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## Article

# Integrated Mobile Laboratory for Air Pollution Assessment: Literature Review and cc-TrAIRer Design

Chiara Boanini , Domenico Mecca , Federica Pognant , Matteo Bo  and Marina Clerico \* 

Politecnico di Torino, Dipartimento di Ingegneria per L'Ambiente, il Territorio e le Infrastrutture, Corso Duca degli Abruzzi 24, 10138 Torino, Italy; chiara.boanini@polito.it (C.B.); domenico.mecca@polito.it (D.M.); federica.pognant@polito.it (F.P.); matteo.bo@polito.it (M.B.)

\* Correspondence: marina.clerico@polito.it

**Abstract:** To promote research studies on air pollution and climate change, the mobile laboratory cc-TrAIRer (Climate Change—TRailer for AIR and Environmental Research) was designed and built. It consists of a trailer which affords particles, gas, meteorological and noise measurements. Thanks to its structure and its versatility, it can easily conduct field campaigns in remote areas. The literature review presented in this paper shows the main characteristics of the existing mobile laboratories. The cc-TrAIRer was built by evaluating technical aspects, instrumentations and auxiliary systems that emerged from previous studies in the literature. Some of the studies conducted in heterogeneous topography areas, such as the Po Valley and the Alps, using instruments that were chosen to be located on the mobile laboratory are here reported. The preliminary results highlight the future applications of the trailer and the importance of high temporal resolution data acquisition for the characterization of pollution phenomena. The potential applications of the cc-TrAIRer concern different fields, such as complex terrain, emergency situations, worksite and local source impacts and temporal and spatial distributions of atmospheric compounds. The integrated use of gas and particle analysers, a weather station and environment monitoring systems in a single easily transportable vehicle will contribute to research studies on global aspects of climate change.

**Keywords:** air pollution; mobile laboratory; atmospheric pollutant dispersion; sources monitoring; alpine region; complex terrain; climate change



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## 1. Introduction

Air quality and atmospheric pollution are still serious challenges worldwide [1–3]. Indeed, air pollution contributes to at least 7 million deaths worldwide every year [4–6]. According to the State of Global Air 2020 report of the Health Effect Institute, in 2019, it moved up from the fifth to the fourth cause of global deaths, covering 12% of the total.

Atmospheric pollutants can be directly emitted by both anthropogenic and natural sources: although the former are the most significant contributors to the major compounds, the latter should not be overlooked [7,8]. These primary compounds can also chemically interact to promote the formation of secondary air pollutants [9]. Activities related to the combustion of fossil fuels (coal, oil, gas and gasoline), energy production, agricultural burning or other industrial processes for power generation, space heating and transportation significantly increase the particulate matter (PM) concentration in the atmosphere [10,11]. At the same time, fires, sea spray, soil erosion and resuspension of dust naturally contribute to particulate matter increment [12]. Sources of CO include fossil fuels and motor vehicle exhausts, while the burning of coal and oil raises SO<sub>2</sub> concentration values [13–15]. NO<sub>x</sub> and VOC are two other critical air pollutants with health and environmental aspects, but they are also involved in the ground-level ozone production mechanism. CO, VOCs and CH<sub>4</sub> are, in fact, oxidized in the presence of solar radiation and NO<sub>x</sub> to form ozone, a secondary pollutant responsible for photochemical smog and health risks linked to respiratory diseases [16,17].

Exposure to high concentrations of gas and particle pollutants gives rise to demonstrated negative effects on the environment and on human health [18–21]. In adverse conditions of both outdoor and indoor pollution, a large number of organs can generally be affected, such as the lungs [22], heart and brain [23] and eyes [24]. Air pollution also causes relevant impacts on cancers [25], cardiovascular diseases [26], diabetes and obesity [27] and subjective well-being [28]. Air pollutants are also strongly harmful to the environment, with devastating consequences evident. For instance, soil and water matrices are damaged by the effects of acid rains, which usually corrode buildings, statues and infrastructures too [29]. Anthropogenic emissions, such as those from traffic or industrial activities, contribute to the production of haze, which strongly reduces the atmospheric visibility, especially when opportune accumulation conditions occur [30]. Moreover, the excessive deposition of nitrogen oxides and other nutrients affects the local eutrophication phenomena of surface water and consequently results in damage to aquatic ecosystems [31]. In wider terms, wildlife is dangerously threatened by the effects of air pollution [32].

It is now known that there is a mutual relationship between air pollution and climate change [32]. The compositions of some constituents of PM, such as black carbon, can induce a warming effect on the overall climate through the absorption of solar and infrared radiation [33]. Furthermore, the deposition of these particles on the surfaces of glaciers promotes their melting [34]. Since particles are actively involved in cloud formation, their atmospheric concentration can affect the cloud reflection of solar radiation, the temporal and physical characteristics of precipitations and how long they last [2]. Simultaneously, the main, direct consequences of climate change, such as the warming over the higher latitude areas and the decrease in the frequencies of cyclones, influence the air pollution phenomena [35]. Indeed, the alteration of meteorological events and atmospheric stability directly affects the concentration of PM and ozone [35,36]. The reduction of the number of precipitation and wind events increases the stagnation conditions and decreases the possibility of the dilution and deposition of pollutants [37]. Furthermore, the increase of temperature and the exposure to solar radiation promote higher ground-level ozone concentrations and long-lasting phenomena [38–40].

The effects of climate change are clearly visible in mountain glaciers, which are, for this reason, key strategic indicators of global warming [41]. Due to their morphological composition, the Po Valley and the Alps in Italy are some of the most critical European areas where the combined effect of climate change and air pollution is observable. Their geographical location is interesting from a scientific viewpoint, since it contains different environments (sea, mountains, valley) subjected to continental, Mediterranean and Alps climates, which are sometimes influenced by Saharan contributions too [42].

In light of this, especially in strategic areas such as the Po Valley, the importance of air quality monitoring, depending on the boundary conditions, in order to understand the impacts of megacities, anthropogenic activities and natural sources on atmosphere dynamics and pollutant concentrations is clear, as it makes it possible to examine global climate change effects in depth and to safeguard the environment and human health.

For this reason, additional data as well as those provided by institutional agencies are needed to expand the amount of information from spatial and temporal points of view [43]. In fact, there is an increasing necessity for approaches that are able to reach complex terrain with the aim of carrying out research and promptly intervening in emergencies, taking advantage of high-time-resolution instrumentation.

Mobile laboratories are some of the systems currently used to reach this goal, with a focus on air, soil, water and biota applications [44]. In air studies, monitoring campaigns can be conducted in mobile or stationary ways. The main purpose of the first is usually to obtain the spatial characteristics of collected data, while in the second modality a strategic sampling point is added to the fixed monitoring network. In both cases, these laboratories are complex systems which need an accurate design, especially with regard to instruments' operative conditions, inlet characteristics and power supply. Once collected, the data require a dedicated processing strategy to obtain satisfying results on air pollution

trends [45]. Moreover, the proper selection of instruments that can be easily transported is required. The aim of this work was to describe the design of a mobile laboratory, the cc-TrAIRer (Climate Change—TRailer for AIR and Environmental Research), consisting of a non-motorised instrumented trailer and with the purpose of conducting monitoring campaigns to analyse the effect of specific sources, weather, and atmospheric and boundary conditions on air quality parameters in order to incorporate the examined phenomena in the investigation of global aspects of climate change.

In this article, we present a literature review of the design of existing mobile laboratories (Section 2) and then discuss the equipment of the cc-TrAIRer (Section 3), focusing on instruments and the management of auxiliary systems, such as the electrical, informatic and energetic systems. Lastly, a brief overview of the results of campaigns performed in some sites from the Po Valley and the Alps is presented (Section 4). The literature analysis and the previous studies conducted led to the optimization of the trailer design. This article aimed to supply a technical background for future applications of the cc-TrAIRer.

## 2. Literature Review

In recent years, mobile laboratories have become increasingly widespread for activities involving the monitoring of air quality standards and pollutants. They can be applied for urban, rural, background, industrial or emergency monitoring and they can also be used for the assessment of a specific source. Due to their on-going development, studies on mobile air quality measurement campaigns can be found in the literature. In this section, the instrumentation equipment, technical aspects and main purpose of these kinds of laboratories are analysed.

One of the first applications was a semi-trailer designed by the University of California [46], used mainly for research purposes. Despite the possibility of evaluating gas and PM concentration at different points, its bulky structure reduced the chances of easy use in specific tight and uncompromising places. Also, the operational activities were strongly affected by the presence of an electrical network. In fact, the truck did not guarantee an electrical range through generators or internal energy storage technologies.

Technological evolution led to the design of smart and smaller systems, which made it possible to carry out studies with a better electric range and higher versatility from a spatial and temporal point of view. Nowadays, the most popular vehicles for use in mobile monitoring activities with instruments able to assess air pollution parameters are vans [47–49] and trucks [50], but other kinds of transport can also be found in the literature, such as trams [51,52], a trailer [53], SUVs [54–56], a bicycle [57] and recreational vehicles [58–60].

