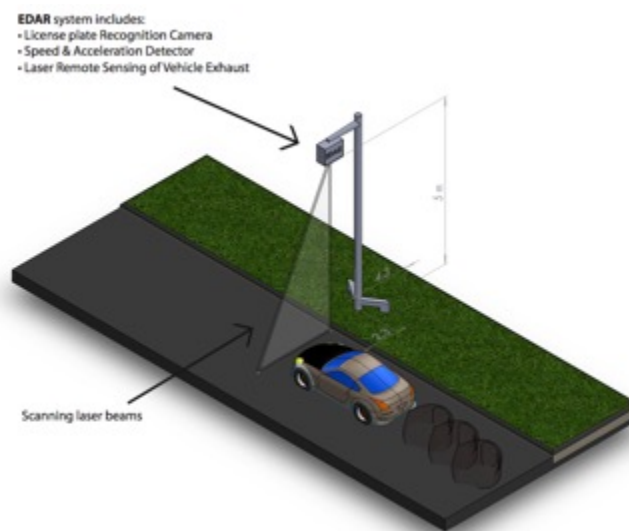
5 Description of Sampling Equipment

5.1 General Equipment Description

The Emissions Detection and Reporting (EDAR) system is Hager Environmental & Atmospheric Technologies' (HEAT) proprietary on-road remote sensing technology. EDAR is an eye-safe laser-based technology capable of remotely detecting and measuring the infrared absorption of environmentally critical gases being emitted from virtually any moving vehicle regardless of the tailpipe location or fuel type. Specifically, EDAR measures the entire exhaust plume as the vehicle passes underneath the unit. Infrared lasers are scattered off the retroreflective tape installed transversely on the road surface and the back-scattered light is then collected by EDAR and focused onto the detector.

The EDAR system is an unmanned, automated vehicle emissions measurement system, which collects data on pollutants such as CO, CO₂, NO, NO₂, (NO_x), Total HC, Speciated HC, and PM. Speed and acceleration measurement sensors and the license plate camera are housed either inside or near the EDAR unit. The entire system is designed so it can be locked down to deter vandalism or theft. The all-in-one EDAR system is fully weatherproofed to protect it from environmental elements (heat, rain, snow, wind, etc.) In addition, EDAR occupies a relatively small footprint, sitting on a single pole that is deployable roadside in either a temporary or permanent application (*see below for configuration*). The components of the entire system are comprised of an eye-safe laser-based infrared gas sensor, a vehicular speed/acceleration sensor, license plate recognition (LPR) camera, weather sensor, and retroreflector, all of which are explained in more detail in the subsequent sections.

Figure 5: EDAR Footprint



EDAR emits a sheet of invisible laser light from above that explicitly measures specified molecules being emitted from any vehicle that breaks the beam. The lasers are tuned for the required pollutants, such as CO, CO₂, NO, NO₂ (NO_x), HC, and PM. EDAR measures each pollutant directly to give an absolute amount of what the vehicle has left behind. EDAR is the only remote sensing technology on the market that can measure absolute amounts of CO₂ and NO₂ directly independent of CO₂ measurements. EDAR is able to report measurements in ratios, stoichiometric concentrations, stoichiometric grams per kilogram, and absolute amounts. Concentrations are **not** a valid measurement for diesel vehicles. In addition, due to the fact that EDAR looks down from above the roadway and can “see” a whole lane of traffic, the sensor can detect an entire exhaust plume as it exits the vehicle regardless of the tailpipe location or vehicle type all in one single footprint. Seeing the whole plume is advantageous since it allows for consistently high signal to noise ratio (SNR) and measurements such as absolute amounts, which allows for the determination of instantaneous emission rates in mass per unit travelled (grams/kilometer). This unique measurement can be used to calculate the absolute amount of emissions produced by each vehicle instead of a measurement in terms of the ratio of the pollutant to CO₂. In addition, EDAR is able to take passive infrared images and dimensional measurements of the vehicles passing below the sensor, allowing the vehicles’ shape or type to be determined (e.g. heavy-duty truck, light duty vehicle, motorcycle, bus, or a vehicle pulling a trailer), as well as any pollution hot spots such as evaporative HC emission leaks on the vehicle. This method also demonstrates the location of the tailpipe by the CO₂ plume’s position.

In addition to the scanning pollution measurement system noted above, the EDAR system also gathers vehicles characteristic data necessary for the analysis of the emissions result. These components include:

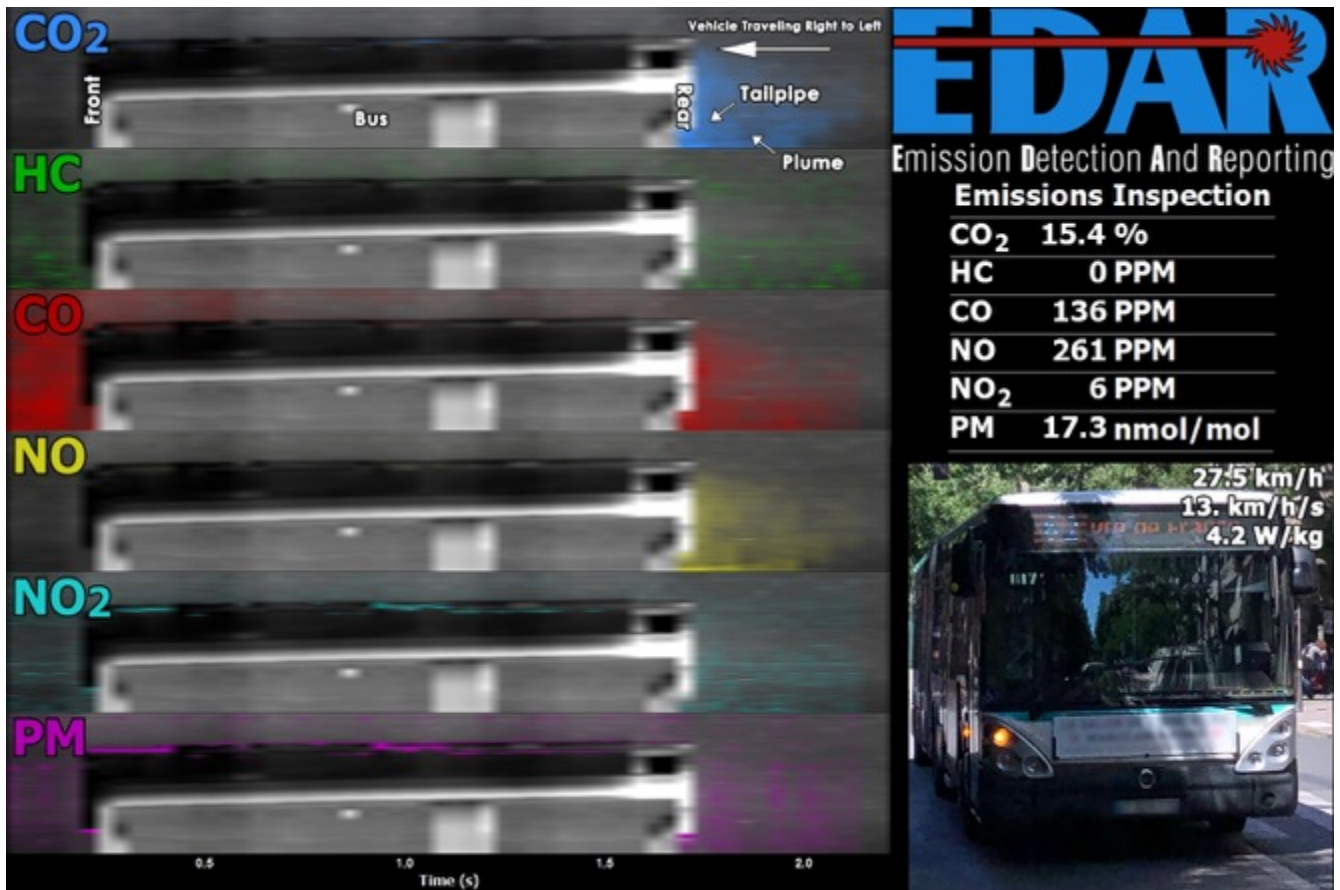
- A laser-based rangefinder system for vehicle speed and acceleration measurements. The rangefinder detects the vehicles from above in the same manner as the gas sensor.
- A system to measure current weather conditions, including ambient temperature, barometric pressure, relative humidity, along with wind speed and direction.
- A license plate recognition (LPR) camera that identifies and transcribes the license plate of each vehicle automatically when its emissions are measured.

Furthermore, the EDAR system has the additional unique capability of using infrared spectroscopic methods in order to measure the temperature of the exhaust as it exits the tailpipe. For each vehicle, the EDAR unit finds the exhaust plume at the location where it exits the tailpipe of the vehicle at the moment when the plume becomes visible. This gives a measure of the temperature of the exiting exhaust gases. The temperature of the exhaust gases relative to the ambient temperature are an indication of if the vehicle is in a warmed-up condition, that is, not in a cold start. If the vehicle were in a cold start, it may have high emissions appearing to indicate

the vehicle has an emissions problem. However, the EDAR unit can be used to identify these vehicles so that they are not recognized as false positive high emitters.

Additionally, EDAR produces a report for every vehicle detected and evaluated. As displayed in the figure below, the EDAR unit captures a 2D image of the vehicle and plume for the detected gases as well as the date, time, speed, acceleration, temperature, barometric pressure, humidity, wind speed, an indication of high emissions, and an actual image of the vehicle itself.

Figure 6: Example EDAR Report



5.1.1 Detector Accuracy

The EDAR system's measurements have higher accuracies than the range of the certified gas sample accuracy and the detector accuracy standards of the California Bureau of Automotive Repair (BAR) On-Road Emissions Measurement Standards (OREMS).

Minimum accuracies according to California BAR are:

- The carbon monoxide (CO%) reading will be within $\pm 10\%$ of the Certified Gas Sample, or an absolute value of $\pm 0.25\%$ CO (whichever is greater), for a gas range less than or equal to 3.00% CO. The CO% reading will be within $\pm 15\%$ of the Certified Gas Sample for a gas range greater than 3.00% CO.
- The hydrocarbon reading (recorded in ppm propane) will be within $\pm 15\%$ of the Certified Gas Sample, or an absolute value of ± 250 ppm propane, (whichever is greater).
- The nitric oxide reading (ppm) will be within $\pm 15\%$ of the Certified Gas Sample, or an absolute value of ± 250 ppm NO, (whichever is greater).

HEAT has participated in validation and correlation studies for on-road emissions in both the United States and Europe. The integrity of HEAT's data has been validated by various blind studies comparing the EDAR system to a Portable Emissions Measurement System (PEMS), chaser vans, calibrated gases, as well as other in-situ measurement devices.

In the United States, an independent blind validation study was performed by the Colorado Department of Public Health and Environment (CDPHE), the United States EPA and Eastern Research Group (ERG) using an RSD audit truck equipped with calibrated gases. The results show a remarkably high correlation (R^2 of 0.99) could be attested for all gases with speeds ranging from 24 km/h to 96 km/h during the CDPHE and EPA blind validation study.

EDAR system accuracies as performed by Colorado, ERG and EPA, which only included the gases CO, NO and HC, the median values can be seen in the table titled "EDAR Accuracies" on the next page (for PM and NO₂ accuracies, please, see the real-world evaluation section).

Table 1: EDAR Accuracies

Gas	Accuracy
Carbon Monoxide (CO)	$\pm 0.0075\%$
Nitric Oxide (NO)	± 20 ppm
Total Hydrocarbons (HC)	± 125 ppm

- The carbon monoxide (CO%) readings are within an absolute value of $\pm 0.0075\%$ of the Certified Gas Sample.
- The nitric oxide reading (ppm) are within an absolute value of ± 20 ppm NO.
- The hydrocarbon readings are within an absolute value of ± 125 ppm hexane.
- The EDAR system has been found to have no drift allowing for the unit to be set up to run continuously collecting accurate data without any need for calibration.
- The r-squares of the linear regression between the EDAR unit's measurements and known concentrations of each gas at the various speeds were calculated. A "r squared" of one means perfect fit and an "r squared" of zero means no fit. The EDAR system's r-squares show excellent correlation and high linearity for all gases:
 - Methane – 0.983
 - Propane – ranged 0.996 to 0.934
 - NO – 0.998
 - CO – 0.996

5.1.1.1 Real World Validation

In the United Kingdom, a real-world comparison was made by a University of Leeds researcher at a worldwide emissions conference.² This research showed strong correlation between HEAT's Colorado Evaluation mentioned above, which was a blind study using dry gases, and the UK real world study performed in February 2016. During the UK study, a series of devices were used to compare to the EDAR system including a Portable Emissions Measurement System (PEMS) and a SNIFFER or car chaser. It was found that the EDAR system is in good agreement with other real-world measurement methods.

