OPUS REMOTE SENSING EUROPE

TRUE – The Real Urban Emissions Initiative

Brussels 2020

Fieldwork and methodology report

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Secondly, we would also like to thank Bruxelles Environnement, specially Louise Duprez, for her endless work in coordinating so many actors in this ambitious project.

We also thank all entities and people that have been involved in the project, throught different collaborations and guidance, including GOCA Vlaanderen, La Sécurité Automobile and Labo Bruit.

Finally, special thanks to our partner Securoad (lead by Carl Schwenke), for their professionalism in the execution of their work on this project.

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EXECUTIVE SUMMARY

Along with the FIA Foundation, the **International Council on Clean Transportation** (hereinafter, **ICCT**) has established The Real Urban Emissions Initiative (TRUE). The TRUE initiative seeks to supply cities with data regarding the real-world emissions of their vehicle fleets and equip them with technical information that can be used for strategic decision-making.

Opus Remote Sensing Europe (hereinafter, **OPUS**) was contracted to conduct measurements on real-world, real-driving emissions of the circulating road traffic fleet in Brussels. Two types of Remote Sensing Devices (RSD) were used in this project: the Opus AccuScan^{TM} RSD5000 and RSD5500.

Project management and data analysis has been done by OPUS, who partnered with **SecuRoad n.v.**, to perform the roadside measurements.

The objectives of this project have been succesfully accomplished:

- 247,230 final valid records were delivered to the ICCT, exceeding by far the 165,000 valid records target specified in the tender. This means we delivered 50% more measurements than expected. The data was collected in 29 days, from October 12th to November 20th.
- Brussels public buses were measured in the entrance of a bus depot, including those with exhaust pipes on the top of the vehicle. The setup for those measurements was prepared in about 30 minutes, confirming the Opus RSD can also easily measure this type of vehicles.
- Vehicles accessing a vehicle inspection station were measured with the RSD. The particulate matter (PM) measurements at free flow driving with the RSD were compared to particulate number (PN) counting at idle condition with PN-counter systems.
- Noise sensors from Labo Bruit of Bruxelles Environnement were co-located on some sites with the RSD. The data from the RSD was used to enhance the acustic analysis of road traffic on those sites.

Data analysis is reported in a separate document, published by the ICCT. This document only reports the fieldwork and methodology used during the project.

1 PROJECT OVERVIEW

The main objectives of the project, associated to the remote sensing measurements, are:

(1) To characterize and analyze the road traffic emissions in the city of Brussels;

(2) To measure Euro V buses of Brussels public transport, including those with exhaust pipes on the roof;

(3) To compare opacity measurements (PM) done with the RSD versus the particulate number counted with PTI equipment.

From a more general perspective of the whole project, the consortium establishes some strategic objectives:

- To have a better understanding of on-road vehicle emissions, especially from the latest diesel vehicles (Euro 6d);
- To enrich the assessment of the impact of policies such as the Low Emission Zone (LEZ) and the phase-out of diesel, gasoline and LPG vehicles;
- Study the extent of particulate filter fraud among diesel vehicles;
- To better understand the noise emitted by different types of vehicles and at different speeds.

To perform this project, OPUS partnered with the Belgium company Securoad. www.securoad.be

1.1 Real-world traffic emissions characterization

One of the first objectives of the project was to collect more than 165,000 valid measurements to perform a proper fleet characterization of the city of Brussels. This large amount of data would provide detailed insights about the real-world emissions of that fleet. More than 247,0000 valid measurements were finally collected, outperforming the targets specified in the tender by 50%.

Table 1. Expected vs Final data sample.

	Tender Objectives	Final collected data
Raw measurements	285,000	356,661
% Valid	~70%	73%
Valid vehicle emission measurements	199,500	261,103
% VSP within RFP requirements	~90%	95%
Total and Final Valid	180,000	247,230

1.2 Euro V buses measurements

Other objective of the project was to measure public buses in Brussels. Some of these vehicles were Euro V buses with the exhaust pipe on the roof. To measure these vehicles, it was decided to deploy the RSD at a certain height to measure at the height the exhaust gases are expelled. The final setup is shown in the photographs of section •.

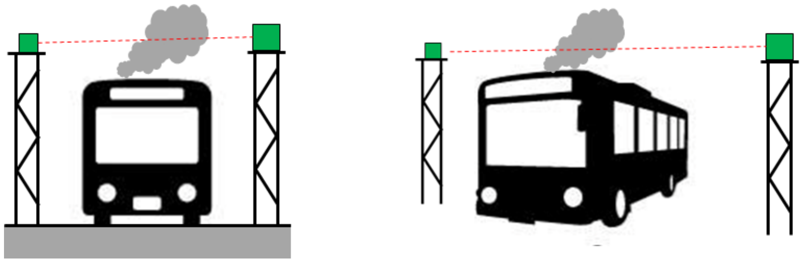


Figure 1 RSD setup scheme for Euro V buses with exhaust pipes on the top.