Unlike in the past, one of the main goals of current studies is the monitoring of the most important air quality parameters to evaluate compliance with limits imposed by national and international environmental legislation. As reported in the literature [61–63], the main parameters responsible for air pollution and dangerous for the environment and for human health that are tracked by mobile laboratories are PM, black carbon,  $\text{NO}_x$ ,  $\text{O}_3$ ,  $\text{SO}_x$ , CO,  $\text{CO}_2$ ,  $\text{NH}_3$  and VOCs. There are also some systems that have been designed to identify only specific pollutants. For instance, Bush et al. [64] monitored  $\text{CH}_4$ ,  $\text{CO}_2$  and CO concentrations in order to understand the influence of urbanization, traffic and point sources on their spatial distribution. The implementation of these technologies for a specific parameter can also be found for transcontinental  $\text{CH}_4$  concentration characterization [58,59] and for more local conditions, such as to identify the location of fugitive pipeline leaks around an urban area [65,66]. Tao et al. [67] investigated the concentrations of greenhouse gases and air pollutants through  $\text{CO}_2$ , CO,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ,  $\text{NH}_3$  and  $\text{H}_2\text{O}$  QCL and LICOR sensors. Other mobile laboratories [68] are able to verify the presence of metals or halogens, such as chromium and bromine, in different environments. Finally, the impact of local sources has been studied thanks to mobile campaigns assessing the main greenhouse gases [69]. In addition to the principal purposes of the mobile laboratories, some of them can be modified to host different technologies or they can be partially exploited for specific

measuring campaigns [70,71]. In this way, versatility becomes an important advantage in terms of potential use.

Weather conditions significantly affect the dynamics of the atmosphere, gas transformation processes and the transportation of pollutants [72,73]. For this reason, meteorological parameters are usually monitored simultaneously with air quality ones, in order to characterize their relationship. The most common measured parameters are temperature, relative humidity and barometric pressure [74,75]. Wind intensity, wind direction and rain intensity are usually monitored too [76,77]. Rarely, global radiation [47] and the solar spectrum are investigated [78]. In addition to air quality and weather parameters, traffic flows are sometimes supervised through traffic cams or sensors [79].

The main purpose of this section is the analysis of the designs of existing mobile laboratories available in the literature. An accurate selection of papers with detailed descriptions of the technical aspects of these systems was implemented. To do that, vehicle structure, power supply, inlet system, air conditioning and instrumentation were evaluated. The chosen studies included only multi-parameter laboratories and road transport vehicles (van, truck, SUV, trailer). Trains, trams, airplanes and bicycles were excluded from the focus, since the field is broad and they need further detailed studies. The investigation was performed considering one of the main characterization parameters of mobile laboratories: the conditions of use. Indeed, vehicles can be designed to conduct measuring campaigns in mobile or stationary modalities. The first refers to measuring campaigns done when the vehicle is in motion while the second concerns stationary activities, and the two modalities usually work with different aims. In Tables 1–3, the main technical aspects of laboratories used in stationary, mobile or both modalities are shown. In particular, the vehicle type, monitored parameters, measurement technique and instruments, time resolution, detection limit and meteorological parameters are reported.

Generally, mobile campaigns are conducted on roads [80,81], railways [51] or specific urban and rural routes [82] along an entire path with a high instrumental temporal resolution. The processed data allow the definition of a concentration map along the paths performed in order to identify hot spots of specific pollutants, such as industrial areas [83], highways [49] or urban canyons [48]. Due to their configuration, these moving measurements require extremely high-time-resolution sampling to describe in an adequate way the evolution of concentration values. Furthermore, if the same path is frequently travelled, these kinds of acquisitions can lead to the analysis of the effects of external conditions, such as wind intensity and direction, on local sources [84] over time. However, these parameters are difficult to correctly detect while driving, since the vehicle speed is faster than the wind speed or because the car vibrates. Therefore, these measured data need specific processing in which boundary conditions, such as the vehicle speed, are considered. Mobile laboratories can also be deployed in a chase mode to specifically inspect vehicles' traffic emissions [80] or to sample the road dust emissions from tires [85].

As stated before, mobile laboratories can be also used in a stationary way. These vehicles have the significant advantage of allowing long-term campaigns in arduous places [53] or in areas normally not supervised by fixed institutional measuring stations. Differently from the acquisition of mobile measurements by means of moving devices, the stationary vehicles make it possible to obtain in-depth knowledge of the temporal variability of pollutant concentrations at the measuring location. This acquisition method can contribute to understanding the background trends and the impact of local sources on a specific site.

**Table 1.** Instrument equipment from laboratories used in a stationary way in the literature (Nd = not determined).

Study	Vehicle Type	Pollutant/ Parameter	Instruments	Time Resolution	Detection Limit	Meteoclimatic Parameters
Bekr et al., 1978	Semi-trailer	CO CO <sub>2</sub> O <sub>3</sub> NO-NO <sub>x</sub> SO <sub>2</sub> N <sub>2</sub> O-C <sub>2</sub> H <sub>6</sub> Aldehydes, NH <sub>3</sub> Selected OC Aerosol size distribution	NDIR/Mine Safety Appliances—Lira 202s NDIR/Mine Safety Appliances—Lira 303 UV adsorption/Dasibi 1003—AH Chemiluminescence/Thermo Electron 14D UV fluorescence/Thermo Electron 14D IR Chemical reaction/absorption (gas bubblers) Absorption (Tenax GC Absorption Tubes) Optical particle counter/Royo Particle Counter 225			Temperature, dry bulb temperature, RH, wind speed, wind direction, solar radiation, metric rain gauge
Maciejczyk et al., 2004	Van	PM <sub>10</sub> PM <sub>2.5</sub> BC CO O <sub>3</sub> NO SO <sub>2</sub>	Sequential gravimetric sampler TEOM with ACCU and gravimetric sampler (via X-ray fluorescence (XRF)) Aethalometer, Andersen Instruments AE-14 dual channel Model 48C, Thermo Environmental Instrument Model 103-PC, Thermo Environmental Instrument Model 8840, Monitor Labs Model 8850, Monitor Labs			Wind direction and wind speed
Ionel et al., 2009	Van	NO, NO <sub>2</sub> , NO <sub>x</sub> SO <sub>2</sub> CO O <sub>3</sub> THC, NMHC, CH <sub>4</sub> PM <sub>10</sub> , PM <sub>2.5</sub> , TSP	Chemiluminescence method/APNA-370 Horiba UV fluorescence/APSA-370 Horiba IR analysis method/APMA-370 Horiba UV adsorption/APOA-370 Horiba Selective combustion combined with hydrogen ion methane/APHA-370 Horiba TEOM		0.1 ppm Nd 5 ppm 0.1 ppm 0–5 ppm Nd	Temperature, relative humidity, barometric pressure, wind direction, wind speed

Table 1. Cont.

Study	Vehicle Type	Pollutant/ Parameter	Instruments	Time Resolution	Detection Limit	Meteoclimatic Parameters
Petäjä et al., 2013	Trailer (model: Eurowagon 4500 U)	Aerosol number and size distribution	DMPS	10 min	10–840 nm	Temperature, relative humidity, wind direction, wind speed, precipitation, solar radiation
		Aerosol mass concentration	TEOM 1400a with a custom inlet switcher	Nd	Nd	
		Air ion number and size distribution	AIS	3 h	0.4–40 nm	
		SO <sub>2</sub>	Thermo Environmental Instruments Inc. 43S	Nd	100–200 ppb	
		NO <sub>x</sub>	Teledyne Instruments 200AU	Nd	100–2000 ppb	
		CO	Horiba APMA 360	Nd	10,000 ppb	
		O <sub>3</sub>	Environment S.A. O341M	Nd	500 ppb	
Borrego et al., 2016	Van	PM <sub>10</sub> –PM <sub>2.5</sub>	Beta ray adsorption method/Environment MP101M		0–200 µg/m <sup>3</sup>	Temperature, relative humidity, barometric pressure, wind speed, wind direction, solar radiance
		CO	Nondispersive IR spectroscopy/Environment CO11M		0–100 mg/m <sup>3</sup>	
		NO <sub>x</sub>	Chemiluminescence/Environment AC31M		0–500 µg/m <sup>3</sup>	
		C <sub>6</sub> H <sub>6</sub>	Gas chromatography/Environment VOC71M		0–50 µg/m <sup>3</sup>	
		O <sub>3</sub>	UV photometry/Environment O341M		0–500 µg/m <sup>3</sup>	
		SO <sub>2</sub>	UV fluorescence/Environment AF21M		0–1000 µg/m <sup>3</sup>	
Zhang et al., 2019; Zhang et al., 2020	Van (model: Dodge Sprinter 2007)	Aerosol chemical composition	Aerodyne HR-ToF-AMS			Weather station: temperature, relative humidity, rain, wind direction, wind speed and solar radiance Lidar: wind velocity vertical profile
		Particle number concentration	TSI water condensation particle counter/CPC model 3785			
		PM	Light scattering/Thermo Scientific MIE pDR-1500			
		O <sub>3</sub>	UV absorption/Teledyne API model 430 and 2B model 205			
		NO <sub>2</sub>	CAPS spectroscopy/Teledyne API model 500U			
		VOC	Canister samplers			