The controlled gas study and the "real-world" comparisons are feature in a peer review journal article *Evaluation of EDAR vehicle emissions remote sensing technology*³
Illustrations and tables as seen in the Ropkins Presentation are below:

²Some Observations Based On Complementary International Evaluations Of Edar Vehicle Emissions Remote Sensing Technology, Karl Ropkins, University of Leeds, 27th Annual Real World Emissions Conference, 2017

³ K. Ropkins et al. / Science of the Total Environment 609 (2017) 1464–1474

Figure 7: Illustration of PEMS Vehicle

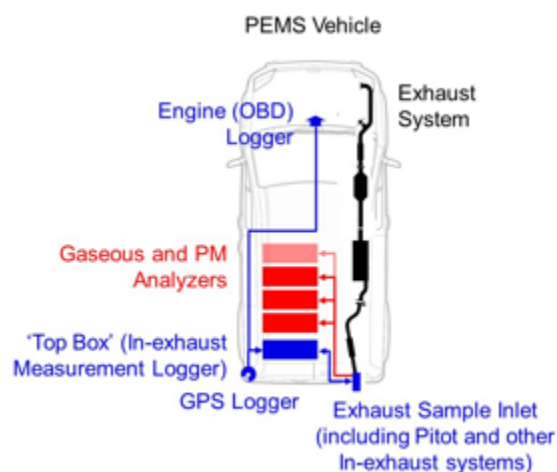


Figure 8: Illustration of SNIFFER (Car Chaser) Vehicle

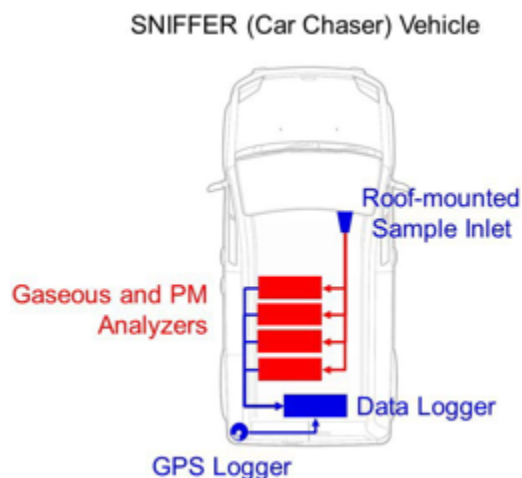
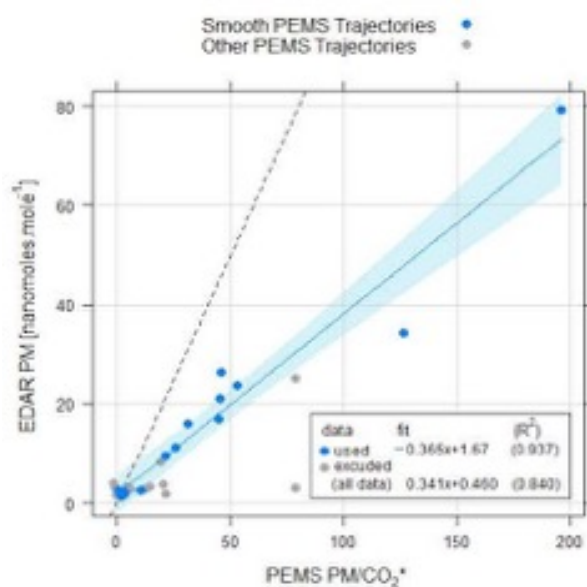


Figure 9: R^2 Agreements in UK Study

Gas	R^2 Agreement with PEMS
NO/CO ₂	0.97
CO/CO ₂	0.92
PM/CO ₂	0.94
NO ₂ /CO ₂	0.84

Figure 10: EDAR and PEMS Correlation in UK Study



Photos from Ropkins presentation cited in footnote.⁴

⁴ Some Observations Based On Complementary International Evaluations Of Edar Vehicle Emissions Remote Sensing Technology, Karl Ropkins, University of Leeds, 27th Annual Real World Emissions Conference, 2017

5.2 EDAR System Equipment

EDAR Unit

Measures CO, CO₂, NO, NO₂ (NO_x), HC, and PM being emitted from vehicles

Laser Rangefinder

Determines the speed and acceleration of vehicles

Automatic License Plate Recognition

Camera (ALPR /ANPR)

Detects and transcribes the license plates of the vehicles measured by EDAR

Security Camera

Allows for remotely checking on the security of the system

Retroreflector

Reflects the light back up to the EDAR system

Electrical Panel

Conditions incoming AC power to operate all system components

Mounting

The EDAR unit, laser rangefinder, weather sensor, and cameras are mounted above the road. This can be performed on a permanent pole or temporary Truss System (*truss detailed in the following section*)

Figure 11: System Equipment



5.3 Truss Structure Drawings and Detail

For EDAR's temporary deployments in Europe a **highly movable** truss system (*see below*) is easily and securely installed on road. This truss system can be set into place and then raised by the push of a button to its full structure and then just as easily stowed back down for transport. This truss system is deployable roadside and once all components are in place the system will run unmanned 24 hours a day, 7 days a week without human intervention. The EDAR system is monitored remotely and will alert technicians of any anomalies that may exist. When the truss is erected to its full structure, EDAR sits approximately 5 metres or higher above the roadway.⁵

