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The Smart Ring Experience in l'Aquila (Italy): Integrating Smart Mobility Public Services with Air Quality Indexes

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Abstract: This work presents the "City Dynamics and Smart Environment" activities of the Smart Ring project, a model for the smart city, based on the integration of sustainable urban transport services and environmental monitoring over a 4–5-km circular path, the "Smart Ring", around the historical center of l'Aquila (Italy). We describe our pilot experience performed during an experimental on-demand public service electric bus, "SmartBus", which was equipped with a multi-parametric air quality low-cost gas electrochemical sensor platform, "NASUS IV". For five days (28–29 August 2014 and 1–3 September 2014), the sensor platform was installed inside the SmartBus and measured air quality gas compounds (nitrogen dioxide, carbon oxide, sulfur dioxide, hydrogen sulfide) during the service. Data were collected and analyzed on the bases of an air quality index, which provided qualitative insights on the air status potentially experienced by the users. The results obtained are in agreement with the synoptic meteorological conditions, the urban background air quality reference measurements and the potential traffic flow variations. Furthermore, they indicated that the air quality status was influenced by the gas component NO_2, followed by H_2S, SO_2 and CO. We discuss the features of our campaign, and we highlight the potential, limitations and key factors to consider for future project designs.

Keywords: low-cost electrochemical gas sensors; air quality index; mobility on demand; urban environment

1. Introduction

In April 2009, a series of earthquakes rated more than five on the Richter scale happened throughout central Italy. The main shock, which occurred on 6 April 2009, severely damaged the city of l'Aquila and the villages nearby. Afterwards, several actions were taken to support the population, drive disaster funds to the area and to plan the city reconstruction. Among these, a collaborative agreement between ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Development, University of Rome "La Sapienza", AMA (Agenzia Mobilità Aquilana), Assessorato alla Smart City and the l'Aquila local government was established in 2010 to help reconstruct the l'Aquila city center according to a Smart City paradigm (e.g., [1]). The collaborative agreement produced the "Smart Ring" project, which aimed at proposing a functional and energy-efficient city model along a 4–5-km circular path, the Smart Ring, around the historical center of l'Aquila [2].

Here, the concept "smart" refers to the implementation of ICT (Information and Communication Technology), infrastructures for real-time monitoring of energetic, lighting, traffic-related and environmental parameters in connection with "green" technologies. The final objective is to make urban networks and connected public services much more sustainable and efficient.

This work describes the activities of the "City Dynamics and Smart Environment", Smart Ring project work package (details in [2]).

Within a six-month experimental campaign with an innovative urban mobility service, a pilot study of a five-day duration was performed to assess the potential impact of integrating the novel urban mobility service with an air quality gas sensor platform (see also [3]).

Several national and international projects, such as RES-NOVAE [4], OPENSENSE [5], CITI-SENSE [6] and EVERY-AWARE [7], already established tools that integrate sustainable energy-efficient technologies, environmental monitoring and community-based sensing platforms, so as to understand the impacts and geographical distribution of outdoor ambient air pollution.

However, also indoor air pollution in urban cities should be carefully monitored, as some of the pollutants (e.g., NO_x, SO_2, O_3 and particulate matter) are common to both indoor and outdoor environments and may originate from outdoor ambient air (e.g., [8,9]). In particular, the air within the vehicles can be strictly related to traffic intensity (e.g., [10–12]). Dons et al. ([10,11]) considered black carbon exposure within vehicles, while Zagury et al. [12] looked into carbon monoxide, fine suspended particles and nitrogen oxide exposure.

Therefore, our basic idea was to deploy the innovative low cost air quality gas sensor platform named "NASUS IV" (see [13,14]) within the experimental public service named "SmartBus".

The vehicle, equipped with an embedded geographic positioning system, used green technologies for an experimental on-demand public service lasting several months (from May–October 2014).

Within the Smartbus service, for five days (28–29 August and 1–3 September 2014), the multi-sensor platform measured the gas compounds: nitrogen dioxide NO_2, carbon oxide CO, sulfur dioxide SO_2, hydrogen sulfide H_2S, temperature and relative humidity as meteorological parameters.

The aim of our campaign was to test the SmartBus-NASUS IV approach in view of obtaining qualitative indications on the ambient air quality status along the Smart Ring track. In particular, the focus concerns: (i) the status of the ambient air the SmartBus users were exposed to; and (ii) geographical indications associated with the experienced air quality status. The recorded pieces of information could become very useful to evaluate potential personal exposition to air quality when considering the time spent using public transport [10]. Furthermore, if the measured gas components do not differ too greatly from the outdoor values, these data can be used for a hypothetical representation of urban air quality on the road networks, and they could contribute to a better city management in terms of traffic flow planning.

The novelty of this study consists of:

- Presenting the features of our time-limited measurement campaign performed integrating air quality sensor platforms with an innovative on demand urban service, preferable to conventional services for optimized distance traveled and less fuel consumption.
- The detection of potential indoor air pollution concentrations as experienced by the users of the SmartBus.
- A detailed discussion of the key factors to consider when planning further integrated mobility and air quality sensor-based campaigns.

This paper is organized as follows. Section 2 reports an overview of recent developments in sensor-based air pollution monitoring in urban environments and our motivation for deploying NASUS IV. Section 3 presents the methodology of this study and includes: a brief review on air quality gas compounds and the current legislation; the description of the mobility service SmartBus;

the multi-parametric sensor NASUS IV; the air quality index adopted; and a description of the quantitative analyses performed on the data collected. Section 4 summarizes the most important results from the data analyses performed. From this pilot experimental campaign, in Section 5, we outline key aspects to keep in mind to improve both our multi-sensor system and field campaigns. The final Section 6 presents our conclusions.

2. Related Work

In recent years, according to Penza et al. [13], several national and international R&D projects on wireless sensor networks deployed in the urban areas and cities have been funded for air quality monitoring with emphasis on sensor performance [15], fixed sensor-nodes distributed in the city (e.g., [4,16–20], dust sensors [21]), mobile sensors mounted over public buses [5] and participatory environmental sensing involving citizens ([6,7]). Several studies conducted overviews of the existing methodologies. To quote some, Budde et al. [21] investigated the feasibility of particular matter measurements using inexpensive, commodity dust sensors, small enough to be incorporated into mobile devices. Kumar et al. [18] presented an overview of environmental monitoring systems focused on energy efficiency and low-cost environmental monitoring systems. Velasco et al. [19,20] discussed the benefits of a distributed approach and analyzed the main elements to take into account during the design of air quality monitoring systems.

In addition, a concerted Action (COST (European Cooperation in Science and Technology), Action TD1105— EuNetAir (European Network on New Sensing Technologies for Air Pollution Control and Environmental Sustainability)) is devoted to establishing a European Network on New Sensing Technologies for Air Pollution Control and Environmental Sustainability [22], including a large participation of experts from academia, research and industry from 28 COST countries (EU-zone) and seven non-COST countries (extra-Europe) (see [13]). Monitoring air pollution using low-cost gas sensors has gained high interest in recent years. Low-cost sensors can be embedded in sensor-nodes that are part of fixed and/or mobile sensor networks, and some studies will be here quoted.

The MESSAGEproject [16] developed low-cost wireless sensors, and their deployment created a dense, pervasive, ad hoc network for monitoring traffic pollution in a road environment. Forty sensor nodes (CO, NO_2, CO_2) were attached to streetlights and traffic lights in Cambridge city to complete the air quality monitoring task (see [13]). Each node transmitted sensing data to a gateway via the ZigBee protocol, and the gateway sent the data to a control center via a GSM network. Mapping of urban pollution was created for the analysis.

The project SNAQ-Heathrow [17], coordinated by the University of Cambridge (Cambridge, UK), deploys a high density air quality sensor network in and around London Heathrow Airport (London, UK). This uses low-cost sensors for selected gases (NO, NO_2, CO, CO_2, SO_2, O_3, VOCs (volatile organic compounds)) and for size-speciated particulates.