**Table 2.** Instrument equipment from laboratories used in a mobile way in the literature (Nd = not determined).

Study	Vehicle Type	Pollutant/Parameter	Instruments	Time Resolution	Detection Limit	Meteoclimatic Parameters
Shorter et al., 1996	Van	CH <sub>4</sub>	IR adsorption/ARI methane monitor—canister for sampler	6 s	5 ppbv	Wind direction
		CO <sub>2</sub>	LiCor LI-6262	1 s	1 ppmv	
		SF <sub>6</sub>	WSU SF6 analyser	0.5 s	10 pptv	
Bukowiecki et al., 2002	Van (model: IVECO Turbo Daily Transporter)	Aerosol size distribution	Scanning mobility particle sizer (SMPS)/TSI DMA 3071, CPC 3010	3 min	7–310 nm	Temperature, pressure, relative humidity, wind direction, global radiation
		Aerosol number concentration	Condensation particle counter (CPC)/TSI UCPC 3025	1 s	>3 nm	
		Aerosol size distribution D = 0.3–20 µm	Optical particle counter (OPC)/Grimm Dust Monitor 1.108	6 s	1 particle/L	
		Aerosol active surface area	Diffusion charging sensor (DC)/Matter Engineering LQ1-DC	1 s	10 µm <sup>2</sup> /cm <sup>3</sup>	
		Black carbon mass concentration	Aethalometer (visible light absorption)/Magee AE-10	1 min	40 ng/m <sup>3</sup>	
		PM <sub>2.5</sub>	Betameter (beta radiation absorption)/Eberline FH 62 I-R	1/2 h	3 µg/m <sup>3</sup>	
		O <sub>3</sub>	UV absorption/constructed by PSI	2 s	1 ppb	
		CO	Vacuum UV resonance fluorescence/Aerolaser AL-5002	1 s	2 ppb	
		CO <sub>2</sub>	IR absorption/LI-COR	1 s	0.1 ppm	
		NO <sub>x</sub> , NO <sub>y</sub> , HNO <sub>3</sub> , PAN	Chemiluminescence/MetAir/PSI/Juelich	1 s	200 ppt	
		H <sub>2</sub> O <sub>2</sub> , total peroxide	Fluorescence/Aerolaser AL-2002	120–180 s	200 ppt	
		HCHO	Fluorescence/IFU Garmisch	120–180 s	200 ppt	
Kittelson et al., 2000; Kittelson et al., 2004	Truck (model: Volvo container truck)	Particle size	TSI scanning mobility particle sizer (SMPS)	5 min	9–300 nm	Nd
		Particle size distribution	Electrical low pressure impactor/ELPI, Dekati		29–2500 nm	
		Total aerosol concentration	Condensation particle counter (CPC)		3 nm	
		Fuchs surface area of the aerosol	Epiphaniometer	5 min		
		Aerosol surface area concentration	Diffusion charger (DC)	0.5 s		
		CO <sub>2</sub>	High sensitivity CO <sub>2</sub> analyser			
		NO <sub>x</sub>	High sensitivity NO <sub>x</sub> analyser			
		CO	High sensitivity CO analyser			



Table 2. Cont.

Study	Vehicle Type	Pollutant/Parameter	Instruments	Time Resolution	Detection Limit	Meteoclimatic Parameters
Westerdahl et al., 2005	SUV (model: Toyota RAV4)	UFP	TSI portable CPC, model 3007	10 s	10 nm–1 µm	Temperature, relative humidity Temperature, relative humidity, wind direction, wind speed
		UFP	TSI CPC, model 3022A	10 s	7 nm–1 µm	
		Particle length	TSI electrical aerosol detector, model 3070A	2 s		
		BC	IR spectrometry/Magee Scientific Portable Aethalometer, model 42	60 s		
		Particle size distribution 5–153 nm	Differential mobility/TSI scanning mobility particle system, model 3080, classifier Nano DMA, 3025 CPC	60 s		
		Particle size distribution 16–600 nm	Differential mobility/TSI scanning mobility particle system, model 3080, classifier Long DMA, 3025 CPC			
		PAH	UV irradiation/EcoChem PAH analyser, model PAS 2000	2 s		
		PM <sub>2.5</sub>	TSI DustTrack	10 s		
		NO, NO <sub>x</sub> , NO <sub>2</sub>	Chemiluminescence/Teledyne-API NO <sub>x</sub> analyser, model 200e	20 s		
		CO, CO <sub>2</sub> , CO	TSI Q-Trak Plus monitor, model 8554	10 s		
Wa Tang et al., 2006	SUV (model: Corolla Toyota)	CO <sub>2</sub>	IR spectrometry/Di-Com 4000 from AVL	2 s	0–200,000 ppmv	Temperature, relative humidity, wind direction, wind speed
		HC	Electrochemical process/Di-Com 4000 from AVL	2 s		
		NO	Electrochemical process/Di-Com 4000 from AVL	2 s	0–4000 ppmv	
		O <sub>2</sub>	Electrochemical process/Di-Com 4000 from AVL	2 s	40,000–220,000 ppmv	
		PM <sub>1</sub> , PM <sub>2.5</sub> , PM <sub>10</sub>	Light-scattering intensity/DustTrak 8520 from TSI	1 s	0.001–100 mg/m <sup>3</sup>	
Isakov et al., 2007	Minivan (model: Duke minivan)	Hexavalent Chromium	Steam-jet aerosol collector long pathlength absorbance spectroscopy (SJAC-LPAS)	15 s	0.2 ng/m <sup>3</sup>	Nd
		Formaldehyde	Nafion 811 hydrophilic membrane tube	-	9 pptv	
		Fine PM	Stationary scanning mobility particle size (SMPS)	-	12–270 nm	
Wallace et al., 2009	Van IVECO Turin V diesel vehicle (Van)	NO <sub>x</sub>	TECO model 42C NO <sub>x</sub> analyser	-	0–100 ppm	Temperature, pressure, relative humidity, wind speed, wind direction
		SO <sub>2</sub>	Monitor Labs 8850 SO <sub>2</sub> analyser	-	0–100 ppm	
		CO	TECO model 48 CO analyser	-	0–10,000 ppm	
		PM <sub>1</sub> , PM <sub>2.5</sub> , PM <sub>10</sub>	Grimm model 1.107 Dust Monitor	-	1–6500 µg/m <sup>3</sup>	
Tao et al., 2015	SUV	NH <sub>3</sub>	Quantum Cascade Laser NH <sub>3</sub>	0.1 s	150 pptv	Temperature, pressure, humidity, wind speed/direction, precipitation rate
		CO/N <sub>2</sub> O	Quantum Cascade Laser CO/N <sub>2</sub> O	0.1 s	3 ppbv CO 0.2 ppbv N <sub>2</sub> O	
		CO <sub>2</sub> /H <sub>2</sub> O	LI-COR LI-7500 A	0.1 s	0.11 ppmv CO <sub>2</sub> 0.0047 ppmv H <sub>2</sub> O	
		CH <sub>4</sub>	LI-COR-7700	0.1 s	5 ppbv	

Table 2. Cont.

Study	Vehicle Type	Pollutant/Parameter	Instruments	Time Resolution	Detection Limit	Meteoclimatic Parameters
Wang et al., 2009; Zhu et al., 2016	Van (model: Iveco Turin V diesel)	Size distribution	Scanning mobility particle sizer (SMPS)/TSI DMA3081, CPC3772	2 min	15–673 nm	Temperature, pressure, relative humidity, wind speed, wind direction. Temperature, relative humidity, wind speed, wind direction
		Size distribution	Optical particle counter (OPC)/Grimm Dust Monitor 1.108	6 s	1 part/L	
		Active surface area	Nanoparticle surface area monitor/TSI 3550	3 s	0.1 $\mu\text{m}^2/\text{cm}^3$	
		Black carbon	Multi-angle absorption photometer (MAAP)/Thermo model 5012	1 min	0.1 $\mu\text{g}/\text{m}^3$	
		O <sub>3</sub>	UV absorption/ECOTECH 9810A	1 s	0.4 ppb	
		NO <sub>x</sub>	Chemiluminescence/ECOTECH 9841A	1 s	0.4 ppb	
		CO	NDIR gas filter correlation/ECOTECH 9830A	1 s	40 ppb	
		CO <sub>2</sub>	NDIR gas filter correlation/ECOTECH 9820A	1 s	2 ppm	
		SO <sub>2</sub>	Fluorescence/ECOTECH 9850A	1 s	0.4 ppb	
Pirjola et al., 2004; Pirjola et al., 2012	Van (model: VW LT35 diesel)	BTEX	Proton transfer reaction mass spectrometry (PTR-MS)/Ionicon	30 s/cycle	<0.3 ppb	Temperature, relative humidity, wind speed, wind direction
		Aerosol size distribution	Electrical low pressure impactor/ELPI, Dekati	10 s	7 nm–10 $\mu\text{m}$	
		Aerosol size distribution	Nano-SMPS/DMA 3085 and CPC 3025, TSI	150 s	3–60 nm	
		Aerosol size distribution	SMPS/DMA 3081 and CPC 3025, TSI	150 s	10–420 nm	
		BC	Optical method/Aethalometer AE 22, Magee Scientific and MAAP, Thermo Electron Corporation	5 s	-	
		NO, NO <sub>2</sub> , NO <sub>x</sub>	Chemiluminescence/APNA 260, Horiba	1 s	-	
		PM <sub>2.5</sub>	TEOM/Thermo Scientific model 1400AB and light scattering/DustTrack (model 8530, TSI)	1 min	-	
		CO	Model CO12M, Environment SA	1 s	-	
Phillips et al., 2013; Jackson et al., 2014	Van (model: Ford Transit Connect)	CO <sub>2</sub>	Model VA 3100, Horiba	1 s	-	Temperature, relative humidity, barometric pressure, wind speed, wind direction
		CH <sub>4</sub>	Picarro G2301 Cavity Ring-Down Spectrometer equipped with an A0491 Mobile Plume Mapping Kit	1.1 s	2.5 ppm	
Bush et al., 2015	Van (model: Ford Transit Connect)	C <sub>2</sub> H <sub>6</sub> , C <sub>3</sub> H <sub>8</sub>	Flame ionization/Agilent 7890A gas chromatograph	1.1 s	2.5 ppm	Temperature, relative humidity, barometric pressure, wind speed, wind direction
		CO <sub>2</sub> , CO, H <sub>2</sub> O	Picarro model G1302 Sunnyvale, CA	2 s	-	
		CO <sub>2</sub> , CH <sub>4</sub> , H <sub>2</sub> O	Picarro G1301	3 s	-	
		Particle size distribution	Atmospheric aerosol spectrometer, model 1.109, Grimm Technologies	10 s	-	

**Table 3.** Instrument equipment from laboratories used in both stationary and in mobile ways in the literature (Nd = not determined).