Figure 12: EDAR and Its Components Mounted on the Truss System

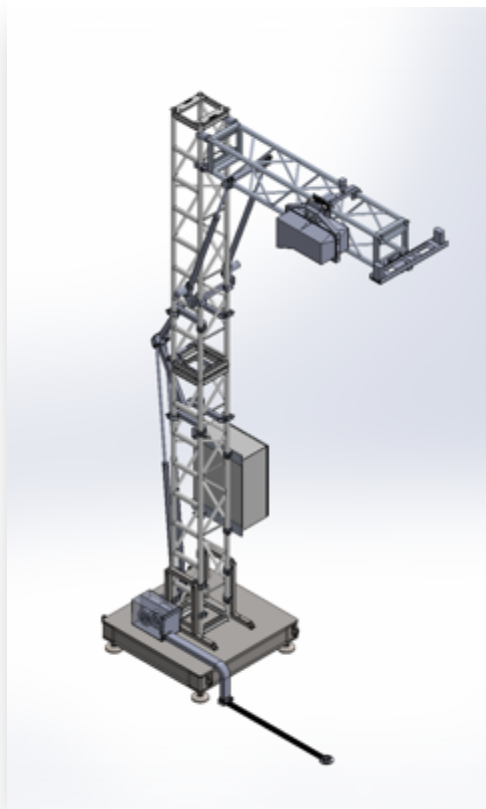
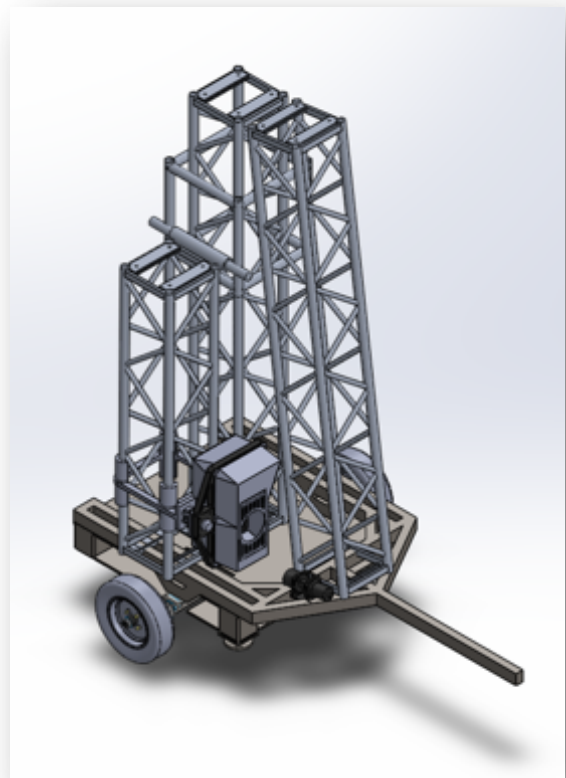


Figure 13: Truss Stowed for Easy Transport

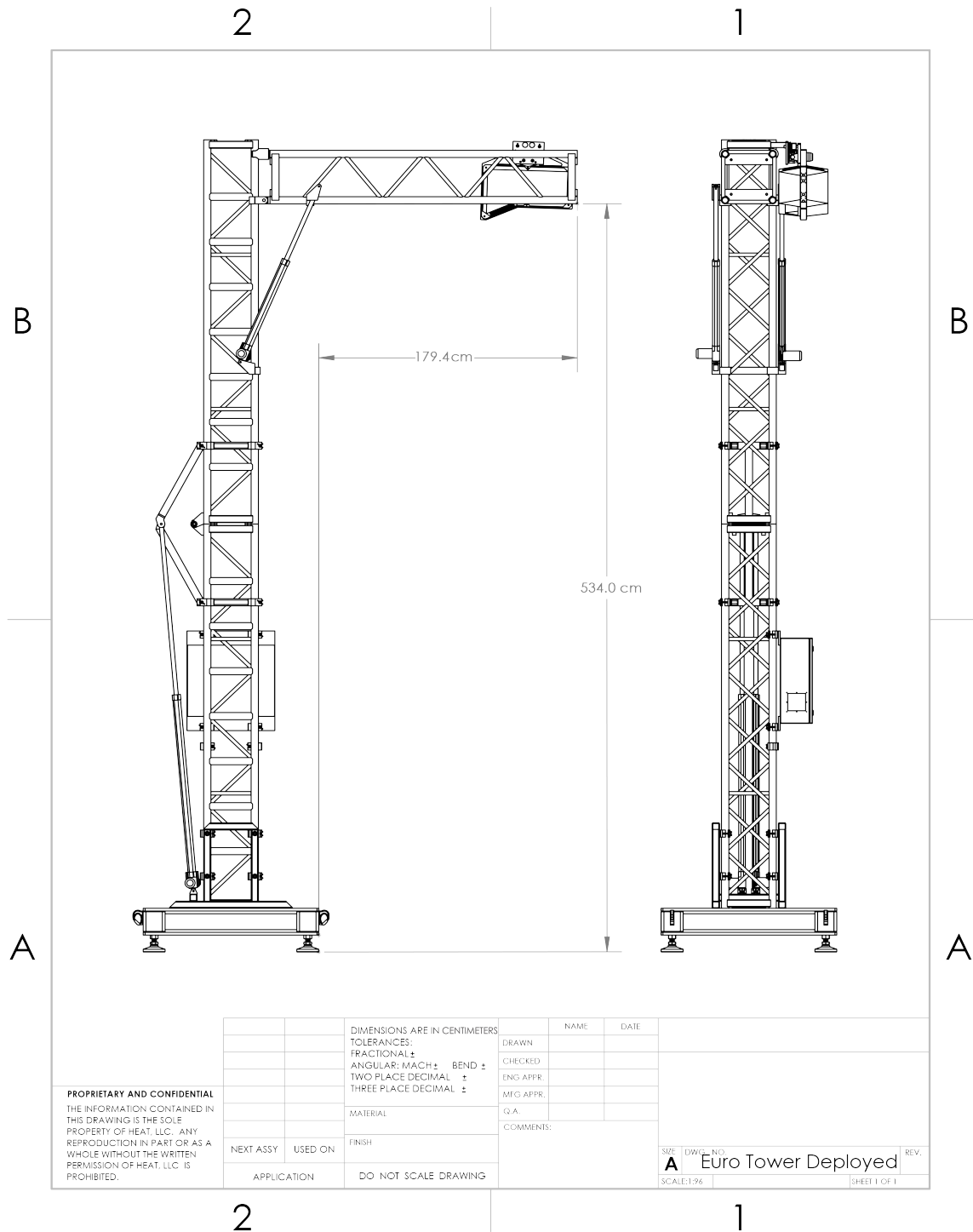


⁵ A video of the truss being erected in Paris can be seen at the following link: <https://vimeo.com/293386534>