RES-NOVAE [4], an Italian national project, aimed at demonstrating a prototype of the smart grid for energy efficiency in buildings and an Urban Control Centerto integrate environmental and energy data coming from distributed sensors in the city of Bari (Italy) (from [13]).

The AirSensEUR project ([23–26]) is a very promising project proposed by the DGJoint Research Centre of the European Commission. AirSensEUR sensor platforms consist of open software/open hardware objects that have the capacity to behave as a node within a network of multi-sensors assuring interoperability and compliance with the Infrastructure for Spatial Information in Europe (INSPIRE) Directive [27]. The aim of the project is to provide a framework for air pollution measurements at low concentration levels and to facilitate the use of air pollution sensors by diminishing the operational and development costs.

Given the context described, we chose the multi-sensor platform NASUS IV for our study, as it represented our in-house-developed sensor platform, and it was the sensor platform available at hand. In addition, NASUS IV was previously calibrated and tested at fixed locations in [13,14,28].

The decision to install our platform inside the SmartBus, supported by studies such as [10–12] already discussed in Section 1, was related to two main motivations. The former consisted of the short limited time dedicated to the "air quality campaign" with respect to the planned SmartBus experimental public service, described in Section 3.2. The latter reason relies on logistic issues, as it was not feasible for just a few days to install the system outside the bus, such as over the bus roof as in [5].

Therefore, our study should be viewed as our first attempt to build an in-house integrated mobile air quality platform deploying an experimental on-demand service, which took place during the SmartBus campaign in l'Aquila. Here, we do not expect to assess the full reliability of our approach. Instead, we looked into our approach potentialities and limitations.

3. Methodology

3.1. A Brief Review of Air Quality under European and Italian Legislation

Taking as reference [9,29–31], a list of the main outdoor air quality pollutants, their sources and their major effects on the environment and human health is reported in Table 1.

Table 1. Main outdoor air pollutants, sources and impacts ([9,29–31]).

Type of Outdoor Air Pollutant	Sources	Impacts
Particulate matter (PM) fine dust less than 10 µm in diameter	road vehicles shipping power generation households sea salt wind-blown soil and sand	cardiovascular and respiratory diseases
Sulfur dioxide (SO_2)	power generation industry shipping households	PM formation impairment of respiratory function soils and inland waters acidification
Nitrogen oxides (NO_x)	road vehicles shipping power generation industry households	ozone (ground-level) formation irritate lungs lower resistance to infection soils and inland waters acidification
Ammonia (NH_3)	livestock farming use of fertilizers in agriculture	PM formation respiratory system soils and inland waters acidification
Volatile organic compounds (VOCs)	use of solvents in products industry household heating road vehicles power generation	ozone (ground-level) formation
Ground-level ozone (O_3)	secondary pollutant NO_x and VOCs in sunlight	asthma and allergic triggers damages on agriculture (e.g., crops) sensitive construction material (e.g., metals and paints)

In urban environments, when human health is considered, the major pollutant sources are generally road traffic and domestic heating. These sources are responsible for the often high concentrations of particular matter (PM_{10} and $PM_{2.5}$), nitrogen oxides and ozone monitored at the reference stations.

In Europe, Cleaner Air for Europe [31] is the European program aiming at protecting human health and the environment from air pollution, by taking active measures to monitor the purity of outdoor ambient air and reducing air pollutant sources. The air quality directive 2008/50/EC [32], adopted in Italy as D.Lgs155/2010 [33], states the basic principles and methodologies to assess and manage air quality in Europe. In particular, it establishes air quality objectives, including ambitious, cost-effective targets for improving human health and environmental quality up to 2020. It also specifies ways of assessing these objectives and of taking any corrective action if the standards are not met. In addition, it provides rules for the public to be kept informed [34].

Following the European legislation, European countries are divided into zones, which reflect the exposure of the population and ecosystem to air pollution, and their size reflects the population density. For each zone, reference networks and/or other assessments methods are indicated to monitor and assess air quality. As concerns Italy, reference measurements networks are managed at the regional level. However, reference stations are also characterized by high setting-up and maintenance costs. For the Abruzzo Italian region, where l'Aquila is located, Figure 1 shows the air quality zone containing l'Aquila (in blue and yellow), the reference fixed monitoring stations for Abruzzo (six stations), as indicated in the European database for the year 2014 [35], and the Smart Ring area (see Figure 2), where our experiment was performed.

The reason for mentioning the main air pollutants, their effects and the current legislation is to underline the impact that potentially reliable low cost gas sensor platforms could have in providing more indications on air quality status, as well as on personal exposure, in areas not directly covered by the reference measurements. Therefore, they could strongly help with supporting environmental monitoring programs.

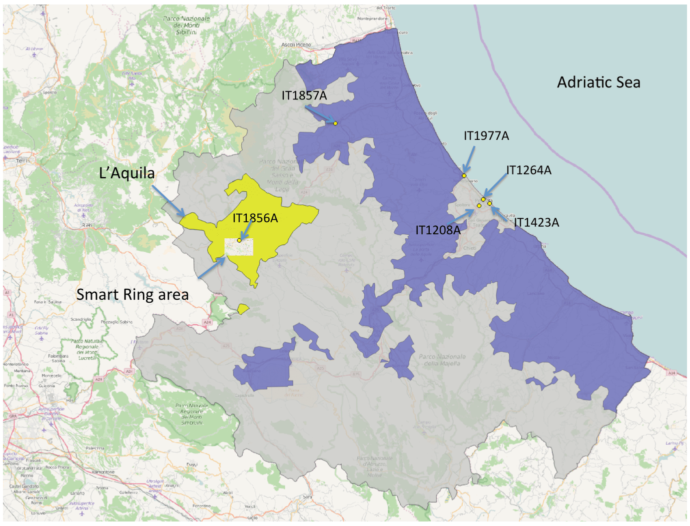


Figure 1. A view of the Abruzzo region where l'Aquila is located. The violet-blue areas indicate the air quality zone IT1306, which includes l'Aquila territory (in yellow). The points represent the reference fixed monitoring stations, as they are indicated in the European databases [35].

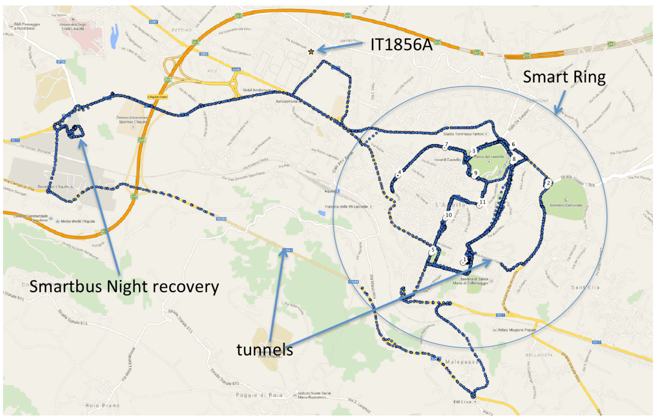


Figure 2. The Smart Ring area and the reference monitoring station IT1856A as indicated in European databases [35]. The blue circles represent the SmartBus positions during the campaign. The white circles with numbers indicate the majorly frequented SmartBus stops along the Smart Ring.

3.2. The SmartBus Public Service

In the framework of a collaboration among AMA (Azienda Mobilità Aquilana) il Comune dell'Aquila (l'Aquila, Italy), ENEA and CTL, Centro di ricerca per il Trasporto e la Logistica, Università di Roma La Sapienza (Rome, Italy), the experimental public transport service, named SmartBus (Figure 3), was in operation for about six months from 19 May–31 October 2014.

Figure 3. The SmartBus.

The aim of the SmartBus service was to demonstrate the advantages in terms of costs, quality of service, energy consumption and pollution, of adopting an "on-demand" bus service with respect to traditional public transport, characterized by a thermal traction drive and a fixed time schedule and tracks. The service covered the mobility to and from the city center, with about twelve bus stops placed along the Smart Ring path. A dedicated website was set up to book the service, where day, time and departure and arrival bus stations had to be indicated. This service was able to link any two stops within and around the town center of l'Aquila. To use the service, customers had to: (i) register/log-in into the website; (ii) book the transport request; (iii) wait for the approval of the submitted request throughout a notification (SMS or email depending on the preferences), which specified the expected times of pick-up, and destination arrival. Once this procedure was completed, the customer could go to the the pick-up location at the foreseen scheduled time.