Study	Vehicle Type	Pollutant/Parameter	Instruments	Time Resolution	Detection Limit	Meteoclimatic Parameters
Canagaratna et al., 2004; Kolb et al., 2004; Zavala et al., 2006	Van (model: Ford Econoline 350)	NO, NO <sub>2</sub> , CO, N <sub>2</sub> O, CH <sub>4</sub> , SO <sub>2</sub> , H <sub>2</sub> CO	Tuneable infrared laser differential absorption spectroscopy (TILDAS)	1 s	<1 ppb	Temperature
		CO <sub>2</sub>	Nondispersive infrared unit/LICOR	1 s	0.2 ppm	
		Particle size distribution	TSI model 3022 CPC	2–3 s	7–2500 nm	
		PM <sub>2.5</sub>	Aerosol photometer/TSI DustTrack	1 s	1 µg/m <sup>3</sup>	
		CH <sub>3</sub> OH, C <sub>2</sub> H <sub>4</sub> O, C <sub>6</sub> H <sub>6</sub> , C <sub>7</sub> H <sub>8</sub> , MTBE	Proton transfer reaction mass spectrometer (PTR-MS)	1 s	1–5 ppb	
		Black carbon	Aethalometer/Magee Scientific AE-16	1 min	0.1 µg/m <sup>3</sup>	
		Particulate PAH	Photoemission aerosol sensor/EcoChem PAS 2000	10 s	10 ng/m <sup>3</sup>	
		Nitrate, sulphate, ammonium, OC	Aerosol mass spectrometer (AMS)	4 s	30 nm–1 µm	
Schneider et al., 2008	Van	Particle number concentration	CPC (TSI 3022)	5 s	<10 nm	Temperature, relative humidity
		Black carbon mass concentration	AVL 483 Micro Soot Sensor	1 s	5 µg/m <sup>3</sup>	
		Speciated non-refractory particle mass concentration and size distribution	Q-AMS	30 s	20–1000 nm	
		Aerosol size distribution	SMPS (TSI 3934)	2 min	10–300 nm	
		NO <sub>x</sub> , NO, NO <sub>2</sub>	Chemiluminescence detector (API200A)	1 min	0.4 ppbv	
		CO <sub>2</sub>	NIR detector	1 s	0.2 ppm	

Table 3. Cont.

Study	Vehicle Type	Pollutant/Parameter	Instruments	Time Resolution	Detection Limit	Meteoclimatic Parameters
Drewnick et al., 2012	Van (model: Ford Transit FT350-L)	BC	Multi-angle absorption photometer/Thermo Electron Corp	1 min	0.1 µg/m <sup>3</sup>	Wind speed, wind direction, temperature, relative humidity, rain intensity, pressure
		PAH	Polyaromatic hydrocarbon sensor/PAS2000	12 s	1 ng/m <sup>3</sup>	
		PM <sub>10</sub> , PM <sub>2.5</sub> , PM <sub>1</sub>	Environmental dust monitor/EDM180	6 s	0.1–1500 µg/m <sup>3</sup>	
		Particle number concentration	Condensation particle counter/model 3786, TSI	1 s	2.5 nm–1 µm	
		Particle size distribution	Fast mobility particle sizer spectrometer/model 3091, TSI	1 s	5.6–560 nm	
		Particle size distribution	Aerodynamic particle sizer spectrometer/model 3321, TSI	1 s	0.5–20 µm	
		Particle size distribution	Optical particle counter/model 1.109	6 s	0.25–32 µm	
		O <sub>3</sub>	AirPointer/Recordum Messtechnik GmbH	4 s	1 ppbv	
		SO <sub>2</sub>			1 ppbv	
		CO			0.2 ppmv	
Levy et al., 2014	Medium-duty truck (model: GMC C7500)	NO, NO <sub>2</sub>	Licor/LI840, Licor, USA	1 s	1 ppbv	Nd
		CO <sub>2</sub> /H <sub>2</sub> O			1 µmol/mol	
		NO	Thermo Scientific/TECO 42CTL	1s	0.4 ppbv	
		NO <sub>2</sub>	Thermo Scientific/TECO 42CTL (with photolytic converter)	1 s	0.8 ppbv	
		SO <sub>2</sub>	Thermo Scientific/TECO 43	10 s	1 ppbv	
		CO	Thermo Scientific/TECO 48	10 s	100 ppbv	
		O <sub>3</sub>	Thermo Scientific/TECO 49	20 s	1 ppbv	
		PM <sub>10</sub> , PM <sub>2.5</sub> , PM <sub>1</sub>	Grimm Dust Monitor 1.100	6 s	0.1 µg/m <sup>3</sup>	
		UPF	Grimm CPC 5.403	1 s	0.6 n/cc	
		BC	Droplet Measurement Technologies/Photo Acoustic	1 s	<3.3 µg/m <sup>3</sup>	
		Organic matter, sulphate, nitrate, HOA			0.02–0.15 µg/m <sup>3</sup>	
		C3 benzene, toluene, xylenes	IONICON High Sensitivity PTR-MS	10s	20 pptv	

Generally, inlet systems of mobile laboratories consist of a single pipe for all the instruments located in the vehicle [86] or of separate systems that allow independent sampling [87]. Otherwise, two inlets are mounted: one for gases and one for aerosols [55]. Due to its configuration, a single-inlet system has a set-up that allows the addition of new analysers in an easy way but, on the other hand, different inlets make it possible to entirely remove specific instruments in order to use them in other measuring campaigns [81]. In accordance with the aim of the study, a configuration with different inlets was chosen. A single-inlet set-up is especially used when the vehicle has to sample while travelling; otherwise, the measurement can be affected by turbulence or external conditions which quickly change. In such cases, the inlet system is based on isokinetic sampling to minimize the effect of vehicle speed on data acquisition [84] and the inlet walls are normally made of Teflon to prevent chemical reactions with atmospheric pollutants [47]. In contrast, vehicles used in stationary mode usually exploit the potential of maintaining separate inlets for each instrument, since the sampling conditions do not require a single sampling point. The inlet head is generally located at heights from about 2.5 m to 3 m a.g.l. when sampling has to assess background conditions or source effects in order to avoid ground particle resuspension [88], while laboratories that chase other vehicles to monitor exhaust gases have a lower sampling head at the front [89]. Pirjola et al. [48] describe a mobile laboratory with one inlet system at a height of 2.4 m and another one at 0.7 m that can be used in both stationary and chasing modalities. The exhaust gases of all instruments should be collected in a single drain pipe and conveyed in such a way that they do not contaminate the data acquisition of the inlet heads system [90,91].

Special attention should be given to nanoparticle studies. The typical horizontal inlet configuration for chasing and in-motion laboratories should be carefully designed to minimize the loss of the finest particles, which can attach onto the sampling pipe [50]. The collection of nanoparticles in mobile campaigns can be strongly affected by the complexity of this kind of sample acquisition due to various technical aspects, such as the flux velocity, inlet direction and instrument stability. In contrast, the generally vertical acquisition head of stationary vehicles allows correct sampling without underestimations.

Electrical management is one of the hardest challenges in a mobile laboratory design. Besides the energy supply necessary for the full operation of instruments, air conditioning, required to avoid the overheating of the technologies, plays an important role in electrical procurement [47]. Pumps, instruments and ancillary elements generate exhaust heat that should be correctly dissipated [90] to preserve the analysers' temperature operating range. Electricity supply is usually provided to mobile laboratories in different ways, depending on the number of instruments simultaneously active and the campaign details. The principal supply system for vehicles used in stationary conditions is an electricity network typically combined with an uninterrupted power supply (UPS), which defend the system from temporary loss of electrical power [53]. In contrast, moving devices need an electrical range that can assure data acquisition while travelling. In some cases, lithium batteries can store the power needed to give power autonomy from a minimum of 4 h [83] up to about 8 h of sampling [77]. Otherwise, gasoline-fuelled generators can guarantee the system activity [86], but some precautions are required. Exhaust gases should be discharged far from inlet heads to avoid interferences with data collection [90]. Devices that normally conduct sampling campaigns, both stationary and in-motion, are equipped with alternators, but they also have the arrangements to be supplied by the electricity grid [47].

Considering their structures, data collection is another crucial aspect of mobile laboratories. Real-time measurements with high temporal resolution require a solid storage capacity design [90]. Also, the large number of monitored parameters, including pollutants, weather conditions and GPS, entails the necessity of an accurate data management system able to archive them in a database [89]. In fact, collected data are generally managed by an on-board datalogger in order to prepare them for subsequent processing and analysis [83]. Data often have to be downloaded in the field [92], especially if the instruments or datalog-

ger do not have high memory capacities. To overcome this issue, mobile laboratories are in many cases equipped with an internet connection to guarantee remote data access. The information is shared inside the laboratory through USB [57] or RS232 serial ports [55] or LAN [89] or WLAN [52] connections, while worldwide access is assured by GPRS [53] or UMTS [52].