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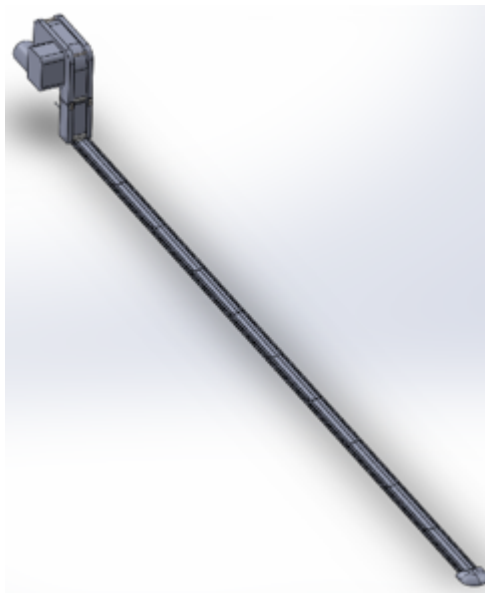
Figure 14: Truss Drawing - Fully Deployed



5.4 Retroreflector Installation

Directly below each EDAR is a retroreflective strip installed on the road. The retroreflector is installed by attaching it to the truss base and then securely adhering the strip transversely across the roadway using butyl. A visual of how the reflector looks when it is installed on the truss can be seen in the Figure 12 titled “EDAR and its components mounted on the Truss system” in the above section. This specially designed intelligent retroreflector ensures optimal operating time due to the fact it allows EDAR to continue detecting emissions in light rain or misty conditions.

Figure 15: Retroreflector



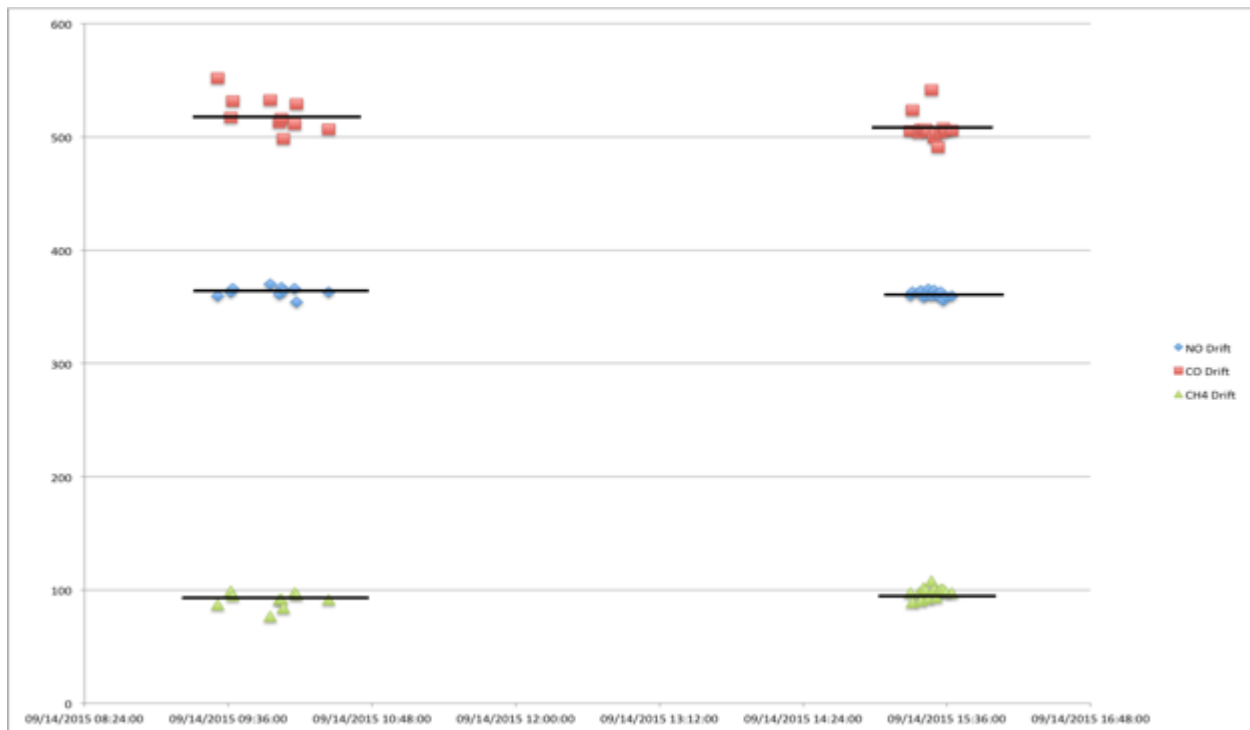
5.5 Electrical Services Required at Each Deployment Site

- Power is needed to be wired into electrical panel
- 240V AC
- 20amp service

6 EDAR's Detection Method (No Calibration Required)

Due to the absolute nature of EDAR's spectroscopic measurements, it can measure the targeted pollutants without explicit field calibration and remain within normal specifications. EDAR can operate for 24 hours a day 7 days a week, unmanned, without any drift. In other words, EDAR does not need to be calibrated in the field for correct operation or accurate measurements. HEAT uses the DiAL method, which is Differential Absorption LiDAR Spectroscopy. In a blind study performed by ERG and USEPA, the EDAR system was proven to have no drift; allowing for the unit to be set up to run continuously collecting accurate data without any need for calibration.⁶ Please, see figure below for the drift results from the blind study:

Figure 16: Drift Evaluation Results



This figure illustrates the drift evaluation from the blind study performed by the USEPA, ERG, and CDHPE

⁶ Tim DeFries (ERG), Carl Fulper (USEPA, Jim Kemper (CDPHE), Sandeep Kishan (ERG), Jim Sidebottom(CDPHE), "Independent Testing of EDAR Accuracy and Sensitivity Performed by EPA, Colorado, and ERG," Denver, Colorado, January 2, 2016

6.1 Factory Testing and Certification of the EDAR System

All EDAR systems are assembled by a highly-specialized manufacturer in the United States under the direction of HEAT's strict quality assurance requirements. After the units are built and aligned, they undergo several tests and verifications before they are deployed in the field. Each EDAR unit arrives assembled from the factory with known spectroscopic settings.