1.3 PM vs PN measurements

The last objective of the project was to compare the measurements of vehicles' PM emissions with the measurements of the same vehicles' PN emissions. This was done in coordination with GOCA Vlaanderen and La Sécurité Automobile. OPUS was responsible for the remote sensing measurements on the road, at free-flow, real-driving conditions, and GOCA was responsible for taipipe PN measurements at idle condition of the vehicles accessing the PTI. The measurements were matched by the identification of the license plate on each measurement.

1.4 Methodology

The project has been completed in three phases:

- Phase 1: Sampling plan development and securement of permits and approvals.

- Phase 2: Data collection.

- Phase 3: Data processing and number plate matching.

The three phases were executed in a short time, meeting the schedule of the project.

2 PHASE 1. SAMPLING PLAN AND SECUREMENT OF PERMITS

Prior to the field Campaign, Opus RSE, in colaboration with Securoad, the ICCT, Bruxelles Environment and Bruxelles Mobilité, made a selection of potential sites in the urban area of Brussels. All parties provided critical knowledge about the traffic conditions in the region, road characteristics, administrative responsabilities, etc. This collaboration led to the identification of a long list of sites potentially suitable for the remote sensing measurements.

Sites were chosen according to their potential of providing good quality of data, also considering the desire to obtain a reasonable traffic intensity to optimize the data collection. Emissions depend on driving conditions (speed, acceleration, gradient of the road and driving behavior), so the selection of the sites was done very carefully, looking for different parameters, while at the same time meeting certain conditions for the correct measurement of exhaust emissions.

2.1 Selection of potential sites

Potential sites must fulfil certain requirements:

1. Single lane roads, so that emissions of each vehicle can be measured without exhaust gases overlapping and therefore each record can be matched to a single vehicle without the problem of possible mixture of gases from the plumes.
2. Smooth traffic flow. Not too busy such that the road is frequently congested (measurements cannot be made in queuing traffic or jams) but where the RSD can measure thousands of vehicles per day.
3. Locations on a slight upward slope, and / or locations where vehicles are under acceleration (e.g. on the exit from a roundabout). This type of locations maximizes the exhaust gas signal and data capture.
4. Some sort of street furniture in the middle (e.g. a small traffic island, or a hatched area) that can be coned off to protect the small sensor reflector.
5. Sites where there is a representative mix of different vehicle types and driving conditions.

Based on these characteristics, and thanks to detailed traffic information provided by Bruxelles Mobilité (i.e. traffic density maps, as shown in Figure 2), a first draft of sites was chosen, which is shown in Table 2.

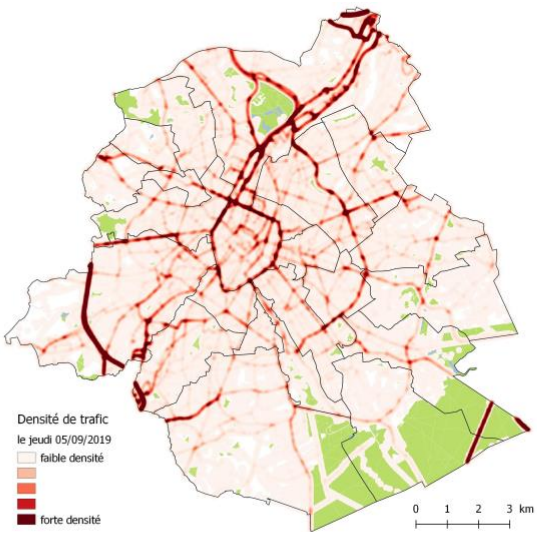


Figure 2. Traffic density in Brussels.

Table 2. Preliminary list of sites.