### 3. The cc-TrAIRer Mobile Laboratory

#### 3.1. The Aim of the Project

The mobile laboratory described in this article (the cc-TrAIRer) was designed by the Department of Environmental, Land and Infrastructure Engineering (DIATI, Turin, Italy) of the Politecnico di Torino as part of the climate\_change@polito project (ministerial funding program “Dipartimenti di Eccellenza 2018–2022”). The main purpose of this laboratory is promoting research on air quality and climate changes through particle, gas and atmospheric conditions sampling. The need for this project emerged from the knowledge and the awareness acquired over the years by the research group thanks to studies of air quality in several circumstances (see Section 4). The laboratory consists of a non-motorised instrumented trailer that is able to conduct sampling campaigns in complex terrain, emergency situations, areas generally not assessed by the authorities and narrow roads. It can also be deployed in operations for the control of diffuse emissions in extended areas where external activities are conducted (such as in construction sites or quarries). Thanks to its structure, it is easily transportable with another vehicle, which can be employed in different activities during long-term campaigns of the trailer.

In general, fixed monitoring networks are used to obtain the spatial distribution of the concentration of pollutants due to the high number of sampling points that represent it. In contrast, the cc-TrAIRer can supply an evaluation of natural and anthropic emissions in different environmental realities with an extremely high temporal resolution. In fact, to be representative enough, several days in a monitoring campaign are needed to evaluate the pollutant trends in different weather and release conditions. To do this, gas- and PM-certificated analysers were appropriately selected as measurement instruments. The collected pollutants included PM fractions (in particular  $PM_1$ ,  $PM_{2.5}$ ,  $PM_4$ ,  $PM_{10}$  and PTS) due to their relevant significance for air quality. For their acquisition, two optical analysers (Fidas 200s, Palas GmbH, Karlsruhe, Germany and Comde Derenda APM-2, Comde Derenda, Stahnsdorf, Germany) and one gravimetric sampler (MicroPNS LVS16, MCZ, Bad Nauheim, Germany) were used. Despite the apparent redundancy, PM measurements were taken with different techniques (optical and gravimetric) because of the necessity of obtaining acquisitions with very high temporal resolution and in order to have a gravimetric measure available to validate the data in accordance with the law. Moreover, the trailer setting makes it possible to install two different optical instruments with different configurations and perform checks at the same time or to choose the most appropriate one for the monitoring campaign. Indeed, all the particle collectors have their own sampling heads and they can be installed or removed from the trailer as necessary. This arrangement permits their use as additional satellite monitoring points in the surroundings areas of the studied site to improve the analysis of the pollutants' spatial distribution. In addition,  $O_3$  and  $NO_x$  were monitored since they are the principal benchmarks of photochemical smog and anthropic sources, respectively, and act as precursor gases for secondary formation of fine particles. The air flow was collected by a single probe to guarantee the needed flow conditions and the instruments were located in a rack that is designed to hold two other possible analysers in the future. The exhaust gases were conveyed in a single discharge pipe that could be extended to move them away from the sampling heads. Since weather conditions strongly affect the atmospheric dynamics and the distribution of pollutants, the trailer is equipped with a meteorological station in order to identify their mutual correlation. Further possible evaluations concern the acoustic field. Even if it is not strictly related to air quality, noise is a strong parameter in the assessment of environmental standards and it also contributes to a global characterization of anthropic sources [93]. For this reason,

sound-level meter systems are integrated within the trailer. Finally, the addition of a solar spectrometer is projected. Indeed, solar spectrum analysis can provide important data in pollutants research through the interpretation of spectral band responses [77,94].

In summary, the cc-TrAIRer is currently able to supply PM<sub>1</sub>, PM<sub>2.5</sub>, PM<sub>4</sub>, PM<sub>10</sub>, PTS, O<sub>3</sub>, NO, NO<sub>2</sub>, NO<sub>x</sub>, weather and noise measurements. The trailer instruments and equipment are described in the following sections and their technical specifications are reported in Table 4. To avoid possible damage to the instrumentation placed in the trailer while travelling, silent blocks to reduce vibrations are installed around the analyser rack and the more vulnerable instruments.

**Table 4.** Monitoring instruments installed in the cc-TrAIRer mobile laboratory.

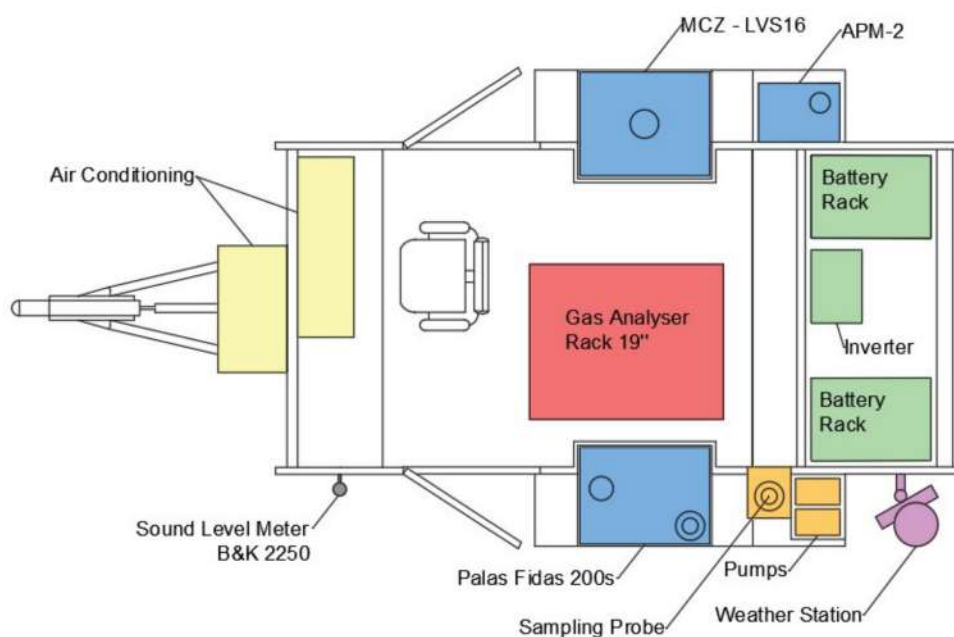
Instrument	Measurement Method/Technique	Parameter	Time Resolution	Detection Range	Flow Rate
Palas Fidas 200s	Optical	PM <sub>1</sub>	1 s	0–10,000 µg/m <sup>3</sup>	0.3 m <sup>3</sup> /h
		PM <sub>2.5</sub>	1 s	0–10,000 µg/m <sup>3</sup>	
		PM <sub>4</sub>	1 s	0–10,000 µg/m <sup>3</sup>	
		PM <sub>10</sub>	1 s	0–10,000 µg/m <sup>3</sup>	
		PTS	1 s	0–10,000 µg/m <sup>3</sup>	
		Cn	1 s	0–20,000 P/cm <sup>3</sup>	
		Size distribution	1 s	180 nm–18 µg	
APM-2	Optical	PM <sub>2.5</sub>	2 s	0–1000 µg/m <sup>3</sup>	3.3 L/min
		PM <sub>10</sub>	2 s	0–1000 µg/m <sup>3</sup>	
MicroPNS LVS16	Gravimetric	PM <sub>2.5</sub>	5 min–168 h	-	2.3 m <sup>3</sup> /h
		PM <sub>10</sub>	5 min–168 h	-	
		TSP	5 min–168 h	-	
Serinus 40 NO <sub>x</sub> Analyser	Chemiluminescence method	NO	1 s	0–20 ppm	0.6 SLPM total flow for two channels
		NO <sub>x</sub>	1 s	0–20 ppm	
		NO <sub>2</sub>	1 s	0–20 ppm	
Serinus 10 O <sub>3</sub> Analyser	UV absorption technology	O <sub>3</sub>	1 s	0–20 ppm	0.5 slpm
Davis Vantage Pro 2		Temperature	10–12 s	−45–+60 °C	
		Humidity	50 s–1 min	0–100%	
		Wind direction	2.5–3 s	0–360°	
		Wind speed	2.5–3 s	0–280 km/h	
		Rain	20–24 s	0–999 mm/h	
		Solar radiation	50 s–1 min	0–1800 W/m <sup>2</sup>	
		UV index	50 s–1 min	0–16	

The power range is a tricky aspect of this kind of laboratory. As already discussed in the previous section, the electricity supply needed for instrument operation should be accurately designed. Moreover, to guarantee the optimal thermal operational conditions the cc-TrAIRer is equipped with an air conditioning system, which prevents the overheating or excessive cooling of the technologies. The trailer can be powered by a traditional external power grid when feasible. Otherwise, a photovoltaic system ensures its independence from the electrical network, above all in isolated places or where a power line is not accessible. In this way, the trailer's functioning is guaranteed without a diesel generator, which is not sustainable from an environmental point of view and its emissions could significantly affect the data acquisition.

To decrease the on-site staff interventions and to facilitate the data management, a datalogger with remote control was installed inside the cc-TrAIRer. It manages a single database for all the analysers. In this way, acquisitions can be consulted in real time and data processing is performed to better and more easily analyse the sampling results.

### 3.2. Trailer Design

The mobile laboratory was built in a Ranger Hero Camper (length: 4.82 m; width: 2.3 m; height: 2.32 m). The internal volume of about 6 m<sup>3</sup> is large enough to host all the selected instruments, even if an accurate placement study was needed (Figure 1). Nevertheless, thanks to its small dimensions, it can easily be moved or parked in almost any place. The frame and the off-road tires allow it to reach dirt tracks or isolated areas, which are not generally examined by the other, traditional moving laboratories.