The quality assurance process includes HEAT further confirming the pollutant measurement settings by performing validation testing with known gas quantities under various conditions and speeds. HEAT then configures each EDAR system with unique field settings catered to the unit's deployment requirements.

HEAT also performs outdoor validation of the EDAR system using test gas tanks mounted to an electric vehicle as well as vehicles with extended tailpipes that deposit its exhaust outside the field of view with a simulated exhaust pipe and gas flow controllers. The test vehicle provides a known ground truth to verify that each EDAR system is operating properly at various speeds. HEAT obtains tanks where each test gas is mixed with specified target pollutants and varies between low and high concentrations for each pollutant. The test vehicle is driven past the EDAR unit a number of times for each test gas flowing at a constant volumetric rate. The test takes place in a controlled area to eliminate unknown emission sources. The results are then checked to confirm that each EDAR unit is configured properly and measuring within normal specifications. After the outdoor verification is complete, each EDAR unit is tested under various environmental extremes (temperature and humidity) in a specially designed environmental test chamber.

6.2 Quality Assurance Test before and after the Paris Project (Calibration and Audits)

In spite of the inherent stability and accuracy of the EDAR technology, HEAT conducts quality assurance (QA) tests before and after each project to document for the client whether the EDAR system's performance significantly changed during shipping or during the deployment. The QA test compares the output of the EDAR system to the known ratios of NO and NO₂ calibration gases mixed with CO₂.

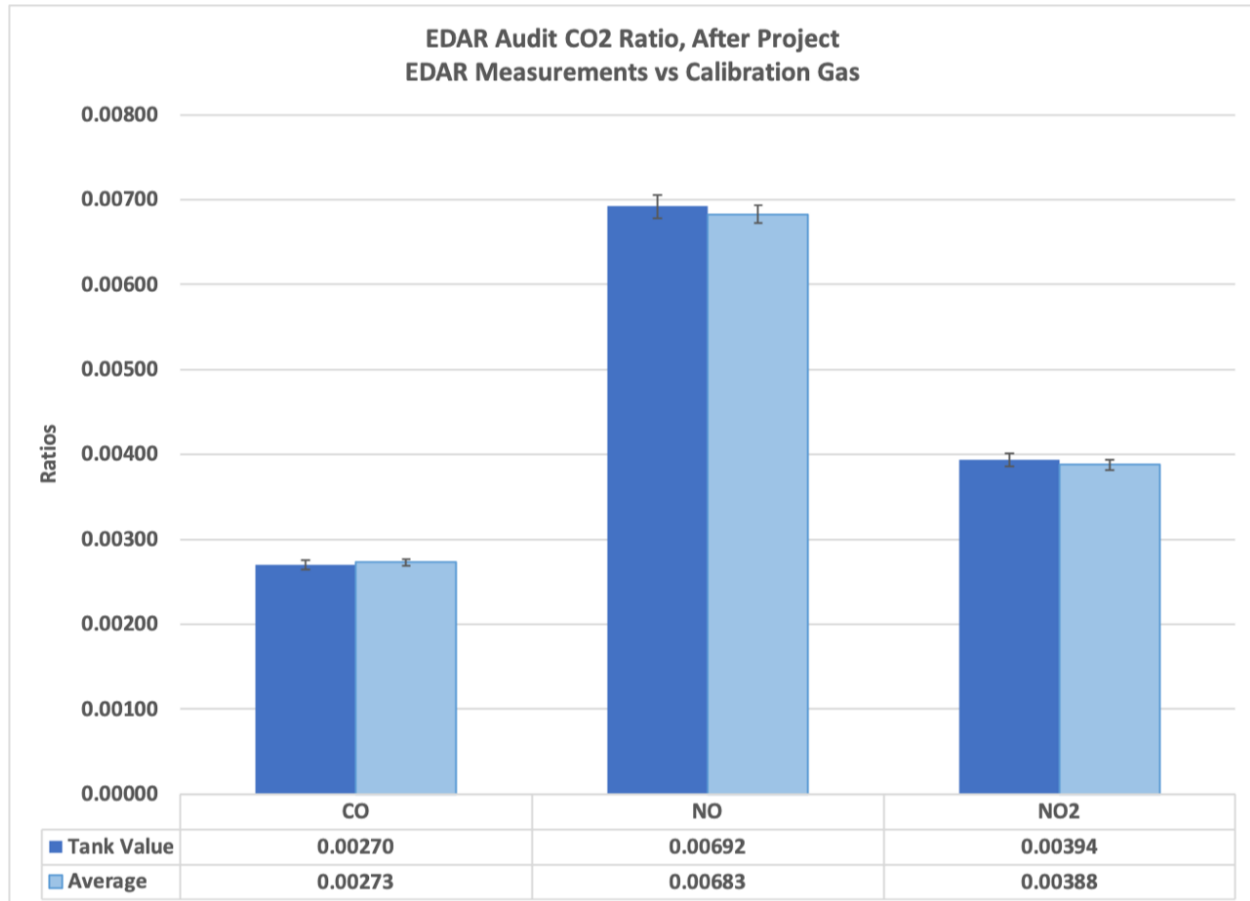
These calibration gases are sourced from well-known specialty gas providers and are produced to US EPA standards. The gas values are all accurate to within 1% of the stated concentration ratios and are traceable to the National Institute of Standards and Technology. The QA test is repeated 10-times before shipping to the project location and 10-times after receiving the EDAR unit back once the data collection project has been completed.

The column plots below show the results of the QA test comparisons for the Paris Project. Figure 17 shows the results for CO, NO and NO₂ calibration gas bottles, which are in the dark blue columns on the left, with the light blue representing the EDAR unit's output before the project. Figure 18 demonstrates the results for the CO, NO, and NO₂ calibration gas bottle testing after the completion of the project. In all cases, the average output of the EDAR unit is within 2% of the known calibration gas cylinder values, proving that the EDAR system's accuracy was not affected by shipping or deployment in Paris.