SITE ID	SHITE SHORT NAME	LINK	COORDINATES
BRU001	N266 at bus stop	https://goo.gl/maps/222PnzNqZwigswme9	50°49'43.2"N 4°18'59.2"E
BRU003	Tunnel N23 to R21 south	https://goo.gl/maps/mkSzDbZCLsVoq2dx9	50°50'53.1"N 4°24'10.1"E
BRU004	Tunnel N23 to R21 north entrance	https://goo.gl/maps/nyogW5SZQgmo8bPx8	50°50'59.5"N 4°24'13.8"E
BRU104	Tunnel N23 to R21 north exit	https://goo.gl/maps/2jGiqkQy6xkFg2Kq9	50°51'01.4"N 4°24'06.3"E
BRU005	Tunnel N23 entrance	https://goo.gl/maps/zsq7z5Cur84yPcoC9	50°51'02.2"N 4°24'25.8"E
BRU006	Tunnel Stefannia	https://goo.gl/maps/icmxyjHnsKotHx9j8	50°50'07.5"N 4°21'19.8"E
BRU007	A12 from Parc de Laeken	https://goo.gl/maps/5jpgECCorEqYCid8A	50°53'44.3"N 4°21'10.1"E
BRU008	Pont de Buda	https://goo.gl/maps/mvCD9ms67uaEftaQ9	50°54'18.0"N 4°24'24.9"E
BRU009	R21 from Docks Bruxsel	https://goo.gl/maps/Nu29R4r6hJBTjeuJA	50°52'39.3"N 4°22'29.1"E
BRU011	Avenue Tervueren	https://goo.gl/maps/tDceRQBqNVATjWas6	50°49'57.0"N 4°25'56.6"E
BRU012	Quai Léon Monnoyer	https://goo.gl/maps/3v9wdpJ8JLV6h3LS8	50°52'56.7"N 4°22'39.1"E
BRU013	E19 km16	https://goo.gl/maps/MqmzRdCBF58wNNz47	50°49'12.5"N 4°17'02.6"E
BRU014	Avenue Louis Dehoux	https://goo.gl/maps/VTGg6xErCiupYAiN8	50°48'47.7"N 4°25'20.8"E
BRU015	Boulevard de Berlaimont	https://goo.gl/maps/PukFrG7T6Hbq7QX58	50°50'54.9"N 4°21'30.4"E
BRU016	N205 Avenue d'Auderghem	https://goo.gl/maps/BBFMdDZAfbrXaXRC8	50°50'18.7"N 4°23'09.6"E
BRU017	Rue de la Loi	https://goo.gl/maps/1yvMWEU2gU9KcgeN9	50°50'35.3"N 4°22'50.4"E
BRU018	Dépôt STIB Jacques Brel	https://goo.gl/maps/X9maf5ZorMiTHJyv5	50°50'42.0"N 4°19'11.9"E
BRU019	PTI entrance	https://goo.gl/maps/Map8Btzd7cFtw3C46	50°48'36.6"N 4°18'19.9"E

2.2 Securement of permits

The permits to conduct the measurements were prepared and requested by the company **SECUROAD** and its subsidiary, **JACOPS**. This was done thorugh **OSIRIS**, an e-tool used by the city of Brussels to coordinate all requests to open the public domain.

Maps and safety plans were prepared and introduced in the system. A close and direct contact with local authorities and police was also done, to ensure permits were facilitated as fast as possible.

3 PHASE 2. DATA COLLECTION

This section describes the data collection phase of the project.

3.1 Description of the remote sensing technology

Opus AccuScan™ RSDs remotely measure exhaust emissions from motor vehicles as they are driven past the remote sensing device on streets and highways. The emissions are measured spectroscopically by casting a narrow infrared (IR) and ultraviolet (UV) beam of light across the road and through the trailing exhaust of passing motor vehicles. A mirror then reflects the IR/UV light back to a series of detectors that measure the amount of transmitted light at characteristic wavelengths absorbed by the pollutants of interest.

By subtracting any pre-vehicle background absorption from the amount of IR/UV light absorbed by the various tailpipe pollutants, the system can determine the pollutant levels in the vehicle's exhaust. As the emissions are measured, the video camera captures a digital image of the license plate and the speed/acceleration sensors record the speed and acceleration of the vehicle. The emissions, weather conditions, slope, speed and acceleration data as well as the license plate image are merged within less than a second to complete a measurement record which is then stored in a computer database for future analysis and reporting.

The RSD can measure the emissions of vehicles circulating under real driving conditions. Since it takes only a second to capture a measurement, these devices can capture large quantities of vehicle emissions data in a short period of time. Also, since it is a non-intrusive technique, the RSD audits the circulating vehicles without interfering with the traffic flow, therefore it can audit an entire fleet in a short period and with no impact on daily operations.

AccuScan™ RSDs have measured **hundreds of millions of vehicles worldwide**, far more than any other technology.

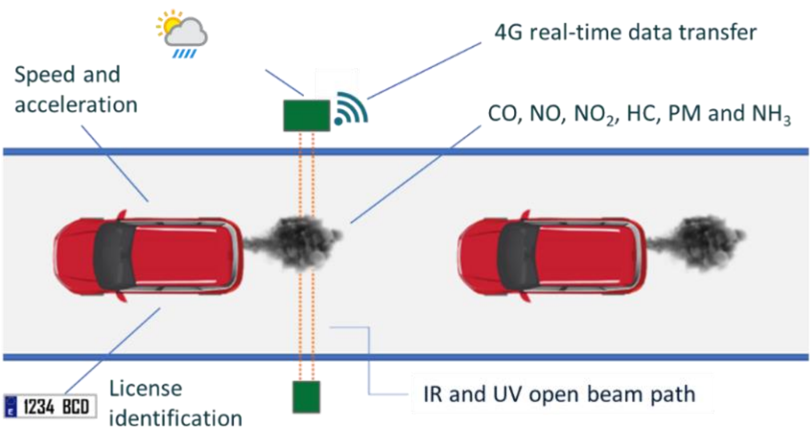


Figure 3 – Opus RSD schematic.

