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An integrated low-cost road traffic and air pollution monitoring platform for next citizen observatories

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Abstract

An integrated monitoring platform was developed for real-time monitoring of air pollution and traffic flows in urban areas. The air quality monitoring unit, integrating the "Arduino" open-source technology with low-cost and high-resolution sensors, collects concentrations of CO, NO_2 and CO_2. The traffic monitoring device, equipped with a camera sensor and a video analysis software, collects vehicles' counts, speed and size. Air pollution and traffic readings are archived on a spatial data infrastructure composed of a central GeoDatabase, a GIS engine, and a web interface.
A platform's description and the results of its installation in Florence (Italy) are presented.

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Keywords: Urban air pollution; Air quality indicative measurements; Road traffic; Integrated monitoring platform; Low-cost sensors.

1. Introduction

Over the 2004–2013 decade, mostly as a result of improvement in vehicle technology and renewal/turnover of vehicle fleet (Progiou and Ziomas, 2012), the transport sector has considerably reduced its air pollutant emissions in Europe (EEA, 2015): the highest emission reductions were registered for SO_x (67%), CO (62%) and non-methane volatile organic compounds (nmVOCs; 59%). However, road transportation remains a crucial concern for air quality

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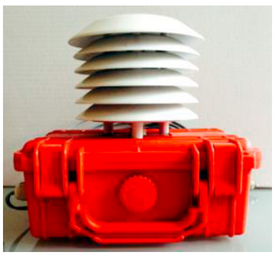
in urban areas as it is the predominant contributor of air pollution (Wang et al., 2008). The most updated surveys (2013) carried out in Europe (EEA, 2015; 2016) report that the road transport sector contributes to total annual emissions by 46% for NO_x, 23% for CO, 15% for primary $PM_{2.5}$, 12% for primary PM_{10}, and 10% for nmVOCs. Based on concurrent (2013) nationwide emission inventory (ISPRA, 2016), in Italy road transport contributes to total annual emissions by 49.5% for NO_x, 22.7% for CO, 18.7% for nmVOCs, 12.2% for primary PM_{10}, and 11.8% for primary $PM_{2.5}$. Shares rise to 30.8% for total PM_{10} and 32.9% for O_3 precursors if emissions from precursors of secondary aerosol and O_3 are also considered. Also, transportation contributes to global warming with CO_2, CH_4 and N_2O emissions. In Italy, transportation is the highest contributor of global equivalent CO_2 emissions (26.4%) over electricity and heat production (25.8%), and non-industrial combustion (18.4%). Currently enforced 2008/50/EC EU Directive (EC, 2008) states that urban air pollution levels mostly influenced by road traffic emissions shall be measured by fixed urban traffic (UT) stations. To provide adequate information on air quality spatial distribution, the directive also states that those fixed measurements may be supplemented by indicative measurements. Thus, the legislative importance of indicative measurements is to be stressed, as "the results of indicative measurement shall be taken into account for the assessment of air quality with respect to the limit values" (EC, 2008). On the other hand, the recent push towards Intelligent Transport Systems (ITS) within modern-day smart cities requires a large amount of high-quality traffic data acquired in real-time. Traffic data are generally used by city administrators, consultants and developers for traffic management and road network planning, mainly with the aim of solving traffic congestion problems, promoting economically and environmentally sustainable transportation modes, communicating in real-time traffic conditions, anomalies or events possibly impacting on traffic and park searching, etc. In any case, the combined monitoring – at the same urban site – of pollutant concentrations and the traffic flows directly involved in those concentrations is quite rare (Moreno et al., 2015). To pursue both goals of providing air quality indicative measurements and related automated road traffic measurements, an integrated monitoring platform (IMP) was developed for real-time combined monitoring of air pollution and traffic flows in urban areas. This work has two main objectives: (i) to provide a detailed description of the IMP and related spatial data infrastructure; (ii) to analyse the results of a 1-month campaign from an IMP installation at a road site in the city of Florence (Italy).

2. Description of the monitoring platform

2.1. The air quality unit: "AirQino"

The "AirQino" air quality monitoring unit (Fig. 1a), developed within the national SMARTCITIES project (Vagnoli et al., 2014; Zaldei et al., 2015), is based on an Arduino Shield Compatible electronic board, equipped with low-cost and high-resolution sensors (Fig. 1b). AirQino provides measurements of both meteorological parameters (i.e. relative humidity and temperature), and pollutant/species concentrations (CO, NO_2, CO_2). The board integrates a microprocessor that acquires all readings from the installed sensors. Through the General Packet Radio Service (GPRS) technology, the sensor transmits geolocated data to a data server connected to the applications and webserver allowing to visualise real-time observations on a web browser. Sensor calibration has been performed following Williams et al. (2013). Air quality measurements have been validated based on the calibration protocol of low-cost sensors developed by the Joint Research Centre (Spinelle et al., 2013). Total cost of AirQino is about 820 €.

a) 

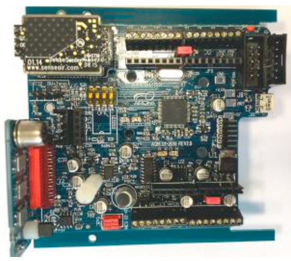
b) 

Fig. 1. Pictures of: (a) the AirQino monitoring unit; (b) the integrated circuit board.