The ecological vehicle Iveco Daily was chosen for the bus. The vehicle could transport up to eight people and was provided with both thermal and electric traction. The SmartBus drivers were asked to use the electric traction particularly when driving along the way of the Smart Ring, accordingly to the load, the road slopes and the available electric charge. The electric traction was provided by batteries, and the vehicle had an internal control system to monitor the geographical position, battery charge status, speed and load/number of passengers. These vehicle parameters were sent in real time to a remote server while driving along the Smart Ring.

The results of the whole six-month SmartBus experimental campaign are the following. In terms of transport:

- There were 53 registered customers. Half of them used the SmartBus more than once;
- There were 540 transport requests accepted by the system. About 96.4% were processed successfully, which accounted for about 4.2 journeys a day;
- A total of 1830 passengers per kilometer (pax/km), 15.3 pax/km per day (pax/km/day);
- A total of 6800 vehicles per kilometer (veh/km), 51.5 veh/km per day (veh/km/day);
- The occupancy rate (number of passenger on board) was equal to 0.3 pax/km/veh/km;

- Waiting time at pick-up stop of less than one min;
- The average journey duration was less than six min (5 min and 46 s).

Transport demand was distributed during daily time, as shown in Figure 4. About 33% of all requests were in the time slot from 7:30–9:30; approximately 40% requests were in time slot from 13:30–15:30; and 11% were in time slot from 15:30–17:30. The remaining requests (16%) were spread in other time ranges.

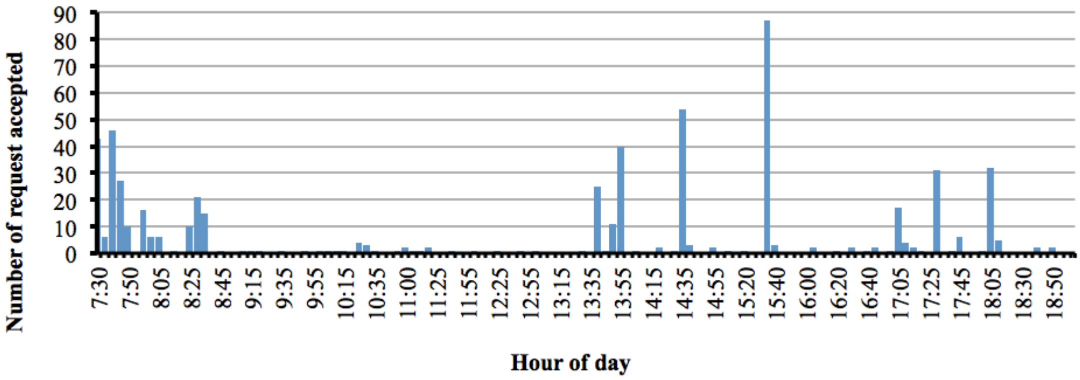


Figure 4. Daily transport request distribution from 19 May–31 October 2014.

In terms of energy consumption and air pollution and with respect to the conventional Bus Line M17, which covered three of the SmartBus stops, the results of fuel saved and pollutants not released were:

- 310 L of fuel not used;
- 703 kg of CO_2 not emitted;
- 17 kg of total pollutants (HC, CO, NO_x, PM) not emitted.

In terms of costs:

- The cost for the daily service was 314€/day (210€/day with M17), which accounted for 75€/journey (42€/journey for M17) with 4.2 journeys (5 journeys for M17) per day;
- The cost for passenger per kilometers was equal to 20€/pax/km (14€/pkm for M17);
- The cost of each kilometer for passenger amounted to 6.1€/veh/km (1.2€/vkm for M17), and the average length was about 51 veh/km (175 veh/km for M17).

The daily cost of the SmartBus was larger than for the M17 line, as a result of a more limited usage of the SmartBus with respect to the M17 line (managed by a private cooperative).

Costs (in percentage) were distributed as: for the vehicle 19%; for the driver 76%; fuel 3%; hardware (PC and server) and subscription (communication) 2%.

The SmartBus operated for only 20% of a 12-h working time period. With much larger user requests, possibly covering the whole twelve-hour service, the costs in €/pax/km could be more competitive than those for the M17 line, falling to 2.1€/pax/km, 1.5€/veh/km, 4.6€/journey.

In terms of service quality, telephone surveys reported the results presented in Table 2. The responses produced a general appreciation for the novel experimental service. Customers were quite satisfied with the service quality, which was fulfilled on both punctuality and reliability aspects. About 96.4% of all requests were accepted and fulfilled, a percentage that is generally higher than for conventional public transport. The results show that improvements can be performed in order to better advertise and facilitate the service accessibility itself. According to customer surveys, to increase the service appeal and make the system operationally and costly viable, several actions needed to be taken. The most important were: to increase the number of SmartBus stops on the base of majorly frequented city nodes and to introduce higher fees for downtown parking places.

Table 2. Responses for service quality on a scale from 1–5 (where 1 means poor and 5 means excellent).

Parameters	Response
Easy of use	4.0
Reliability	4.1
Information comprehension and availability	4.3
Customers satisfaction	4.3
Ticket cost	4.3
Cleanliness	4.8
Comfort	4.5
Safety	4.6

3.3. The Multi-Parametric Sensor System NASUS IV

The multi-sensor platform NASUS IV, which is described in detail in [13,14], is a portable sensor system equipped with four low-cost electrochemical gas sensors (NO_2, CO, SO_2 and H_2S) by Alphasense Ltd. (Great Notley, Essex, UK) [36], one temperature sensor (LM35CZ) by National Semiconductor Co. (now Texas Instruments Inc., Dallas, TX, USA) [37] and one relative humidity sensor (HIH-3610 Series) by Honeywell (Morris Planis, NJ, USA) [38].

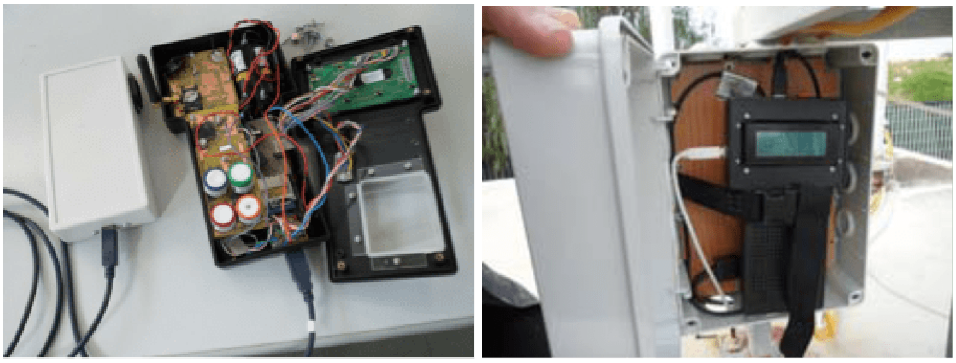
The main technical characteristics of the low-cost sensors for air quality monitoring are reported in Table 3. The table reports the sensors operational ranges, in terms of ppm limit of performance warranty, as reported by the manufactures. During the Smart Ring campaign, the observed ranges for the gas components were as follows:

- NO_2: [0–420] ppb, mean value 30 ppb;
- SO_2: [0–286] ppb, mean value 25 ppb;
- H_2S: [0–406] ppb, mean value 50 ppb;
- CO: [0–20] ppm, mean value 1.8 ppm.

The low-cost set of four electrochemical gas sensors (shown in Figure 5) is formed by four modules: a main module, a sensor module, a wireless module and a power module. The first three modules (PCBs) are packed in the same handheld case, but the power module is arranged in a separate case as in Figure 5 (see [14]).

Table 3. NASUS IVmulti-sensor system: sensor characteristics.