Two types of systems were used in the project: the Opus AccuScan™ RSD5000 and RSD5500. Although both versions measure primary NO_2 emissions, the RSD5500 includes an enhanced and dedicated channel for measuring this pollutant, as well several hardware upgrades for an overall improved performance. The operating basics and measurement techniques of both systems are equal, so their measurements are comparable.

3.2 Performance of the remote sensing technology

OPUS RSD5000 can measure within specifications in the following conditions:

- Operating humidity range: 0% to 95% (non-condensing).
- Operating Temperature range: -7°C to 49°C.
- Power source: 48VCD, with variations between 36VCD and 56VCD.

CO, HC, NO and NO_2 results are calculated tailpipe concentrations from their measured ratios to CO_2 and are corrected for both water vapor and any excess in the air exhaust. The performance of the RSD5000 will meet or exceed the following absolute and relative accuracy specifications:

Table 3. RSD5000 measurement specifications.

Parameter (unit)	Max. relative tolerance (%)	Max. uncertainty of the road sensing measurement (%)
CO/CO_2 (%/%)	15	21 (relative uncertainty)
NO/CO_2 (ppm/%)	15	21 (relative uncertainty)
NO_2/CO_2 (ppm/%)	15	21 (relative uncertainty)
NH_3/CO_2 (ppm/%) [1]	15	21 (relative uncertainty)
HC[propane]/CO_2 (ppm/%)	15	21 (relative uncertainty)
Opacity (%)	2	2.6 (absolute uncertainty)

The RSD5000 measures speed and acceleration (S/A) by determining the time required for front and rear tires to cross through two electronic gates created by two lasers traversing the single lane of travel at close to two inches above the road surface. S/A performance specifications are:

- Speed: +/- 1 mph when the vehicle is traveling 5 to 100 mph.
- Acceleration: +/- 0.5 mph/second when the vehicle is traveling 5 to 100 mph.

The Opus Speed and Acceleration Module (SAM) was certified on RSD3000 and RSD4000 series systems by the California Bureau of Automotive Repair as part of their OREMS acceptance testing. Today, the Colorado Department of Public Health and Environment

[1] Channel not yet accredited in ISO-17025.

(CDPHE) certifies the RSD5000 SAMs placed into service in their RapidPass program. In Europe, the Spanish Metrology Center performs a metrological study of this system every year, providing a metrological certificate.

The standard camera and license plate imaging system that Opus provides is a high-zoom ratio AF lens 18x optical + 12x digital zoom camera.

OPUS establishes the accuracy and precision of each Accuscan™ RSD unit deployed in its programs prior to its deployment. This is accomplished through a comprehensive set of pre-deployment, real-time, and post-data collection protocols which are briefly described below.

- Factory Certification: Each RSD unit is first factory-certified for accuracy and precisions using several known dry-gas mixtures in accordance with the COVERS requirements.
- Laboratory Certification: Each RSD unit is certified for accuracy and precisions using several known dry-gas mixtures in accordance with the ISO-17025 protocols.
- Field Calibration and Audit: Each RSD unit is then calibrated, and the calibration verified, prior to each data collection session. This means the RSD is calibrated again following a dry-gas mixtures audit every time it is deployed on the roadside.
- Periodic Audits: Each unit is then audited regularly during the course of the session to verify the system is performing within specifications and does not need re-alignment and/or re-calibration.
- Real-time Measurement Validation: As data is collected, sophisticated Accuscan™ exhaust plume validation software (developed and improved over decades) reviews each measurement in real-time to ensure it is of adequate strength, that the exhaust plume decayed in a manner consistent with warm loaded-mode vehicle operations, and that the prevailing background levels are stable and can be accurately determined. Valid measurements that have passed the real-time filters are marked accordingly for each pollutant (independent validity flags).
- Post-Collection Filters: Each session's dataset is reviewed post-collection to normalize statistical variances, outliers or to apply VSP filters. These and other post-collection reviews have been developed over our decades of conducting studies, pilots and programs and are typically agreed with each client.

The Factory and Laboratory Certifications focus on ensuring the unit is measuring within accuracy and precisions tolerances. The Field Calibration and Audits focus on ensuring the unit is optimally calibrated and effectively subtracting background levels. The Real-Time Validation software filters out any measurements that cannot be used with a high degree of confidence in monitoring or screening applications. The Post-Collection Filters further remove those measurements that might have been captured during operating conditions when the vehicle (by design) is unable to effectively control its emissions.

Following the sequential stages of quality assessment, review, and control only the most accurate and representative measurements of the vehicle's emissions are used in analysis.

Apart from the above, our RSDs have also been audited by other entities:

- CIEMAT (Center for Energy, Environmental & Technological Research of Spain), 2015, 2020.
- IVL (Swedish Environmental Research Institute), 2016.
- JRC (European Commission's Joint Research Centre), 2017.
- RICARDO E&E, 2018.
- Applus+ IDIADA, 2018.

3.3 On-site evaluation and selection of final sites

From the list of potential sites (Table 2) all the locations were carefully reviewed on site. From the initial list, eight (8) definitive sites were selected for the data collection phase. Selected sites can be seen on the next table and map:

Table 4 List of definitive sites.