2.2. *The road traffic unit: "TrafficFlow"*

"TrafficFlow" (http://chest-trafficflow.magentalab.it) is an innovative, flexible and low-cost platform for road traffic monitoring and analysis. Based on sensors equipped with advanced video analysis software, it meets smart cities' needs for sustainable and minimally invasive systems to improve transport management. Within the CHEST project (http://www.chest-project.eu/), Magenta s.r.l. used the TrafficFlow technology to perform an extensive traffic measuring campaign in the Florence metropolitan area, thus demonstrating for the first time that reliable traffic data can be obtained, on a large scale, without the need of dedicated infrastructure or intrusive devices: sensors have been hosted by public buildings, private offices or shops, and even private smart citizens (Fig. 2).

a) b)

Fig. 2. TrafficFlow monitoring unit installation examples.

TrafficFlow is based on the well-known Raspberry Pi credit card computer (https://www.raspberrypi.org) and runs a video analysis software capable of collecting meaningful statistics of traffic flow along the observed road. Real-time collected data are periodically transmitted to a remote server and stored into a no-SQL database, from where they can be queried and visualized with different representations and according to the desired aggregation degree (1-min to 1-day). Observed parameters include vehicles' flow, average speed, sensor occupancy, and vehicle's class distribution. Traffic measurements have been indirectly validated by transport experts from six local municipalities, where measures have been used for almost one year as a decision support on traffic management. TrafficFlow is cheap to purchase (hardware total cost is about 100 €), quick and inexpensive to install (infrastructure is borrowed by the host), and easy to maintain (the device is physically reachable without complex procedures).

2.3. *The spatial data infrastructure*

A Spatial Data Infrastructure (SDI) has been implemented, which integrates low-cost open-source sensors and services at urban scale, including sensors management, data acquisition, effective management of geospatial data as well as transparent access to sensor data and data analysis. The SDI components are organized in typical client-server architecture and interact from the sensing process to the representation of the results to the end-users (De Filippis et al., 2013) adopting the OGC® SWE (Sensor Web Enablement) Common standard. Web infrastructure is composed of a central Geo Database for data storage and management, a GIS engine, and a web interface. Specific Application Programming Interfaces (API) have been implemented to interact with the low-cost urban traffic monitoring platform for deployment of web services and test new approaches on multisource data fusion and platforms interoperability. Web interface and functions have been developed using J2EE technology with Java Server Faces and PrimeFaces library for GUI (Graphic User Interface) customization. Through common web or mobile browsers, all collected data are visualized in table or chart format, or tracks and spot values on a Google mashup.

3. IMP installation: material and methods

3.1. *Road site and experimental data*

The IMP has been installed in Florence (Italy) at Via della Villa Demidoff (43°47'17" N, 11°13'36" E), a road located within a densely inhabited area in the northwestern part of the city (Fig. 3): it is a two-way road with one lane per direction; site's average width (between opposite building walls) is 16 m, while road segment total length is 350 m. Via della Villa Demidoff is a residential road delimited by two major roads, Via di Novoli and Via Baracca, which connect the city centre to the Florence international airport and two major highways. The AirQino (AQ) monitoring unit was installed on a windowsill (Fig. 3) about 4 m from ground level, while the TrafficFlow (TF) monitoring camera was mounted upon the inner pane of the adjacent window. Since AirQino was installed at an elevation between 2 and 4 m (about 8 m from road centreline), collected pollutant concentrations might be used as indicative measurements possibly supplementing the official fixed UT measurements. A 1-month monitoring campaign (from 30/01/2016 to 29/02/2016) has been carried out by the installed IMP, with a 2-min time resolution.

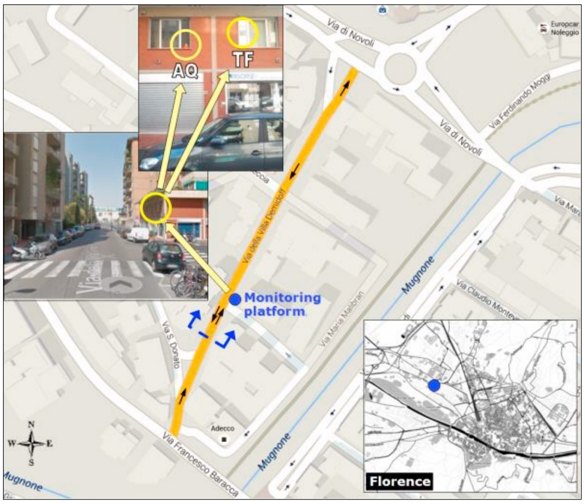


Fig. 3. Map of the IMP installation road site in Florence, also displaying a street-level cross-section picture and blow-up of the windows where the AirQino (AQ) and TrafficFlow (TF) monitoring units are installed (cartography sources: Google Maps and Bing).