Sensors	Model and Factory	Operativity Range
NO_2	NO_2A1-A3 Alphasense Ltd. (UK)	0–20 (ppm)
CO	COCX-A3 Alphasense Ltd. (UK)	0–2000 (ppm)
SO_2	SO_2AF-A3 Alphasense Ltd. (UK)	0–50 (ppm)
H_2S	H_2SA1-A3 Alphasense Ltd. (UK)	0–100 (ppm)
Temperature	LM35CZ National Semiconductors Co. (USA)	−55 °C–150 °C
Relative humidity	HIH-3610 Series Honeywell (USA)	0–100% RH



(**a**) (**b**)

Figure 5. The NASUS IV multi-sensor system architecture, (**a**) Modules in NASUS IV; (**b**) NASUS IV as installed in the case.

Considering the gas compounds (see also Table 1), nitrogen dioxide can be traced back to emissions from road vehicles, power generation and households. Carbon monoxide is commonly found in air at concentrations not harmful to humans. The main sources of additional carbon monoxide are motor vehicle exhaust and some industrial activities, such as those relating to steel manufacturing. The gas components SO_2 and H_2S are more indicative of industrial productions processes, geothermal and/or volcanic activities [39]. However, H_2S concentrations were surprisingly high in some urban traffic sites ([40–42]), probably due to car catalytic converter processes linked to the storage of sulfur during fuel lean conditions and its subsequent release as H_2S during fuel-rich conditions (e.g., [40,41,43]). Hydrogen sulfide is a toxic compound, with documented effects on human health starting from concentrations larger than 10–20 ppm [44].

By relating to the studies of [13,14], the NASUS gas sensor calibration was performed in the following way. In a gas chamber, at constant temperature and relative humidity (21 °C for temperature and 40% relative humidity), the gas sensors were firstly set at zero air, and the output voltages (here called V_o) were all measured. After this, chamber gas concentrations were set at known values (100 ppb for NO_2, H_2S and SO_2, 10 ppm for CO), and we measured the resulting output voltages. Then, by basing on a linear response between output voltages and concentrations, we calculated the coefficient K_1 for the relationship between gas concentration, C, and measured output voltage, V:

$$C = K_1(V - V_o).$$

The multi-sensor system was tested through experimental campaigns in outdoor ambient air in collaboration with ARPA-Puglia ([14]). In addition, after a comparison with reference measurements in a controlled indoor chamber, the portable system was tested within the premises of the European Reference Laboratory for air pollution (ERLAP) at the European Monitoring and Evaluation Programme [45] (EMEP) station of the Joint Research Centre for atmospheric research (45°48.881′ N, 8°38.165′ E). The EMEP station is a rural background station, which is located at the northwest edge of the Po valley (Italy), and it is equipped with meteorological sensors and reference gas analyzers. The reference measurements were used for data validation, comparison and data treatment of sensor responses as documented in [13,28]. Among the major outcomes, these experimental campaigns suggest that the measurements obtained with NASUS IV may not yet satisfy the data quality objective prescribed by the legislation into force ([32,33]) as measurements uncertainties may be more than 30% with respect to reference data. Therefore, data from the NASUS IV portable system should currently be used only as potential indications for ambient air quality status and not for policy purposes.

3.4. Reference Data from ARTA Abruzzo

ARTA Abruzzo, the regional agency for environmental protection [46], provided us with reference measurements for the following components: NO_2 and O_3 (hourly based); and benzene C_6H_6, which is a NMVOCspecies directly hazardous to human health, $PM_{2.5}$ and PM_{10} and SO_2 (daily based) from the station Amiternum IT1856A (see Figure 2 where the station is indicated with red starred point), for the time period from 28 August–5 September 2014. The reference station was located further apart with respect to the Smart Ring area. Therefore, reference data provided a picture of the urban background outdoor air quality status during the campaign, but could not be directly compared with the multi-sensor system data.

3.5. The Air Quality Index

An air quality index (AQI) approach was selected to report the gas compound concentrations in relation to a reference concentration, because this index is a useful dimensionless way of comparing different air pollutants. In addition, air quality indexes are generally used for citizen awareness purposes, i.e., to inform citizens on air quality status in a very simple way (e.g., [47]). The approach proposed by [13] was adopted to present the air quality status.

The air quality index is calculated as the ratio of the measured concentration with respect to a reference level:

$$AQI = 100 \cdot \frac{measured \quad concentration}{reference \quad concentration} \tag{1}$$

For NASUS IV gas components and reference data, the reference levels were identified on the basis of the air quality legislation [33]:

- CO: 8 ppm;
- NO_2: 100 ppb;
- H_2S: 90 ppb;
- SO_2: 130 ppb;
- C_6H_6: 5 $\mu g \cdot m^{-3}$ (data from ARTA Abruzzo);
- PM_{10}: 50 $\mu g \cdot m^{-3}$ (data from ARTA Abruzzo);
- $PM_{2.5}$: 25 $\mu g \cdot m^{-3}$ (data from ARTA Abruzzo).

According to the AQI value, five categories were defined to indicate the air quality status (Table 4).

Table 4. Air quality index (AQI) values in relation to the air quality status.

AQI Values	Air Quality Status	Colors
<33	Excellent	Blue
34–66	Good	Green
67–99	Moderate	Yellow
100–150	Bad	Red
>150	Worse	Violet

Furthermore, the index AQI_{hi} was defined as an aggregated index for several gas components. The index AQI_{hi} was chosen as the worst case indication for air quality as determined by the largest AQI calculated for each gas component (AQI_{NO_2}, AQI_{SO_2}, AQI_{H_2S}, AQI_{CO}). The approach is consistent with other literature studies (e.g., [47]).

3.6. Experimental Campaign

The multi-parametric system was installed inside the SmartBus and operated for these five days: on 28–29 August and on 1–3 September 2014.

Table 5 reports the parameters collected from the SmartBus and NASUS IV. The on-board vehicle control system provided the parameters related to the bus motion, at a time resolution of one second. The gas components measured by the multi-sensor system were collected on a memory card (time resolution of four seconds).

Before starting the measurement campaign, the time of the SmartBus and NASUS IV internal clocks were recorded and assumed to provide the same time difference for the whole five-day campaign. This assumption was essential in order to match data from the two systems on the timestamp base afterwards, as no further time checks were conducted.

After the experimental campaign, data from NASUS IV were downloaded from the memory cards and processed with bash UNIX scripts to format the records consistently with the SmartBus data. Data from the SmartBus system were checked and corrected to report them into a single timestamp format, as due to a software bug, the pieces of information on date and time were reported in three different formats. Then, data from NASUS IV and the SmartBus system were imported and matched, taking into account recorded two-minute discrepancies between the two systems. Elaborations were performed with R-cran software packages [48].

Georeferenced data were visualized on maps by using QGIS software [49]. An area covering the Smart Ring was selected since it contained the majority of the data collected.

Table 5. Main parameters measured by the SmartBus and NASUS IV. DD: Decimal Degrees.

SmartBus	NASUS IV
Date time (timestamp)	Date time (timestamp)
Latitude (DD)	NO_2 (ppm)
Longitude (DD)	SO_2 (ppm)
Altitude (m)	H_2S (ppm)
Speed (km/h)	CO (ppm)
Ambient air Temperature (°C)	Temperature (°C)
	Relative humidity (%)

We corrected for the GPS SmartBus positioning over the Smart Ring area since some data (less than 5%) suffered from signal distortion (e.g., the GPS signal was stopped or deviated by urban buildings). We use the road network shapefiles provided by [50] and corrected them to properly match the road segments of interest. Afterwards, the R-cran package "maptools" [51] was used to report data points to their closest road network segment.

Air quality indexes, including AQI_{hi}, were calculated for NASUS IV and ARTA chemical compounds. Afterwards, statistical analyses were performed on the air quality indexes. The minimum, median, mean and maximum values were determined on a daily basis for each AQI (e.g., AQI_{NO_2}, AQI_{SO_2}, AQI_{H_2S}, AQI_{CO}).