Site ID	Site Short Name	Latitude	Longitude	Slope (°)	Data collection (# of days)
1	BRU001	50.828791	4.316631	0.3	22
2	BRU001A	50.827798	4.314836	0.2	16
3	BRU005	50.850969	4.407269	0.4	10
4	BRU011	50.831672	4.433003	0.3	4
5	BRU012	50.882595	4.375679	0.1	1
6	BRU017	50.8440624	4.373651	0.3	2
7	BRU018	50.84501	4.320248	3.9	5
8	BRU019	50.810135	4.305747	0.1	4

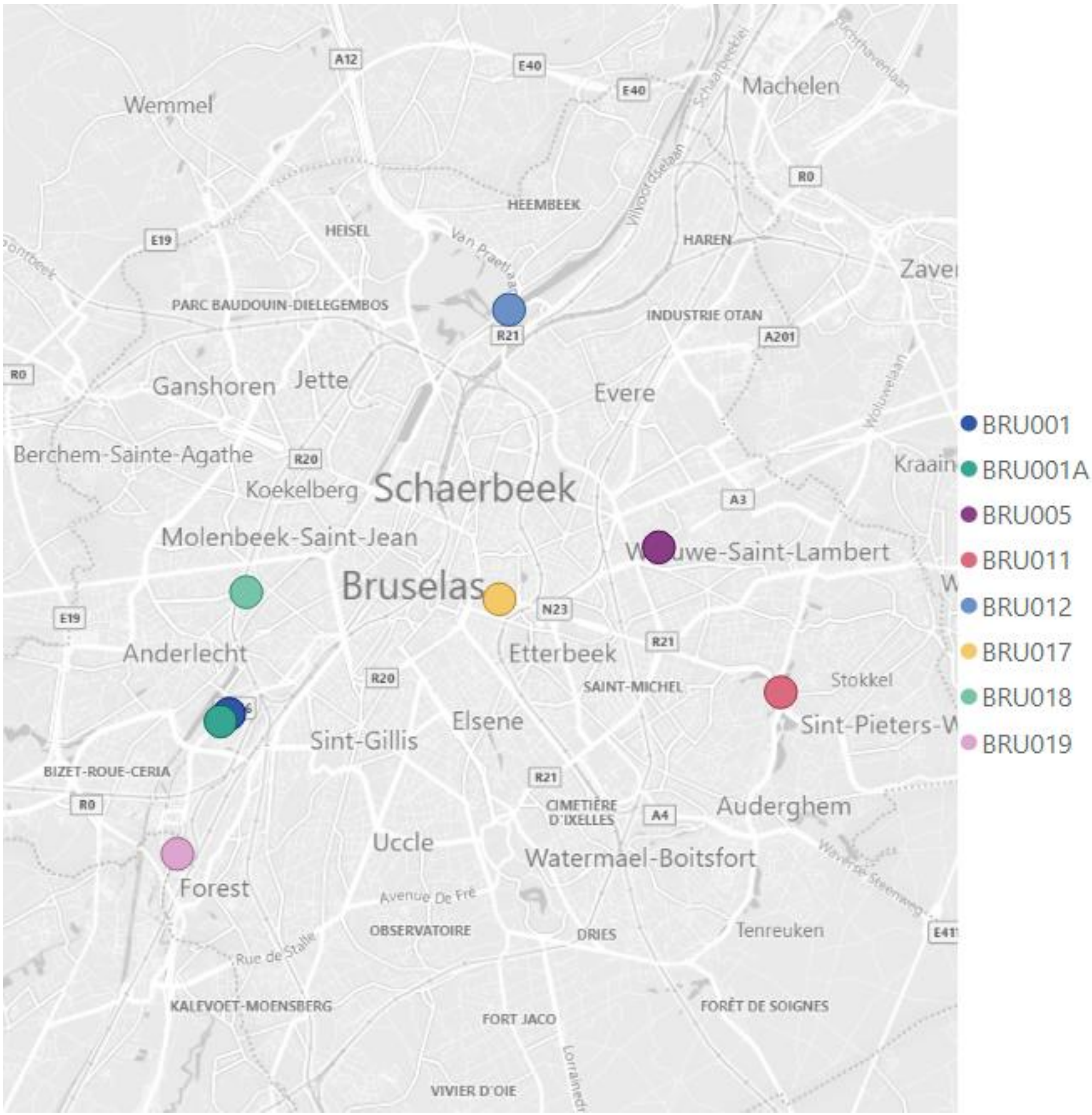


Figure 4 Map of final sites.

The following photographs show each measurement site, including a short description.

Site 1 – BRU001

Site located at the N266 after a bus stop. Traffic was fluid, with a high number of vehicles per hour and a high percentage of valid measurements, as vehicles accelerated after a rounabout. This site was frequently used for noise measurements too, as shown in the next photograph.

Figure 5 BRU001.