**Figure 1.** cc-TrailRer plan view: locations of instruments and auxiliary systems.

As the Hero Camper is originally intended for travelling, some structural changes were made to adapt it to the instruments' requirements for research purposes. The roof window was removed to improve the thermal insulation of the vehicle, decreasing the potential heat losses. For the same reason, all the holes that allow the electrical, hydraulic and cable connections through the walls were properly assembled. The kitchen facilities on the back side were taken off to obtain exploitable space where the batteries packs were placed. A support surface was built as a workstation and the personal computer and the datalogger placed there. Additionally, a recess for each side of the trailer was created to externally place different PM analysers. The symmetrical positioning of these two instruments with respect to the trailer's axis significantly helps to optimize the weight distribution. Indeed, a specific analysis of the load distribution was undertaken to ensure the vehicle stability, paying particular attention to the heaviest elements (such as the rack, the batteries and the air conditioning system). Finally, the majority of the apparatus is located at the centre of the back of the trailer in order to transfer the load to the tires and two rear stabilizers and not exceed the load limit on the hitch.

The baggage rack was used as a support base for the photovoltaic system. The latter was placed horizontally to optimize the electricity generation and to contribute to the aerodynamic shape of the trailer while travelling. However, when solar power is needed to support the functioning of the instrumentation during sampling campaigns, the panels can expand to increase the exposure surface. To stabilize the trailer, they can also be fastened to the soil to avoid the raising of the entire vehicle due to external events.



### 3.3. Instrumentation

The cc-TrAIRer provides measurements of PM, gases and weather conditions. Table 4 gives an overview of all instruments' technical specifications. The measurement techniques are described below.

#### 3.3.1. Palas Fidas 200s

The Palas Fidas 200s (Palas GmbH, Karlsruhe, Germany) is an optical analyser with a continuous monitoring system for fine particles in the size range of 180 nm–18 µm. The particle size diameter is computed using Lorenz–Mie scattered light analysis. The instrument provides PM<sub>2.5</sub> and PM<sub>10</sub> measurements in accordance with the law and others fractions that are useful for research purposes (PM<sub>1</sub>, PM<sub>4</sub>, PM<sub>tot</sub>, particle number concentration Cn and particle size distribution). The instrument has been tested and certified according to the standards VDI 4202-1 (2010), VDI 4203-3 (2010), EN 12341 (1998), EN 14907 (2005), the Guide of Demonstration of Equivalence of Ambient Air Monitoring Methods (2005), EN 15267-1 (2009) and EN 15267-2 (2009). The inlet system is made up of a Sigma-2 sampling head and an Intelligent Aerosol Drying System (IADS). A dried flow is ensured according to the external temperature, humidity and pressure measured by the weather station in order to avoid data acquisition errors due to condensation [95]. The number of monitored parameters and the high temporal resolution of this instrument justify its presence inside the cc-TrAIRer.

#### 3.3.2. APM-2

The Air Pollution Monitor APM-2 (Comde-Derenda GmbH, Stahnsdorf, Germany) is a particle optical analyser for the detection of PM<sub>10</sub> and PM<sub>2.5</sub> fractions. The instrument has been tested to guarantee its compliance with VDI 4202-1 (2010), VDI 4203-3 (2010), EN 12341 (1998), EN 14907 (2005), the Guide of Demonstration of Equivalence of Ambient Air Monitoring Methods (2010), EN 15267-1 (2009) and EN 15267-2 (2009). The incoming flow is divided into two flows (PM<sub>10</sub> and PM<sub>2.5</sub>) by a virtual impactor with a perpendicular jet. Then, the two flows move alternately through the scattered light photometer unit, where particles are illuminated by a laser diode. The particle size is obtained as a function of the scattered light detected from the photodetector [96].

#### 3.3.3. MicroPNS LVS16

The MicroPNS Type LVS16 (Umwelttechnik MCZ GmbH, Bad Nauheim, Germany) is a PM sequential sampler. All of the instrument specifications are in accordance with EN 12341:2014. The particle collection takes place in an automatic way through 16 filters with diameters of 47 mm. An on-field operation by a qualified staff member is required after 16 days to replace the membranes. The sampler is able to collect just a single fraction (PM<sub>10</sub>, PM<sub>2.5</sub> or TSP) at a time, depending on the inlet head that is assembled [97]. The collected specimens are weighed and examined in order to perform chemical and gravimetric analyses.

#### 3.3.4. Serinus 40 NO<sub>x</sub> Analyser

The Serinus 40 (Ecotech Pty Ltd., Knoxfield, Australia) is a gas analyser that uses the gas phase chemiluminescence method to detect nitric oxide (NO), total oxides of nitrogen (NO<sub>x</sub>) and nitrogen dioxide (NO<sub>2</sub>) in the range of 0–20 ppm [98]. The instrument has been tested and found to comply with VDI 4202-1 (2010), VDI 4203-3 (2010), EN 14211 (2012), EN 15267-1 (2009) and EN 15267-2 (2009), according to its US EPA approval (RFNA-0809–186) and EN approval (TÜV 936/21221977/A). The ambient air is collected through the sampling probe described below. The auxiliary pump of the analyser is located outside the trailer to reduce the amount of power needed for air conditioning, while the instrument is placed inside the rack to guarantee suitable operation conditions.

### 3.3.5. Serinus 10 O<sub>3</sub> Analyser

The Serinus 10 (Ecotech Pty Ltd., Knoxfield, Australia) is a gas analyser for the detection of Ozone (O<sub>3</sub>) in the range of 0–20 ppm that uses non-dispersive ultraviolet (UV) absorption technology [99]. The instrument has been tested and found to comply with VDI 4202-1 (2010), EN 14625 (2012), EN 15267-1 (2009) and EN 15267-2 (2009) according to the US EPA approval (EQOA-0809-187) and EN approval (TÜV 936/21221977/C). As for the Serinus 40, the ambient air is collected through the sampling probe described below. Despite the instrument being equipped with an internal pump, the optimization of the trailer temperature required the relocation of the pump in an external arrangement. Due to the potential ozone influence on the other data acquisitions, the instrument was placed above the Serinus 40 in the analyser rack.

### 3.3.6. Sampling Probe

The gases sampling probe (Sartec—Saras Srl, Milan, Italy) collects the ambient air to send it to the specific pollutant analysers. The air is taken by the sampling head and it moves to the heating probe system, which heats the flux and keeps it over the dew sample point to avoid condensation formation. To prevent the gases' absorption on the inner wall, the internal channel is insulated and made of PTFE, and a suction fan is installed in the lower part to guarantee the required residence time. The distribution system, consisting of a manifold, allows the connection of up to 12 analysers by Teflon pipes.

### 3.3.7. Davis Vantage Pro 2 Weather Station

The Davis Vantage Pro 2 (Davis Instruments, Hayward, CA, USA) enables surveying of the main weather conditions. It includes several sensors and devices gathered in a versatile integrated suite. The anemometer is separately installed and it provides both the wind direction and wind speed. The main body of the station consists of a rain collector, temperature and humidity sensors placed inside radiation shields and solar radiation and UV sensors. The weather station also provides other relevant indices, such as the wind chill, heat index, THW index, YHSW index, evapotranspiration and dew point [100].

### 3.3.8. Sound-Level Meter (Noise)

The sound-level meter used for the acoustic acquisitions is a Bruel Kjaer, Nærum, Denmark, type 2250. The device is class 1 according to international standards. The sound pressure is collected by the microphone, which is screened off by a windscreen, and is sent to the microphone preamplifier. The entire detection structure can be directly linked to the handheld analyser or it can be extended up to 100 m thanks to a small tripod. In this way, the sound-level meter can also be easily managed in the cc-TrAIRer design when a remote location for the microphone is needed. The sound-level meter records the A-weighted sound pressure level to obtain the time history of acquisition campaigns [101].

## 3.4. Power Supply and Air Conditioning System

The power autonomy of the cc-TrAIRer is ensured by the possibility of its connection to the traditional power network, which should give the needed power consumption of 3 kW. When the electrical grid is not available, the photovoltaic off-grid system is sufficient for all the operational activities from a power point of view. To meet electrical safety standards, the installed contactor is able to immediately cut off the power supply in cases of system or single instrument failures. It can also intervene if the fire protection temperature limit is exceeded.

The photovoltaic system is made up of seven top-efficiency solar panels (Sunpower Maxeon 3400 W) with a parallel connection. They can also be used in a limited configuration, which guarantees the proper functioning of some panels when the others are not expanded. The MPPT solar charge controller (SmartSolar MPPT 150/60-Tr, Victron Energy Almere, The Netherlands) manages the panels' inverter connections and maintains operation at the maximum power point in order to improve the system efficiency. The

multifunctional inverter/charger (Multiplus-II 48/5000/70-50, Victron Energy Almere, The Netherlands) charges the battery pack to 48 V DC and produces 230 V AC to supply the device loads (including instrumentation and air conditioning). The power storage apparatus consists of four 48 V/50 Ah lithium batteries (Pylontech US2000B Plus, Pudong, Shanghai, China).

Particles instruments are designed for external conditions, but gas analysers have an operational temperature range (15–30 °C) that demands an accurate air conditioning design. The cc-TrAIRer was designed to be capable of carrying out sampling campaigns in remote places with critical thermal conditions (such as mountains or particularly dry climate areas).