Time series for AQIs were represented together with a five-minute average AQI_{hi}, which provides an indication of the personal exposure experienced by the SmartBus users, when considering an average travel time of five min (see Section 3.2).

For each day of the measurement campaign the minimum, mean and maximum AQI_{hi} values were calculated and reported on maps.

4. Results

4.1. Geographical Representation of NASUS IV-SmartBus Data

The SmartBus positions with the sensors data were reported graphically (Figure 2). Measurements covered a wider area than the Smart Ring, extending to peripheral roads, tunnels, roundabouts and a nighttime recovery. More than 85% of the data was located on the Smart Ring area, the region chosen for the analyses.

Besides the nighttime recovery, where the SmartBus was kept for battery recharging, the road segments outside the Smart Ring were characterized by a low frequency passage. These road segments were covered during early morning and in the evening when traveling from the nighttime deposit to the Smart Ring and vice versa.

Preliminary analyses showed that the gas concentration measured over peripheral roads were generally higher than over the Smart Ring. This result may be related to the presence of: (i) major road traffic; (ii) congestion at the roundabouts; and (iii) tunnels, which indirectly influenced the measurements inside the SmartBus.

4.2. Reference Measurements from ARTA Abruzzo

The chemical compounds indexes AQIs for the reference measurements are represented in Figure 6, where the components $AQI_{C_6H_6}$, AQI_{SO_2}, were not plotted as they were too low with respect to the others, whose highest values were around 25 for AQI_{NO_2}, 26 for $AQI_{PM_{10}}$ and 32 for $AQI_{PM_{2.5}}$.

The outdoor air quality status was generally good and primarily determined by the ozone concentration, characterized by the highest AQI values. During the days 28–29 August 2014, a stable high pressure system was over l'Aquila (e.g., see [52,53]). Ozone showed typical daily cycles during these days, with the highest AQI reaching about 60 and the lowest AQI values around 10. For NO_2, AQI was relatively low during the last days of August (values lower than 15). Afterwards, the AQI increased with values less than 33. Reasons for the increase in NO_2 concentration during the first days of September (about 48% on average considering the mean values) may be motivated by a general increase in road traffic associated with the start of the work activity after summer holidays. This time period overlapped with the first days of the working week. As the NO_2 concentration increased, ozone diminished during the first days of September due to rainfalls (see [52,53]) and also to the titration process, where high concentrations of freshly emitted road traffic NO concentration may have locally scavenged O_3, a process leading to the formation of NO_2 (e.g., [54]). Particle matter $PM_{2.5}$ and PM_{10} have AQI values close to 24–26 and 30–32, respectively, for 28–31 August. Afterwards, the values decreased significantly (by more than 30%, reaching $AQI_{PM_{10}}$ and $AQI_{PM_{2.5}}$ of about 12), due to a front passage with rain on 1 September (e.g., [52]).

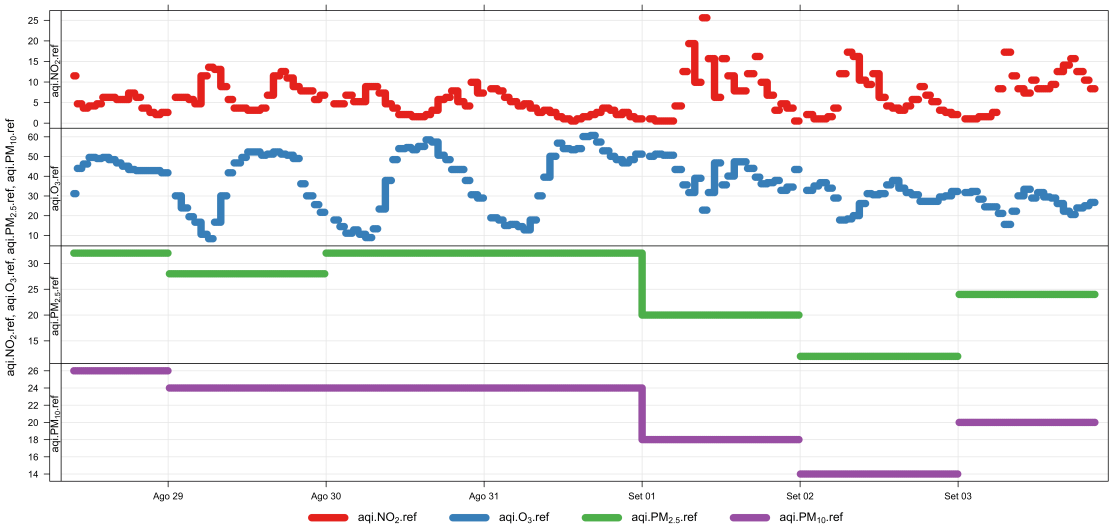


Figure 6. Time series of the AQIs resulting from the reference measurements for NO_2, O_3 and PMs.

4.3. Statistical Analyses

Table 6 reports the statistical analyses performed with the data collected over the Smart Ring. In support of Figure 6, statistics for AQIs relating to the reference gas components NO_2 and SO_2 indicate that the air quality status for urban background area was relatively good for the whole five-day campaign (maximum values for AQI_{O_3} less than 55, AQI_{NO_2} less than 22 and AQI_{SO_2} less than zero).

When considering the NASUS IV gas components, the maximum values were often related to AQI_{NO_2}, which showed the lowest values for August 28 (AQI_{NO_2} mean value of about 32) and the highest on September 3 (AQI_{NO_2} mean value of about 68). For the SO_2 component, the highest values are found during 28–29 August (AQI_{SO_2} mean values of 27 and 31), while in the other days the values are not significant. Furthermore, for H_2S, the highest values were found on 28–29 August (AQI_{H_2S} mean values of 36 and 31) and, to lesser extent, on September 2 (AQI_{H_2S} mean values of 18). The AQI_{CO} was generally very low, with mean values less than 10.

Over the five days of the campaign, NO_2 provided the highest values for AQI (AQI_{NO_2} mean value of about 68), followed by H_2S (AQI_{H_2S} mean value of 36), SO_2 (AQI_{SO_2} mean value of 31) and CO (AQI_{CO} mean value of nine).

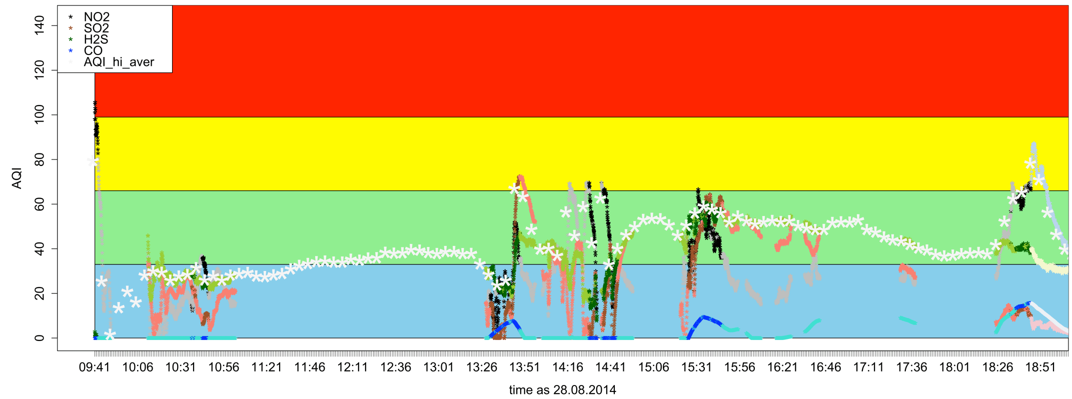
Table 6. AQI data analyses over the Smart Ring.