Site 2 – BRU001A

Site also located on the N266, on the opposite direction, also exiting the roundabout. This site had the highest validity percentage of the campaign and the second highest number of valid measurements per hour.

Figure 6 BRU001A.

Site 3 – BRU005

Located on the N23, near the entrance of the tunnel. Site with the highest number of valid vehicles per hour and the highest valid speed and acceleration percentage. Vehicles could be measured at medium to high speeds, in order to characterize traffic at this condition.

Figure 7 BRU005.

Site 4 – BRU011

Located on the Avenue Tervueren, next to the tram tracks. Low volume of valid vehicles per hour compared to the first three sites, also with a low valid gas percentage (60%). Operating conditions were not ideal for emissions characterization (gas pedal not pushed).

Figure 8 BRU011.

Site 5 – BRU012

Site placed on Quai Léon Monnoyer, on the north part of the city. Site with rather low valid gas percentage and a very low number of valid vehicles per hour, but still considered to evaluate vehicles in this district.

Figure 9 BRU012.

Site 6 – BRU017

Located on rue de la Loi, next to the European Comission. A lot of traffic jams occur on this site. It is the most centric site of the campaign.

Figure 10 BRU017.

Site 7 – BRU018

Located at the Boulevard James Graindor, next to the entrance to the Bus depot. This site was used to measure the Buses with the exhaust on the top. Two lift scissors wre used to place the two RSD components (emitter and reflector). The allignment of the optical path was done in about 20 minutes, completing deployment, allignment and calibration in aproximately 30 minutes. Each monitoring day, this setup was prepared and retired.

Figure 11 BRU018

Site 8 – BRU019

Site located at the Rue du Liutenant Lotin, at the entrance of the PTI, vehicles measured here were compared to the results obtained in the entrance to the PTI with PN-counters.

Figure 12 BRU019

3.4 Data collection results

The fieldwork consisted of **29 total days of measurements**, capturing data for about 12 hours a day, from October 12th to November 20th. The field campaign was led by Carl Schwenke, from Securoad.

The RSD is always first calibrated prior to each data collection session, in a process that takes a few minutes. During the course of the session, the RSD is audited each 45 minutes, to verify the system is performing within specifications and does not need re-alignment and/or re-calibration. This methodology is the standard approved in the industry, to ensure the data quality.

The calibration procedure involves a two-stage process of calibrating then auditing the system. Firstly, the SDM (Source Detection Module) alignment signals are maximized. Then the calibration is done, with the use of an internal cell calibration cell which contains known values of calibration gases. Following this, audits are undertaken using certified gas cylinders with known gas mixtures. Controlled releases of known quantities of gases are introduced into the optical beam path of the system. The system confirms that it is measuring correctly comparing to these known concentrations.

The system is calibrated in less than 20 minutes, then in begins to collect all the data autonomously and automatically.

As data is collected, sophisticated AccuscanTM exhaust plume validation software (developed and improved over two decades) reviews each measurement in real-time to ensure it is of adequate strength, that the exhaust plume decayed in a manner consistent with warm loaded-mode vehicle operations, and that the prevailing background levels are stable and can be accurately determined. Each session's dataset is compiled every day and put together into a large database later on.

Table 5 shows the number of days measured in each site, the number of total and valid registers and the percentages of the validity of the data.

Table 5 Measurements per site.

ID	Site ID	Days	Total records	Final valid records	% Valid gas records	%Valid VSP records	% Final valid records
1	BRU001	22	142684	104569	88%	89%	73%
2	BRU001A	16	125061	102654	94%	90%	82%
3	BRU005	10	52106	38865	82%	98%	75%
4	BRU018	5	1494	1054	90%	82%	71%
5	BRU011	4	21854	10940	59%	90%	50%
6	BRU019	4	3245	1914	92%	84%	59%
7	BRU017	2	5268	456	41%	34%	9%
8	BRU012	1	4949	651	22%	67%	13%

Table 6 Number of records per site

Site ID	Site Short Name	Total time per site (hours)	Number of valid records per hour
1	BRU001	243	423
2	BRU001A	197	533
3	BRU005	74	540
4	BRU011	54	173
5	BRU012	14	53
6	BRU017	10	71
7	BRU018	36	54
8	BRU019	35	71

A **total of 356,661 records** have been captured, with 247,230 of them considered as valid for a proper emission factor estimation. Each record is composed by:

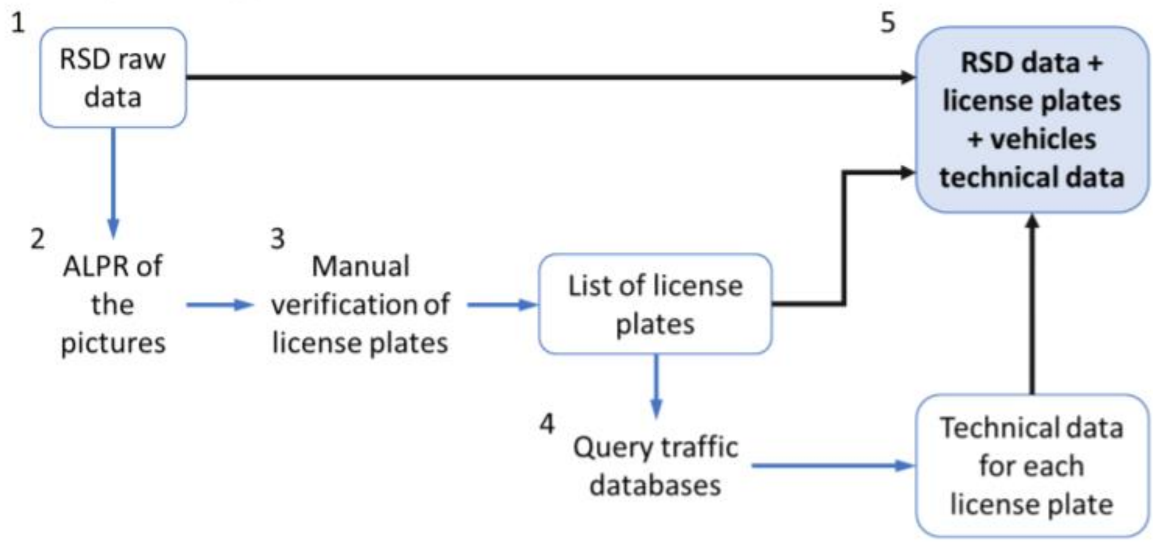
- Photograph of the license plate, wich allows to retrieve the technical data of each vehicle (vehicle type, fuel type, euro standard, brand, model, etc.).
- Kinetic conditions: speed, acceleration and engine load (VSP)
- Pollutant concentrations (CO, HC, NO, NO_2 and PM) reported in emission ratios, that are later converted to othersignificant units, such as fuel-specific emissions or distance-travelled emissions.
- Environmental conditions (pressure, temperature and relative humidity).

The RSD measures the amounts of gas present for CO, CO_2, HC, NO and NO_2., and plume opacity, to estimate particulate matter (PM). The measured quantities of the gas are specifically the number of molecules along the path of the measurement beam. The light beam passes through the exhaust plume and is reflected by the CCM (Corner Cube Module) back to the detector, which records the changes in light intensity produced by the absorption of the different gases. From this absorption, concentrations can be calculated by applying Lambert-Beer's law. However, due to the remote nature of the equipment (we do not know the length of the optical path), it is not possible to report absolute concentrations, but the RSD provides emission concentrations (ratio of concentrations of each of the pollutants with respect to CO_2). This is known as pollutant concentrations and are the basic remote sensing emission information from the vehicles' exhaust emissions:

- NO/CO_2.
- NO_2/CO_2.
- HC/CO_2.
- CO/CO_2.

4 PHASE 3. DATA PROCESSING AND NUMBER PLATE MATCHING

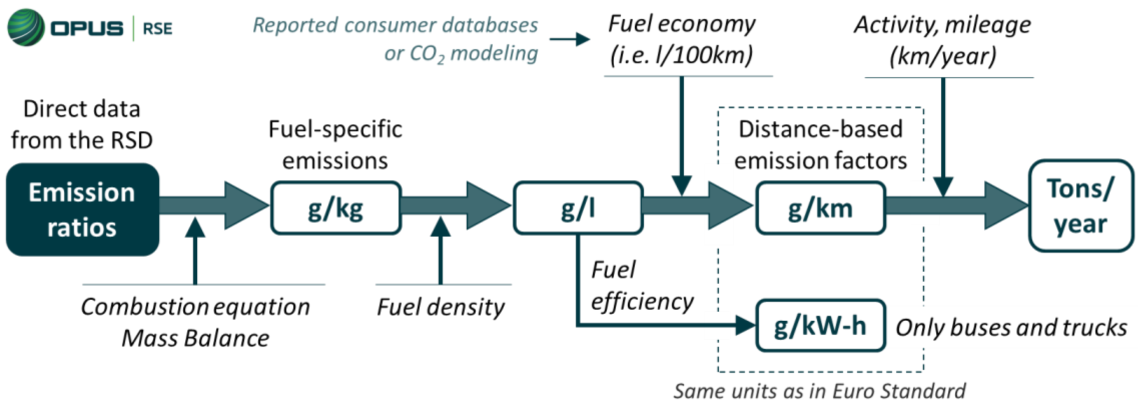
The data processing process is sumarized in the following scheme.



1. The RSD compiles all the collected data, which is composed of:
    a. Database with all the data measured by the RSD.
    b. All the pictures taken during the session by the videocamera.
2. The pictures taken by the RSD camera are processed by an ALPR software (Automatic License-Plate Reader) that recognizes the characters of the license plates of the vehicles and delivers a text-format result, to update the database.
3. Because of different conditions on the sunlight, the camera distance, the vehicle speed and other factors, the ALPR software does not recognize all the license plates. Therefore, all records are checked manually.
4. The list of identified license plates is created, to retrieve the vehicle technical information of each vehicle from the traffic databases. We receive the technical information associated to each vehicle's license plate in a secured protocol.
5. The RSD data is matched to the license plates and the vehicles' technical information, to create a large database that provides complete information for each record.