A preliminary evaluation of the heating load to be removed from the inside of the trailer was undertaken, converting the energy absorbed by the devices into heat. This led to the estimation of a value in BTUs (British thermal units) that would be needed at a minimum. The internal volume of about 6 m<sup>3</sup> and the heat produced by the instruments led to the requirement of about 4000–4500 BTU in this study. During the trailer design, some expedient measures were adopted to reduce the device heat stress, which adds a burden to the total amount of needed BTUs. In fact, the analyser pumps were moved outside the trailer to a purpose-built section that protects them from external weather agents.

The selected air conditioner (Fujitsu ASYG07KGTA, nominal power: 400–500 W) is quite small and it was placed in the front side of the trailer in order to provide the flow homogeneously all over the trailer, without directly affecting the analysers. The external unit is located outside, near the internal one.

### 3.5. Data Management

To optimize the analysis performance and to achieve a suitable parameter overview, a data management system was designed. The cc-TrAIRer is equipped with an operator station where a central data acquisition computer is placed. All the instruments are connected to the computer through a multiport device for serial RS-232 and LAN transmission.

Acquired data are then shared online thanks to a Router RUT240 LTE, Teltonika, Kaunas, Lithuania, which exploits an UMTS system. It provides an internet connection with an external SIM to all the equipment through Ethernet cables or a wireless network. Therefore, the data simultaneously collected by all the instruments are generally sent in real time to a server to allow remote control of the parameter trend. Potential internet signal failure is not a limitation of the mobile laboratory, since all the measurements are always locally stored before being sent online.

Data undergo initial pre-processing before reaching the server. Indeed, their structure is organised to guarantee smart visualisation and data are averaged across a time frame that can be set according to the operator's choice. A following tool is used to perform the diagnostic phase of the process, highlighting potential errors during the sampling operation. It also allows the insertion of the data in an integrated database and it displays graphical evaluations for the subsequent analysis.

The datalogger also develops reports on potential instrument or system failures. An alert is sent to the operator on different occasions, such as in cases of power breakdown, temperature range errors, exceeding of critical thresholds or other operational condition faults.

The possible implementation of other instruments in the trailer can be easily managed with the central computer of the mobile laboratory, since it can be quickly commanded by the system with the remote connection.

## 4. Measurement Applications

The cc-TrAIRer has several potential research applications. It can be used to promptly intervene in emergency situations or to identify the impact of local sources on air quality. Moreover, the laboratory can also monitor pollutants' temporal and spatial distribution in heterogeneous contexts in long term campaigns. These different uses have already been

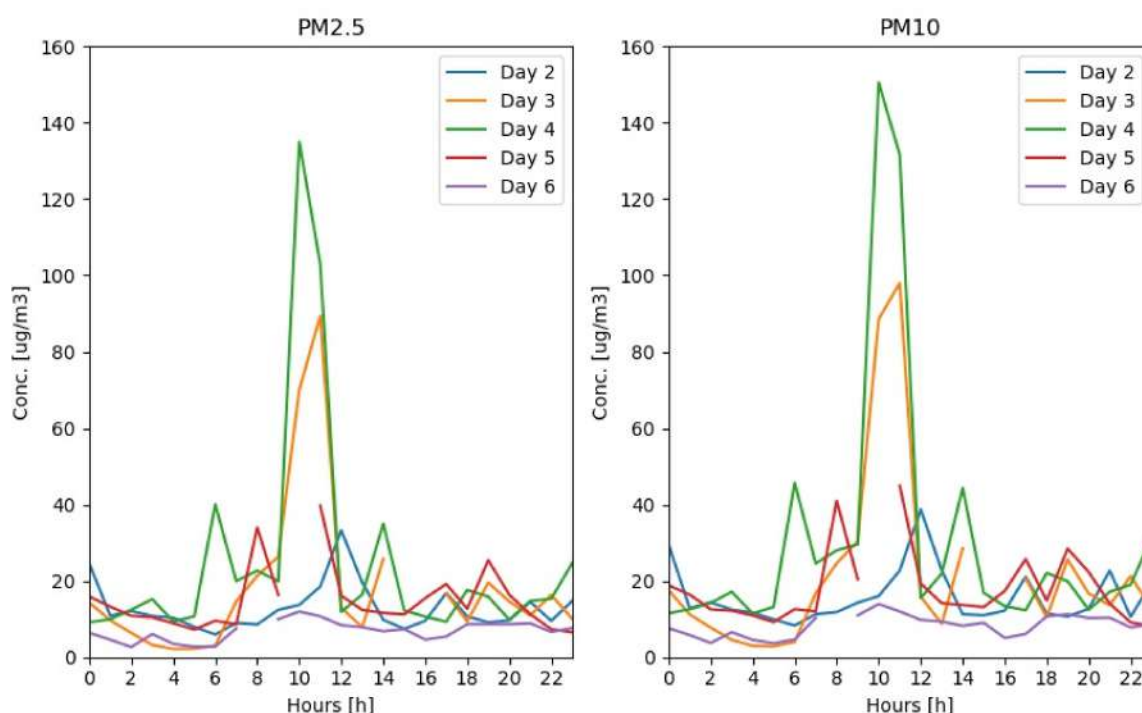
strongly documented by different sampling studies conducted by the research group in the last few years (e.g., [102]). These surveys led to an understanding of the necessity of a complete monitoring laboratory for the integrated study of air pollution. In fact, the conception of the cc-TrAIRer was strongly influenced by the aim of bridging the gaps in previous studies and implementing new investigations, such as the simultaneous detection of meteorological conditions and gas concentration. In this section, the results of some of the most relevant surveys for this purpose are reported. The sampling studies described here analysed PM concentrations using the instruments that were chosen for the moving laboratory.

Immediate-response air quality monitoring was carried out during an emergency situation in which an industrial site caught fire. The intervention was demanded by the local municipality and had to meet their requirements in addition to the conventional sampling points of public agencies. The study (5 April 2019–13 May 2019) was performed in two areas in Piedmont (Italy), at the foot of the Alps, with the aim of studying the phenomena in order to justify the hazes observed by the citizens, although the public institutions reported concentration values lower than limits. In fact, an assessment of the fire development and of the effects of boundary conditions on the daily variability of haze and pollutant concentrations was conducted with high frequency measurements. An APM-2 analyser was used to determine PM<sub>2.5</sub> and PM<sub>10</sub> trends, initially at a distance of about 3.7 km (days 1–2: Cantalupa) from the burnt site, as shown in Figure 2. Then, the instrument was progressively moved closer to the industrial area (2.2 km, days 3–8: Frossasco 1; 200 m, days 8–40: Frossasco 2).



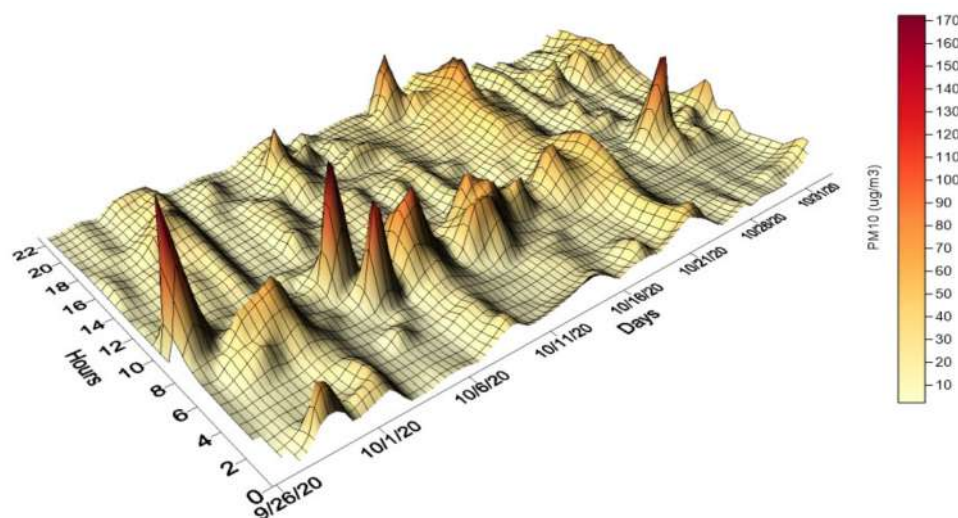
**Figure 2.** Location of the fire site and of the Cantalupa, Frossasco 1 and Frossasco 2 sampling points.

A predominant daily trend influenced by the fire event was identified in the initial sampling period. In Figure 3, the most relevant days are shown. The concentration peak detected in the temporal range 10 AM–1 PM was the effect of the mountain and valley breeze, typical of that period of the day due to the local morphology (see Figure 2) [103]. This morning wind contributed to the transportation of the hazes from the burnt site to the sampling stations, which were at higher elevations with respect to the industrial site. This trend faded over the course of the time thanks to the progressive extinction of the fire. As a general remark, although the PM<sub>10</sub> daily mean concentration was within the EU air quality standards (2008/50/EC), the identified peaks entailed potential exposure to high values of PM. The analysis was performed in a preliminary way and only obtained the PM distribution, but other implementations for trace gas concentrations in comparable fire situations will be carried out with the future application of the cc-TrAIRer.



**Figure 3.**  $PM_{2.5}$  and  $PM_{10}$  daily trends for the Cantalupa (day 2) and Frossasco (days 3–6) monitoring campaigns. The graphs highlight a predominant peak in the temporal range 10 AM–1 PM.