AQI		**28.08.14**	**29.08.14**	**01.09.14**	**02.09.14**	**03.09.14**
		no. 3430	no. 3284	no. 3446	no. 3502	no. 2392
NO_2 (ARTA)	Min value	3.66	3.14	6.80	3.14	7.32
	1st Quartile	4.71	3.66	7.84	3.66	8.37
	Median	5.75	8.89	9.93	5.75	10.46
	Mean	5.94	8.16	11.68	7.65	11.64
	3rd Quartile	6.27	12.55	16.21	8.89	12.55
	Max value	11.50	13.07	19.34	12.25	17.25
O_3 (ARTA)	Min value	31.18	16.70	31.74	18.37	15.59
	1st Quartile	43.99	30.07	36.19	27.28	22.27
	Median	46.77	50.67	39.53	30.62	28.95
	Mean	46.32	42.98	40.75	29.94	25.43
	3rd Quartile	49.00	51.23	47.33	35.64	30.07
	Max value	49.56	52.34	47.33	37.86	33.41
NO_2	Min value	0	16.40	12.4	7.40	31.10
	1st Quartile	20.10	32.20	34.70	32.60	49.80
	Median	27.50	41.10	39.50	42.10	61.70
	Mean	31.97	42.72	41.88	44.01	67.98
	3rd Quartile	41.10	50.10	48.20	54.77	78.50
	Max value	105.8	116.0	81.10	102.90	143.30
SO_2	Min value	0	0	0	0	0
	1st Quartile	11.00	1.0	0	0	0
	Median	22.85	32.0	0	0	0
	Mean	27.13	31.30	0	1.39	0
	3rd Quartile	42.77	48.02	0	0	0
	Max value	72.54	90.92	0	30.31	0
CO	Min value	0	0	0	0	0
	1st Quartile	0	0	0.37	4.19	0
	Median	0	5.31	2.06	7.55	0.06
	Mean	2.73	6.43	2.40	9.21	1.25
	3rd Quartile	5.42	9.43	4.00	10.64	2.16
	Max value	15.7	27.22	9.41	57.06	6.16
H_2S	Min value	0	0	0	0	0
	1st Quartile	26.22	23.78	0	7.56	0
	Median	39.00	33.00	1.33	10.44	1.72
	Mean	36.22	31.04	3.32	18.27	3.21
	3rd Quartile	46.42	37.89	5.89	17.00	6.67
	Max value	61.1	55.89	15.22	119.89	11.0

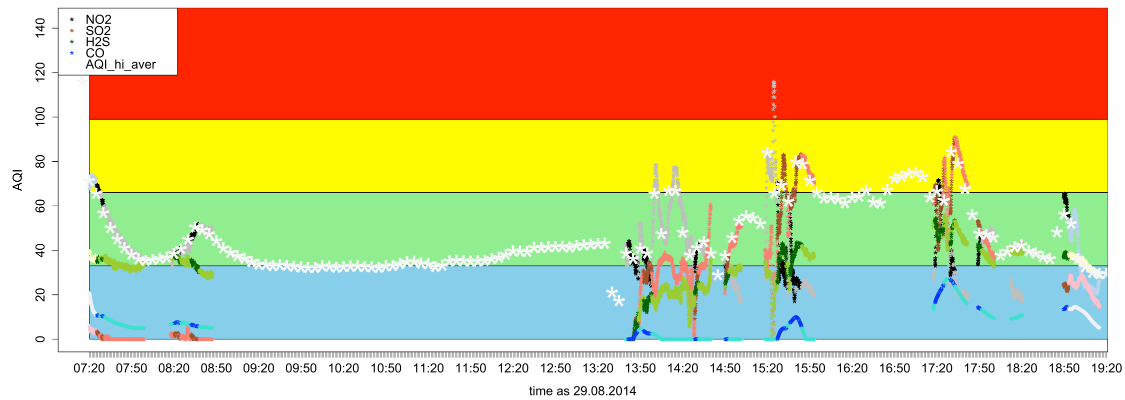
4.4. Temporal Trends of NASUS IV-SmartBus Data

The time series in Figure 7 are consistent with the overall three-month SmartBus usage reported in Figure 4. The SmartBus was called in service in three main time intervals: (i) in the morning between 7:30 and up to 9:00 local time; (ii) between 11:00 and 15:00; and (iii) often after 17:00. As in Figure 4, the majority of user requests were registered for the central part of the day. When the SmartBus was at rest, the internal acquisition system switched off three–four minutes after the vehicle stopped. After this time, no data were transferred by the SmartBus internal system to remote servers. For this reason, AQIs were fragmented in time (see Figure 7). Differently, the average AQI_{hi} exposure was calculated on all NASUS IV data independently from the SmartBus internal time system.

When looking at the averaged AQI_{hi} exposure, the value generally denotes a good air status, with the exceptions of the cases when the SmartBus was outside the Smart Ring (e.g., on 29 August at around 14:00 or on 3 September at around 12:20) and when the SmartBus traveled into tunnels, e.g., 3 September at around 12:20.

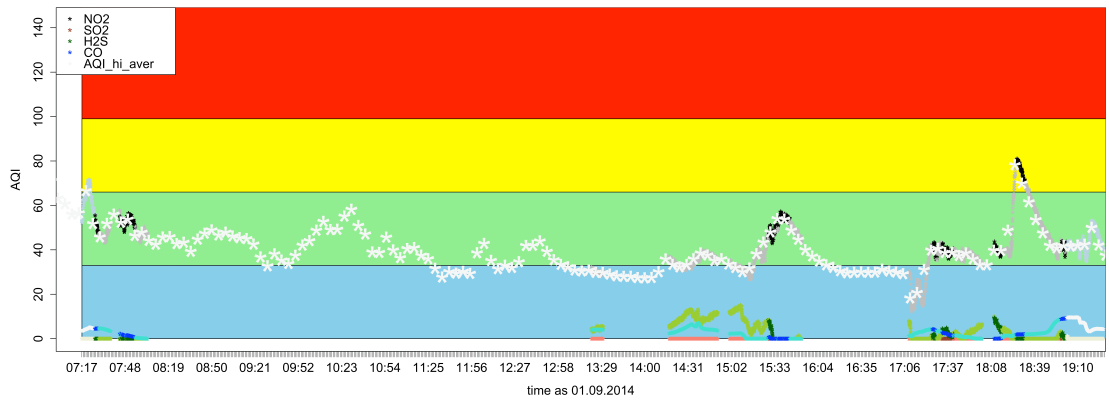


(**a**)

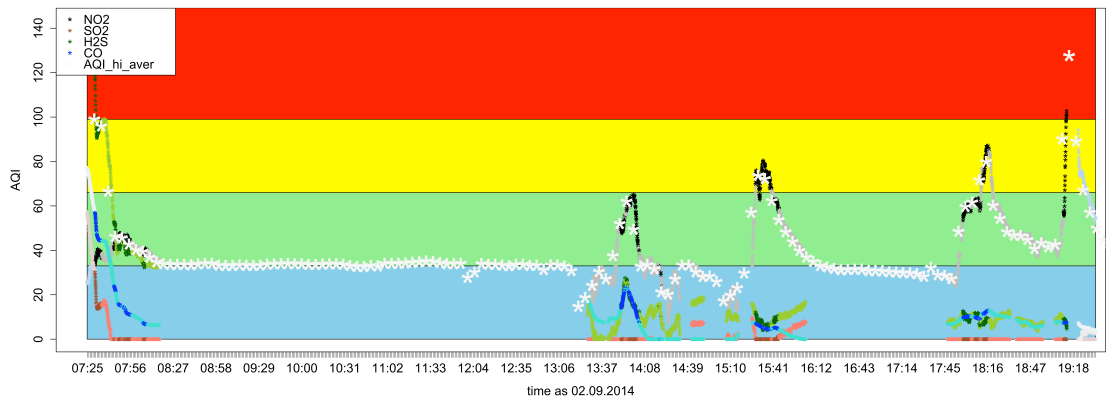


(**b**)