Figure 17: Calibration Gas Audit Prior to Deployment



Figure 18: Calibration Gas Audit After Deployment



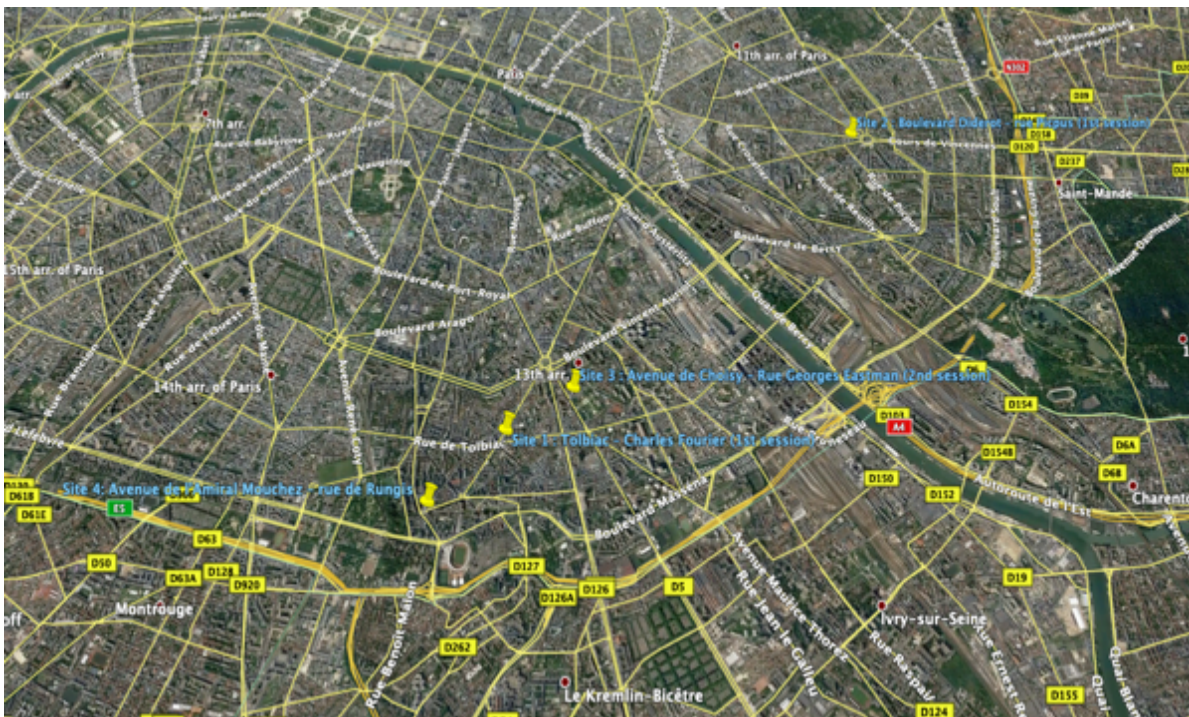
7 Summary of Data Collection Campaign

The data collection campaign in Paris using the HEAT EDAR system was conducted over 20 days in the Summer of 2018 to collect on-road real world emissions from light-duty vehicles in order to gain a significant data set regarding transport-related air pollution that will eventually contribute to future policy making decisions. The data collection goal for HEAT was to obtain valid on-road emissions measurements for 110,000 light duty vehicles at four selected locations. HEAT was able to reach this goal in merely two weeks but decided to continue testing to provide the project partners with an even more statistically significant dataset. Two EDAR units were in operation for the duration of the project and one of the units was moved to a different testing location mid-way through data collection.

As mentioned in the “Description of the Measurement Locations” section, the following locations were selected for data collection (*the locations are plotted on the map below*):

1. Rue de Tolbiac at Rue Charles Fourier
2. Boulevard Diderot at Rue de Picpus
3. Avenue de Choisy at Rue Georges Eastman
4. Avenue de l’Amiral Mouchez at Rue de Rungis

Figure 19: Map of All Deployment Locations



The measurements collected were initially processed to determine if the vehicle tested was light-duty, assign an anonymized ID, and to verify adequate Vehicle Specific Power (VSP). This process is completed by running the data through EDAR's unique and proprietary algorithm developed by HEAT. The license plates corresponding to the vehicles that were determined to be valid were provided to the City of Paris who handled the request for public information from the Vehicle Registration System (SIV) at the Ministry of the Interior (DSCR). Once the data was matched and processed by DSCR, 212,366 vehicles were returned, but 5,231 were not found in the registration database, thus resulting in 207,135 total matched records. From these matched records, 179,336 were confirmed to be light-duty. This combined data set was then provided via secure .csv file to ICCT for further analysis.

The table below shows a statistical overview of the EDAR system's measurements made during the period of testing in Paris.

Table 2: Data Statistics

Paris On-Road Remote Sensing Measurements Statistics	
EDAR Units	2
Sites	3
Data Collection Days	20
Records returned from the City of Paris	212,366
Number of records that did not have vehicle technical information returned	5,231
Number of total matched records	207,135
Valid Light Duty	179,336
Electric Vehicles	937

8 Details of Data Processing and Validation Approach

8.1 Data Processing and Handling

All data collected by the EDAR system was stored on a secure local computer in Paris with multiple layers of security. During the collection process, all emissions data was compiled on one central computer at HEAT's local office in Paris. Only authorized personnel were able access the system within the country. When retrieving the data from EDAR, HEAT engineers downloaded the data to highly secure, encrypted hard drives that require a physical PIN code to be entered on the outside of the device for data downloads to be initiated or for any data to be transferred. Only authorized HEAT personnel were made known of the secret PIN code and were allowed to handle the hard drive. As soon as the data was retrieved by the engineers it was manually transported to HEAT's local office in Paris and stored on the secure computer. After the transfer was complete, all data was destroyed from the transported hard drive. This process was designed to ensure that no data was ever uploaded into a cloud environment or to provide any opportunity for a data breach.

Additionally, no sensitive data, including license plates, left Paris once data collection and processing was completed. As stated above, no cloud storage was utilized during these operations. Confidentiality and anonymity of the motorists is of the utmost importance. An anonymized identifier was assigned to each record and the license plate information was then destroyed after submitting the data to the proper authorities for processing and before the HEAT team leaving the country. As mentioned earlier, this anonymized identifier allowed HEAT to associate the correct vehicle data with the corresponding emissions data without jeopardizing the privacy of any motorists or breaking any privacy laws outlined in the Air'Volution contract.