Another purpose of the APM-2 campaigns was achieved at the mountain site of Salbertrand (Alps, Piedmont, Italy—coordinates: 45.070964, 6.887413). The area was supervised to detect the influence of an anthropic source on the PM local distribution. In fact, a wide area close to the monitoring point was designated for the activities of sand and aggregate industries, with a huge material handling. The instrument was placed at a location about 600 m from this area for 5 weeks (25 September 2020–2 November 2020). The extremely high time resolution of the analyser made it possible to accurately assess the concentration distribution during the day. Figure 4 shows the  $PM_{10}$  trend of the entire period. The working activities had a strong influence on the coarser PM fraction, resulting in a repeated morning peak caused by the particle suspension.



**Figure 4.**  $PM_{10}$  hourly trend for the entire period of the Salbertrand monitoring campaign. Frequent peaks can be observed in the morning hours of the day.



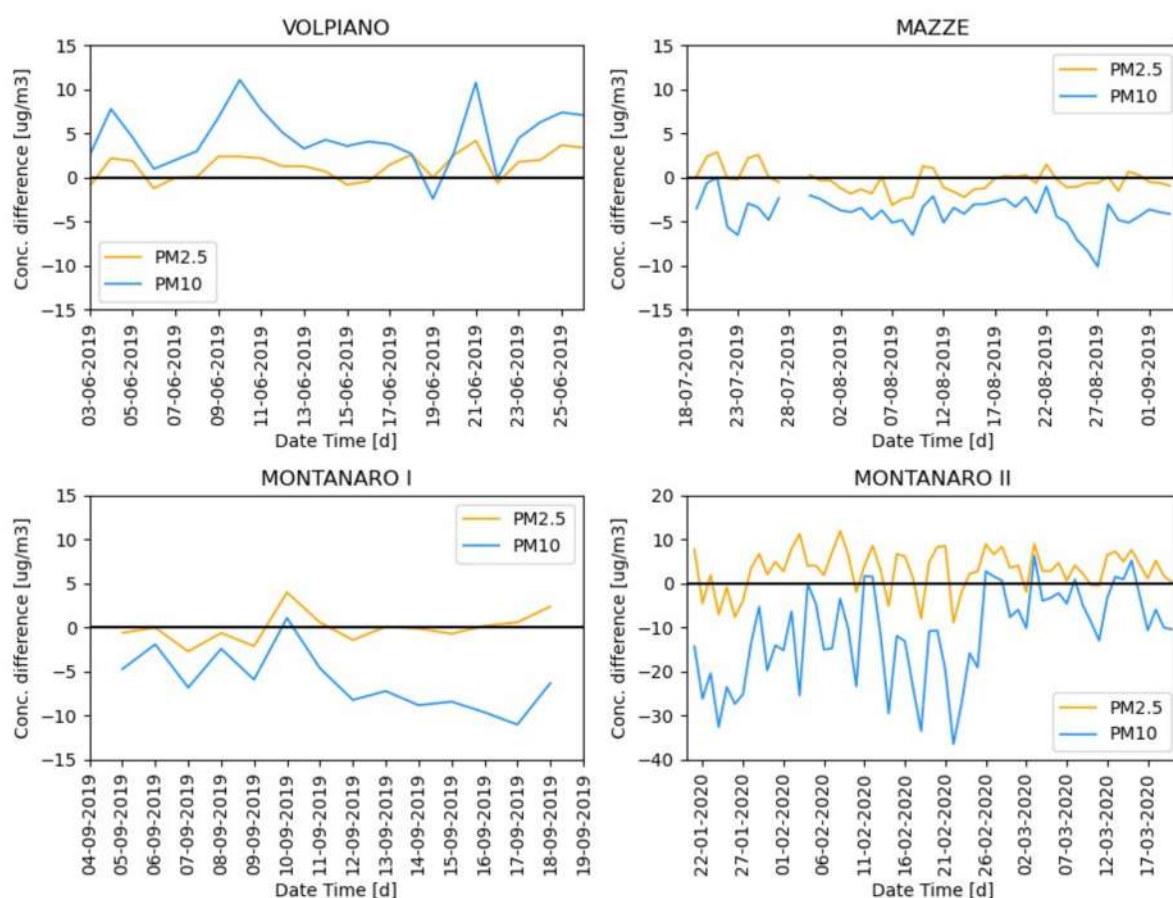
To evaluate the PM<sub>2.5</sub> and PM<sub>10</sub> concentration distribution in different environmental conditions, four monitoring campaigns were performed from June 2019 to March 2020. The sampling points were located in suburban areas at gradually increasing distances from the urban station of Politecnico di Torino, in the direction of the city of Milan (northeast). The array runs along the A4 highway in a flat area of the Po Valley megacity, far from mountains or other high ground. APM-2 analysers were located in the cities of Volpiano, Mazzè and Montanaro, as places identified to have comparable boundary conditions. The details of the single sampling points, concerning the time period and concentration values, are listed in Table 5.

**Table 5.** Details of the array monitoring campaign: coordinates, sampling period, means and maximum and minimum values of PM<sub>2.5</sub> and PM<sub>10</sub>.

Sampling Point	Coordinates	Sampling Period	PM <sub>2.5</sub> (µg/m <sup>3</sup> )			PM <sub>10</sub> (µg/m <sup>3</sup> )		
			Mean	Min	Max	Mean	Min	Max
Volpiano	45.190025, 7.771652	3 June 2019–27 June 2019	13.75	7.80	26.00	23.26	12.50	39.10
Mazzè	45.289311, 7.940933	19 July 2019–3 September 2019	12.09	3.30	27.30	13.59	4.30	30.20
Montanaro I	45.228619, 7.850982	4 September 2019–19 September 2019	11.05	1.1	20.80	11.95	1.40	22.20
Montanaro II	45.228619, 7.850982	16 January 2020–28 March 2020	35.14	5.35	67.14	40.85	8.00	79.57

The results were also compared with the PM trends from the fixed station of Politecnico di Torino in order to observe the difference between urban and suburban areas. Without considering the absolute values, the overall distribution of PM concentrations shows similar trends in urban and suburban sites, suggesting a comparable response to the weather conditions also. Figure 5 shows the difference between the data acquired by the two APM-2s in the external sites and the fixed station. The almost null trend of PM<sub>2.5</sub> delta (Figure 5) confirms the results of previous studies [104] regarding the homogeneous spatial distribution of the fine fraction in comparison with the coarse one. PM<sub>2.5</sub> values were, in fact, similar in both environmental contexts and in different seasonal conditions. On the contrary, the PM<sub>10</sub> trend was affected more by the local situation. As expected, the fixed station values were generally higher than the others, but the Volpiano campaign presented an opposite trend. In this case, the sampled data could not properly be considered as background conditions because of some nearby anthropic activities that had not been considered in the instrument positioning. The material handlings of aggregate industrial work about 400 m away and the people frequently in attendance at the site could have contributed to the high mean value of PM<sub>10</sub>. Finally, the results of this spatial assessment of the concentration distribution suggest a stronger dependence of the coarser PM fraction on the local sources. For this reason, a suitable preliminary study of sites should be performed to avoid issues in the identification of background trends.

The PM assessments were carried out thanks to the great versatility, in terms of repositioning and independence from auxiliary elements, of the APM-2 analyser. The specific thermohygrometric operative conditions of gas analysers and the requirements for sampling accuracy have made gas measurement campaigns with easily movable instruments difficult, up to now, in remote areas. The cc-TrAIRer can guarantee the sampling characteristics needed for all instruments to perform combined gas and particle collections, even those concerning precursor pollutants.



**Figure 5.** Differences between the data acquired by the two APM-2s in the external sites and the fixed urban station located in Politecnico di Torino (Turin, Italy). An almost null trend for  $PM_{2.5}$  delta was obtained. The  $PM_{10}$  trend was affected more by the local situation.  $PM_{10}$  suburban station values were generally lower than the fixed one, but the Volpiano campaign presented an opposite trend because of boundary conditions.

## 5. Conclusions

We designed and developed a non-motorised, instrumented trailer, the cc-TrAIRer, for high-quality research on air quality and climate changes. The results shown in Section 4 proved the usefulness of this mobile laboratory for simultaneous assessment of several air pollutants along with a mutual correlation of meteorological and environmental conditions.

Thanks to its relatively small dimensions, the trailer is easily transportable to narrow areas, which are of scientific interest but generally not assessed since they are beyond the measurements needs of public agencies. The photovoltaic system encourages its versatility in terms of power supply, allowing sampling campaigns where a relevant infrastructure does not exist. The Alps are a clear example of an area where applications are laborious but, at the same time, key points of research, since they are more strongly exposed than other parts of the Earth to the effects of climate change. Due to the data and system remote management, the technical field interventions can be minimised. The instruments were selected by evaluating their adaptability to the trailer purpose, considering the measured parameters, dimensions, operational conditions, ordinary maintenance and the temporal resolution.

Given the listed advantages, the cc-TrAIRer has potential uses for different research studies, such as those on air compounds' temporal and spatial distribution or source impacts or emergency situations with short- or long-term campaigns. After a preliminary design plan of the sampling points, an examination of the investigated area should be done to confirm the proper trailer location, taking into account the surrounding environmental dynamics and, at the same time, the accessibility and the safety requirements of the trailer.

Further sampling surveys of the cc-TrAIRer will analyse the reciprocal influences of air compound concentrations, weather and atmospheric and environmental conditions in different land-use contexts, providing considerable support to the investigation of global aspects of climate change.

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