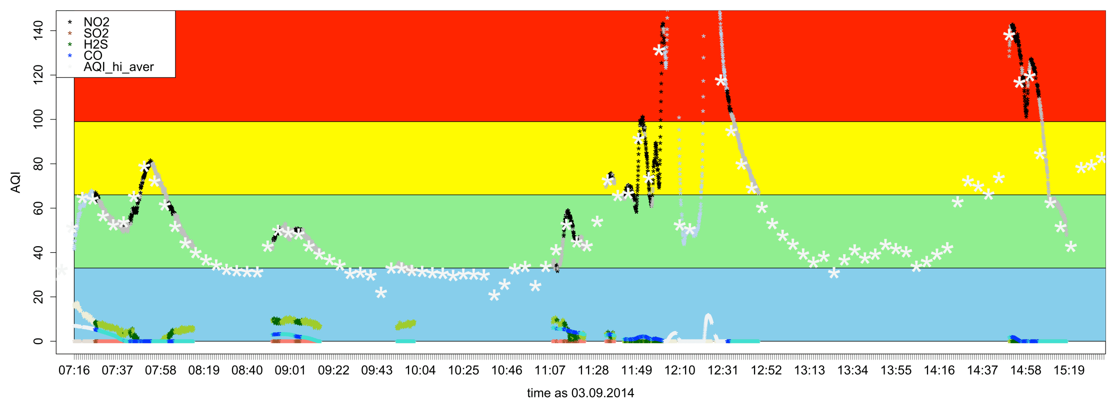
Figure 7. *Cont.*



(**c**)



(**d**)



(**e**)

Figure 7. AQIs' time series during the campaign. The different components are represented in the legend by various colors (black for AQI$_{NO_2}$, brown for AQI$_{SO_2}$, green for AQI$_{H_2S}$ and blue for AQI$_{CO}$). For each component, three color shades are associated: full color when the SmartBus was on the Smart Ring and in motion; a lighter color when the SmartBus was along the Smart Ring, but at rest; the lightest colors relate to the SmartBus position outside the Smart Ring when the bus was in motion. The white-colored stars show the 5-min averaged AQI$_{hi}$. Background areas are colored according to the AQI classification in Table 4. (**a**) AQIs time series for 28 August 2014; (**b**) AQIs time series for 29 August 2014; (**c**) AQIs time series for 1 September 2014; (**d**) AQIs time series for 2 September 2014; (**e**) AQIs time series for 3 September 2014.

4.5. Maps of AQI_{hi} Geographical Distribution

Figure 8 shows AQI_{hi} maps for each day of the campaigns.

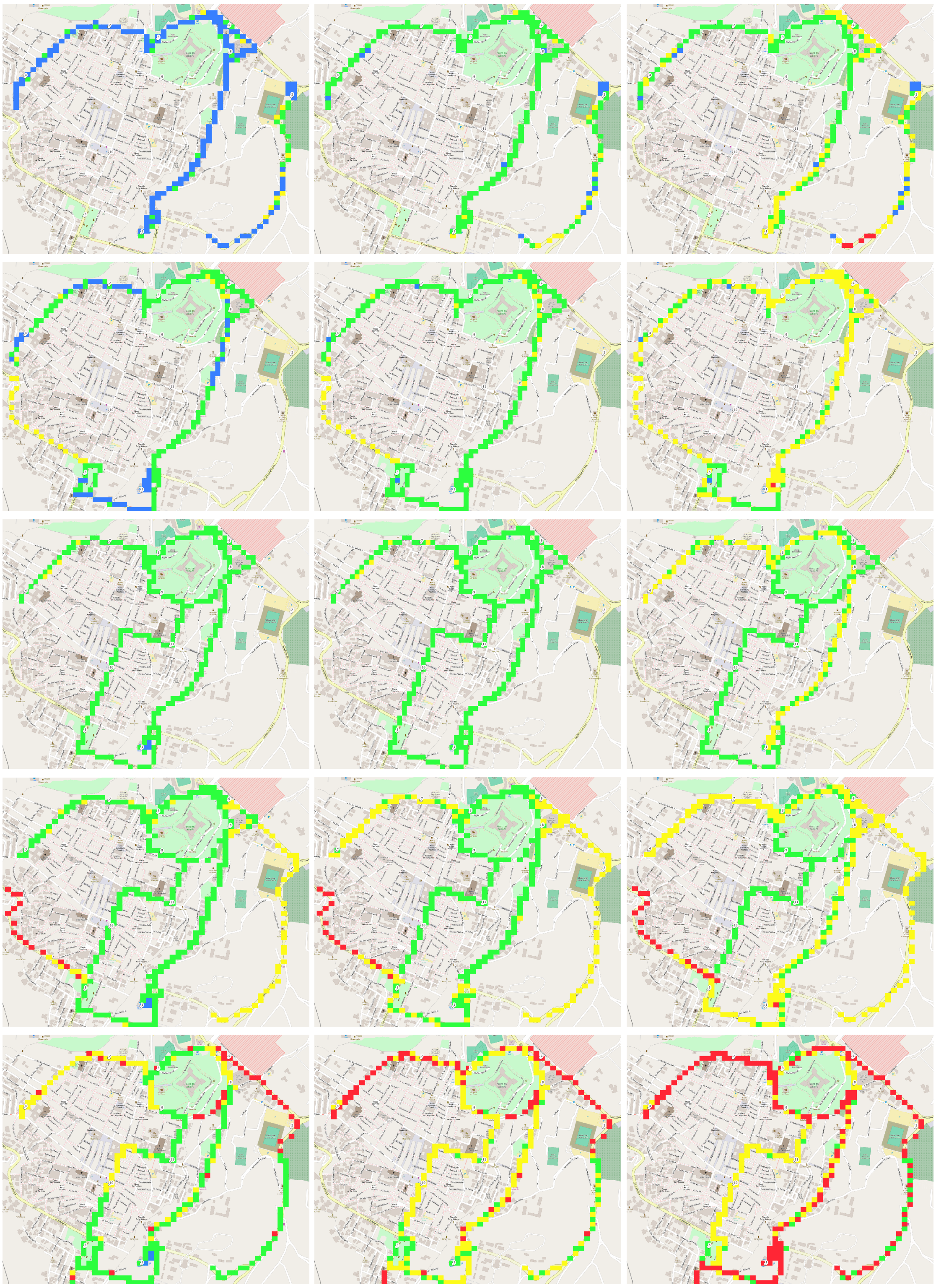


Figure 8. From the top to the bottom, 28–29 August and 1–3 September 2014, maps for AQI_{hi} minimum (left panel), mean (middle panel) and maximum (right panel) values measured during the campaign. Colors are according to Table 4.

The geographical location of the SmartBus data did change during the five-day campaign. The bus terminal station represented one of the locations with the highest data density. There, the bus used to stop and wait for user requests.

Considering the locations, the worst air quality experienced can be found in correspondence of the bus terminal station, the tunnel (see 28 August), at the roundabouts (e.g., 3 September) and on the road segments closer to the most trafficked roads.

Due to the data scarcity, it is difficult to have a clear picture corresponding to a more realistic mean air quality status experienced. Measurements inside the bus could have been influenced by local and time limited sources. These could affect the sensor response, but would not be representative of the average traffic load.

The air quality experienced by the SmartBus users deteriorates during the campaign, getting worse status at the end on 3 September.

Although reference measurements and sensor data should not be compared directly, as they measured different air samples in locations that are far apart, both indicate an air status deterioration as the campaign progressed in time. The two pieces of information could thus potentially be used in conjunction to determine areas/road segments at air pollution risk.

5. Discussion

The major outcomes from Section 4 are briefly summarized here. Due to the short time period and the "exploratory" nature of our campaign, they should be qualitatively evaluated.

The data collected along the Smart Ring, where the majority of measurements were collected, indicated that the air quality experienced by the users was generally better than over the peripheral roads, likely characterized by more traffic and congestions. The average users' exposure, calculated over a five-minute time, reported a good air quality status.

The reference measurements for the ARTA background traffic station showed that the air quality was generally good over the five days. Trends in the reference air pollutant concentrations were plausibly influenced by (i) synoptic variations and by (ii) more emitted pollutants during 1–3 September 2014, in relation to the start of the week and the return back to work after summer holidays.