As an extra measure of security, the proprietary software used for monitoring the EDAR units has a series of alerts or annunciators to signal the engineers if there was a physical issue on site (e.g disconnection of power). With these instant alerts, no matter what time of day or night, HEAT had a specially trained engineer in the city of Paris who was on-call to resolve any issue quickly and efficiently, if necessary. Since EDAR is very robust and secure, fortunately, all operations ran smoothly without any major issues with the exception of the power being briefly disconnected at one of the locations.

8.2 Validation and Screening Process

HEAT applied the following screening checks to the measurements to ensure the data used for fleet evaluation were reasonable, consistent, and within the required parameters:

- Screening of exhaust plumes
- Screening for light duty vehicles
- Screening for Vehicle Specific Power (VSP) range

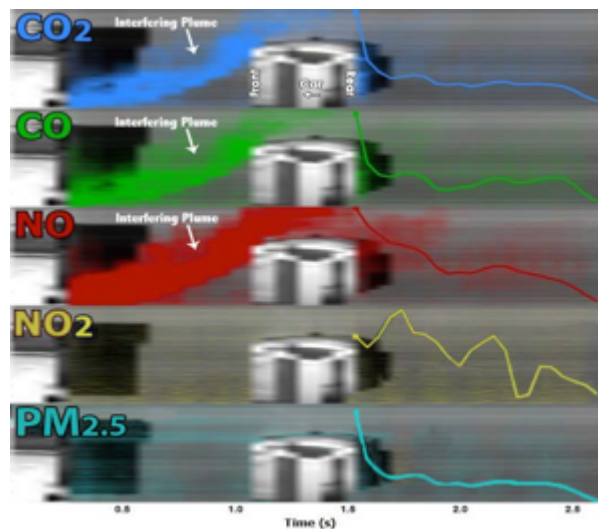
8.2.1 Screening of Exhaust Plumes and for Light Duty Vehicles

Since the EDAR system measures the exhaust plume with a sheet of laser light scanning across the roadway, the EDAR system is able to construct two-dimensional images of passing vehicles and their respective emission plumes. One axis of the image depicts the length across the road, while the other axis depicts the passage of time. The EDAR system can form a 2D passive infrared image of a vehicle as the it moves underneath the unit. The vehicle image can show the shape of the vehicle, its lane position, the position of its tailpipe, and assist in the determination of vehicle type (e.g. light-duty) based on the measurements of the vehicle. EDAR uses a specialized algorithm using the measurement of the height and length of the vehicle detected in order to determine the vehicle type automatically. This indication was calculated in real time.

In addition, the EDAR system forms an active image of a vehicle's emission plume showing the quantity of pollutant detected per unit area or optical mass in moles/m². The plume image shows the position of the plume for each pollutant as well as the dispersion rate of the plume.

The gas record is considered valid if there is one scan where the average measurement of CO₂ in the scan exceeds 0.004 moles/m². Furthermore, the linear correlation coefficient or Pearson's correlation criteria (r) is applied between the CO₂ measurements and the CO, NO and NO₂ measurements. If the correlation factor is relatively high, the measurement is considered valid. This signifies that there are no interfering plumes. Interfering plumes usually have different ratios of pollutant to CO₂; therefore, the linear correlation coefficient drops in value. The highest linear correlation coefficient is 1.0, whereas values near zero indicate no correlation and negative 1.0 indicates complete negative correlation. When gas readings are near zero for CO, NO and NO₂, then correlation values are ignored, because of the lack of presence of those gases.

Figure 20: Interfering Plumes



8.2.2 Vehicle Specific Power (VSP)

In order to make meaningful comparisons between various vehicle emissions testing methodologies, it is important to know the instantaneous loading conditions of the vehicle under test. This is particularly true for the case of remote sensing measurements, where a “snapshot” of the emissions of the vehicle under test is captured at a specific loading condition.

In 1999⁷, Jimenez advanced a new metric called Vehicle Specific Power (VSP) as a development over prior load classification parameters. VSP is an estimate of the ratio of instantaneous vehicle power to vehicle mass. The main advantage of VSP is that it avoids the necessity of knowing intrinsic vehicle and engine parameters in favor of parameters that can mostly be acquired remotely, like vehicle speed/acceleration and road grade. It is also advantageous in its simplicity as being a one-dimensional parameter. Jimenez showed the effectiveness of VSP through comparative analysis and was later adopted by the EPA for use in its modelling efforts⁸.

The equation for VSP incorporates various loading components acting on the vehicle under test. It includes the internal effect of “acceleration resistance,” due to the engine’s rotating components, as well as the external effects of road grade, rolling resistance, and aerodynamic drag. Jimenez developed typical values for each effect which are embedded in the following equation:

$$SP = v \cdot (1.1 \cdot a + 9.81 \cdot \sin(\alpha) + 0.132 + 0.000302 \cdot (v + v_w)^2)$$

Where:

SP is specific power in $\frac{kW}{t}$, $\frac{W}{kg}$, or $\frac{m^2}{s^3}$

v is vehicle speed in $\frac{m}{s}$

a is vehicle acceleration in $\frac{m}{s^2}$

α is roadway angle of inclination to the horizontal

v_w is headwind speed in $\frac{m}{s}$

In summary, the main use of VSP in remote sensing is for screening out vehicles which could be under high load and operating open loop (not near stoichiometry, or in this case a point at which all of the oxygen and fuel has been consumed, and therefore are expected to have high emissions) or at very low load where the vehicle would not produce NO or NO₂ because the vehicle is not under load.

⁷ Cires.colorado.edu/jimenez/Papers/Jimenez_PhD_Thesis.pdf

⁸ www.epa.gov/ttnchie1/conference/ei12/mobile/koupal.pdf

9 Conclusion

The EDAR system was successfully deployed in Paris in the Summer of 2018 utilizing HEAT's unique, temporary, unmanned platform. The EDAR system was deployed in three different locations around the City of Paris for a total of 20 days of testing, collecting over 200,000 records which provided historically the largest remote sensing data set collected in a short period of time in Europe. Accurate and reliable real-world emissions data is the most powerful and advantageous way to assess how vehicles are actually performing while in use. This successful program provided ICCT and the City of Paris with a substantial data set to aid in making informed decisions on the emissions of actual urban traffic as compared to the Euro standard.