As mentioned in previous chapter, RSD readings are ratios (or gas concentrations). Those are the emission values directly given by the RSD. Any other units must be calculated after step 5.

From the concentrations given by the RSD, assuming that they are constant throughout the exhaust plume, emissions can be calculated in meaningful units. The following schemes and equations shos an outline of the different transformations that can be made to transform the emissions measurements into more significant units.



To transform the ratios to emissions in grams of pollutant per kg of fuel, the fuel combustion equation must be used. A series of assumptions must be made, and mass balances must be applied. All these steps are explained in detail on the following website: http://www.feat.biochem.du.edu/whatsafeat.html

The fuel combustion equation is used, assuming CH2 for diesel and gasoline and CH4 for CNG:

$CH2 + m(0.21O2 + 0.79N2) \rightarrow aCO + bH2O + 2c(C3H6\ ) + dCO2 + eNO + fNO2 + (0.79m - (e + f)/2)N2$ (diesel, petrol)

$CH4 + m(0.21O2 + 0.79N2) \rightarrow aCO + bH2O + 2c(CH4\ ) + dCO2 + eNO + (0.79m - e\ 2\ )N2$ (CNG)

Mass balances are applied for each element (carbon, hydrogen and oxygen) and the following equations are obtained:

$$CO\left(\frac{g}{kg}\right) = \frac{Q}{1 + Q + 0.0006xQ'} x \frac{1}{KgMC} xM_w$$

$$CO_2\left(\frac{g}{kg}\right) = \frac{1}{1 + Q + 0.0006xQ'} x \frac{1}{KgMC} xM_w$$

$$HC\left(\frac{g}{kg}\right) = \frac{0.0001xQ'}{1 + Q + 0.0006xQ'} x \frac{HCRF}{KgMC} xM_w$$

$$NO\left(\frac{g}{kg}\right) = \frac{0.0001xQ''}{1 + Q + 0.0006xQ'} x \frac{1}{KgMC} xM_w$$

$$NO_2\left(\frac{g}{kg}\right) = \frac{0.0001xQ'''}{1 + Q + 0.0006xQ'} x \frac{1}{KgMC} xM_w$$

$$PM\left(\frac{g}{kg}\right) = [UV_{smoke}]x10$$

Q, Q', Q'' and Q''' are the ratios directly obtained from the RSD readings:

$$Q = \frac{CO\ (\%)}{CO_2(\%)}$$

$$Q' = \frac{HC\ (ppm\ propano)}{CO_2(\%)}$$

$$Q'' = \frac{NO\ (ppm)}{CO_2(\%)}$$

$$Q''' = \frac{NO_2(ppm)}{CO_2(\%)}$$

Mw: Molecular weight of each gas:

Gas	**M_w (g/mol)**
CO	28
HC (propane)	44
NO	30
NO_2	46
CO_2	44

KgMC is a parameter that represents the proportion of carbon in the fuel. Thus, depending on the fuel, this value will be different:

Fuel	Diesel	Petrol	CNG	LPG
KgMC	0.014	0.014	0.016	1

HCRF is a factor that corrects the hydrocarbon measurements:

Fuel	Diesel	Petrol	CNG	LPG
HCRF	1.63	2.2	3.33	1

To obtain emissions in g/L, it is sufficient to multiply the emissions in g/kg by the density of the corresponding fuel:

Fuel	Diesel	Petrol	CNG	LPG
Density (Kg/L)	0.81	0.73	0.46	0.46

From the emissions in g/l, the emissions in g/kW-h (only necessary for heavy duty vehicles) can be obtained by multiplying by a parameter known as 'diesel efficiency'. The value we use is 0.26L/kW-h, which is provided by Volvo.

From the emissions in g/L, the emissions in g/km can also be calculated by multiplying by the consumption (L/km).

5 CONCLUSION

All the objectives of the project have been fulfilled:

- More than 247,000 valid measurements have been delivered, 50% more data than specified in the tender, collected in 8 different sites, from different parts of the municipality. All the data has been collected in previously selected sites, guaranteeing a diverse sample of Brussels's circulating fleet and different road characteristics.
- The data was collected in a very short time (29 days), without any delays or issues during the three phases of the project.
- Brussels public busses have been measured, both on the city streets and on the entrance to a large bus depot, including buses with exhaust pipes on the top.
- Vehicles that were tested on the vehicle inspection station for PN (number of particles) testing, were compared to the same vehicle measurement performed by an RSD some meters before.

The large quantity of valid measurements collected in the project guarantees an optimal emission characterization of Brussels's circulating fleet. That analysis is performed by the ICCT for the TRUE Initiative, and is published on a separate project report.

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