The integrated mobile system SmartBus with NASUS IV provided AQI values that qualitatively reproduced the trend reported by the urban background monitoring stations, on a daily basis. The gas components, which influenced the AQI most, were also reported. In addition and more importantly, the system indicated higher air-polluted road segments, where further monitoring could take place in the case of hot spot detection.

On this basis, our mobile integrated approach did provide positive outcomes. In particular, our system has the potential to provide more detailed and higher temporal and spatial indications on air quality, as well as on personal exposure, contributing to support air quality monitoring programs.

As such, our approach is not ready to be operationally deployed, as it needs further testing, development and quality assurance checks. In the following subsections, we describe what we learned from our campaign and highlight the issues to tackle to improve the approach in order to obtain a solid reliable sensor-based platform.

5.1. Lessons Learned by Using NASUS IV

5.1.1. Systems Synchronization

The results here presented rely on the strong assumption that the multi-sensor system and the SmartBus system were constantly timely synchronized. On this basis, the parameters measured by the sensor system were associated with the SmartBus position. However, in real cases, a perfect synchronization seldom happens, with the result that data from the air quality multi-sensor may not be precisely geo-localized. For future experiments, NASUS IV should be equipped with a Global

Positioning System (GPS) or, in a better perspective, a unique acquisition system should be envisaged. The acquisition system should also transmit data when the vehicle is at rest.

5.1.2. NASUS IV Enclosure and Architecture

NASUS IV was installed in a polyvinyl chloride (PVC) enclosure (IP65/66), where air comes to the sensors through holes at the bottom of the enclosure. This configuration is not ideal for accurate ambient air gas component samplings. The sensors were partially covered by the enclosure, and our measurements might have been influenced by internal microclimatic processes (e.g., air recirculating within the case). Sensors heads should be placed in direct contact with the open air/air sample to be detected. The direct placement into the air would also avoid the potential effects of the dissipative heat produced by the sensor board electronics, which might influence the response. In addition, it is not advisable to use PVC enclosures for chemically-reactive gas compound sampling. Ozone and nitrogen oxide compounds react directly with the polymers (e.g., [55,56]). Therefore, inert material should be preferred, such as stainless steel or Teflon.

5.1.3. Experimental Campaign

Concerning the experimental campaign, the planned time period of data acquisition should be much longer. Ideally, one year of data could produce a better picture of the temporal and seasonal variations of AQIs. In addition, it would be ideal to have a larger number of "smart" operational buses equipped with multi-parametric sensor platforms to cover several areas of the city simultaneously, such as in the project OPENSENSE [5].

When it comes to the SmartBus vehicle, the operations influencing the internal ambient air conditions, such as door and window openings and air conditioning functioning, need to be carefully monitored and reported in a timely manner. Detailed records of these operations should be kept for a more informative framework on how measurements were taken and/or influenced.

If a pump system bringing outdoor air inside the vehicle at a constant rate could be feasibly installed, the measure of the "indoor" air pollutant concentrations would be directly connected with the outdoor conditions. Measurements performed in this configuration would thus provide indications of the users' personal exposure inside the vehicle, with a more precise geolocalization of the outdoor air quality status.

5.2. Lessons Learned Concerning Electrochemical Sensor Platforms

5.2.1. Chemical Components Choice

When planning future measurement campaigns, the gas sensors to choose for the multi-sensor platform should be able to sample the major gas components of interest for the area considered. In urban environments, sensors for NO_x, VOCs, PMs and ozone should be included in the chemical components selection.

Air pollutant sensors should be chosen according to the best reliable and tested sensors available in the market and documented by the literature (e.g., [28,57,58]). In addition, care should be taken to follow project development, such as the AirSensEUR project [23,25], which aims at building an open data, software and hardware multi-sensor platform for air quality monitoring.

5.2.2. Reliable Sensors Measurements

Low-cost sensors calibrations can indeed be quite cumbersome as, when they are used in laboratories and in the field, they can differ markedly (e.g., [59,60]). Furthermore, most relationships observed in the field only apply to specific locations, for a limited time period [59] and for a specific sensor. To quote, Lewis et al. [59,61] stated that ambient air tests of 20 identical ozone sensors installed on a roof found a difference of a factor of six between the highest and lowest measurements. Furthermore, low-cost sensors' response depends on several other parameters such as: (i) the air quality component concentration itself; (ii) the presence of interfering chemical components, as in the case of ozone and nitrogen dioxide; and meteorological parameters such as wind, temperature and relative humidity (e.g., [62]).

In this view, to develop low-cost sensors platforms to use as complementary tools for reference air quality measurement networks, sensor platforms do need to be calibrated in a timely manner and their response studied in detail. Examples are Spinelle et al. [28,57,58] who performed a field calibration of a large cluster of low-cost air sensors in a rural site for several months in 2014. Hasenfratz et al. [63–65] proposed several types of calibrations of mobile low-cost sensors with reference measurements and already calibrated sensors in an urban environment. Piedrahita et al. [60] conducted collocation, calibration and laboratory calibration techniques to determine the concentrations of low-cost wearable air quality monitors; and De Vito et al. [66,67] presented statistical, machine-learning and dynamical neural network approaches that could be adopted for a better extraction of signals from a mixture of pollutants.

5.2.3. Sensors in Motion

When considering sensor measurements taken on moving objects (e.g., car, buses, bikes), tests should be conducted to determine potential shock impact on sensor response. According to the sensor type, motion could modify the sensor response, and this should be quantified (e.g., Spinelle, 2016 personal communication, and [20]). In addition, since sensors need to be routinely compared with reference networks, field campaigns should be planned with time scheduled passages and stops in the proximity of reference station networks and/or more reliable sensor measurements.

6. Conclusions

We presented the outcomes of a few days' pilot test, representing our first approach of the integration of an experimental mobile urban service and our available sensor-based air quality monitoring system. The measurement campaign took place over a delimited path, the Smart Ring, located at the city center of l'Aquila.

Within the six-month experimental SmartBus, urban mobility on-demand service, for five days, our sensor platform NASUS IV was installed and operated within the cabin. Here, the SmartBus became a sort of mobile air quality sensor providing temporal and spatial indications on air quality status as experienced by the users and, indirectly, of the outdoor ambient air.

The air status experienced by the users along the Smart Ring was generally better than over the peripheral roads, where more traffic could have been expected. Furthermore, the average users' exposure reported a good air status.

The air quality index values calculated from our integrated mobile system qualitatively reproduced the trend reported by the reference urban background monitoring stations, on a daily basis. According to our sensor platform, nitrogen dioxide was the gas component that contributed the most to the air quality status, followed by hydrogen sulfide, sulfur dioxide and carbon oxide.

Our sensor platform is not yet ready to be fully deployed in parallel with reference data. Further tests, development and quality assurance checks need to be performed also to assure reliable air quality information at the standards required by the current legislation.

Despite these limitations, the data obtained through our sensor platform are consistent with: (i) geolocalization of hot spot areas (e.g., bus station terminal, tunnels, roundabouts); (ii) air quality reference measurements trends; (iii) the meteorological synoptic situation; and (iv) air pollutant concentration variations caused by time-driven traffic flow changes (weekly and holiday back-to-work variations).

Therefore, we do support the further development of such integrated sensor platforms as companion tools for air quality reference networks and urban integrated assessment methodologies, as well as citizen awareness purposes.

In this view, we described what we learned from our pilot campaign and highlighted the issues to tackle to improve the approach in order to make it a solid reliable monitoring sensor-based platform. In particular, future developments for our multi-sensor platform may address: (i) the sensor enclosure; (ii) the data acquisition infrastructure; (iii) a wider choice for gas compounds, including also PM sensors; (iv) investigations of alternative sensor brands; and (v) different sensor calibration procedures.

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Author Contributions: Domenico Suriano and Marco Prato were responsible for and provided support for NASUS IV. Fabio Cignini and Fernando Ortenzi were responsible for and supervised the SmartBus service during the experimental campaign with NASUS IV. Maria Gabriella Villani, with Fabio Cignini's indications and contributions, analyzed the data and wrapped up the work.

Conflicts of Interest: The authors declare no conflict of interest.

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