3.2. Pollutant emission estimation: the COPERT emission model

The COPERT emission model – according to its most updated guidebook (Ntziachristos and Samaras, 2013) – was applied to calculate pollutant emissions due to road traffic. COPERT is the most commonly used methodology in Europe for official national inventories of emissions from road traffic. It allows estimation of emissions for several vehicle categories belonging to the following six main classes: passenger cars (PC), light duty vehicles (LDV), heavy duty vehicles (HDV), urban buses and coaches (BUS), mopeds (MOP), and motorcycles (MOT). Vehicles are sorted by fuel type, legislation/technology, cylinder capacity (for PC and MOT), weight (for HDV and BUS), and other variables. COPERT is a steady-state model: it calculates constant emissions over the time period (1 h) and along each road segment (Gualtieri, 2010). Through COPERT total exhaust emissions are calculated as a sum of hot emissions (when the engine is at its normal operating temperature) and cold-start emissions (during transient thermal engine operation); non-exhaust emissions include fuel evaporative emissions (only applying for nmVOCs), as well as vehicle tyre wear and brake wear, and road surface wear (only applying for particulates).

4. IMP installation: results and discussion

4.1. Air quality and road traffic data

Table 1 summarizes the basic statistics of all parameters measured by the IMP at the installation road site through the 1-month period. For convenience, 2-min raw data have been aggregated to 1 h. Measured CO concentrations are quite low, averaging 0.29 mg/m^3 with a maximum of 0.60 mg/m^3: this confirms the CO decreasing trends observed in urban areas throughout EU in recent years (EEA, 2015). Mean concentrations of 47.5 μg/m^3 are measured for

NO_2, with a maximum of 65.4 µg/m^3. In any case, across the studied period air quality limits were never exceeded, neither for CO (10 mg/m^3 maximum daily 8-h value) nor for NO_2 (200 µg/m^3 1-h limit value). The lane towards Via di Novoli is more travelled than the one towards Via Baracca, as a mean value of 219 vs. 139 v/h is observed. However, maximum 1-h traffic volumes observed along both directions (348 and 616 v/h, respectively) are much lower than the typical 1-h maximum lane capacity of 1600 v/h (TRB, 2000): thus, traffic congestion conditions are quite rare. Average speeds along the two directions are similar: 32.9 and 39.4 km/h.

Table 1. Statistics of 1-h air quality and road traffic data observed by the IMP in Via della Villa Demidoff, Florence (30/01/2016–29/02/2016).

Variable	Valid data (%)	Mean	Standard deviation	Range
Air quality				
CO conc. (mg/m^3)	96.64	0.29	0.09	0.00 – 0.60
NO_2 conc. (µg/m^3)	96.64	47.5	14.3	6.9 – 65.4
CO_2 conc. (mg/m^3)	96.64	804.7	49.6	718.1 – 1002.2
Road traffic				
Flow dir. Via di Novoli (v/h)	99.33	219	137	11 – 616
Flow dir. Via Baracca (v/h)	99.33	139	92	5 – 348
Average speed dir. Via di Novoli (km/h)	99.33	39.4	5.1	22.7 – 63.9
Average speed dir. Via Baracca (km/h)	99.33	32.9	7.8	19.1 – 77.1

An analysis has been performed to investigate the association degree between all measured parameters (Table 2). The highest correlation vs. total traffic flows is achieved for CO concentrations (r=0.33). This correlation was remarkably lower than in the past years: road transport was once a major source of CO emissions, but the introduction of catalytic converters significantly reduced these emissions (EEA, 2015). On the other hand, the contribution to CO from non-industrial combustion – likely due to an increase in wood combustion for heating – remarkably rose, e.g. accounting in Italy for 3% in 1990 to 42% in 2010 (Gualtieri et al., 2014). Conversely, the lowest correlation vs. traffic flows is found for NO_2 concentrations (r=0.09), which was expected since NO_2 is a secondary pollutant (Horowitz, 1982). A significant negative correlation (r=–0.63) is observed between total traffic flows and average speed.

Table 2. Correlation coefficients (r) of 1-h air quality and road traffic data observed by the IMP in Via della Villa Demidoff, Florence (30/01/2016–29/02/2016).

Variable	CO conc. (mg/m^3)	NO_2 conc. (µg/m^3)	CO_2 conc. (mg/m^3)	Total flow (v/h)	Average speed (km/h)
CO conc. (mg/m^3)		0.44	0.41	0.33	–0.31
NO_2 conc. (µg/m^3)			0.21	0.09	–0.23
CO_2 conc. (mg/m^3)				0.18	–0.06
Total flow (v/h)					–0.63

In Fig. 4, the average daily course of traffic flows and related driving speeds as sorted by weekdays (Mondays to Fridays) and weekends (Saturdays and Sundays) is plotted. During the working days two traffic flow peaks, detected in the morning (h. 8:00–9:00) and late afternoon (h. 18:00–19:00), strictly linked to traffic rush hours may be clearly observed, with maximum values of 723 and 679 v/h, respectively. In the weekends the pattern is smoother and the two peaks lower than in the weekdays; the morning peak, which is lower than the afternoon peak (512 vs. 589 v/h), is 3-h forward time-shifted (h. 11:00–12:00) with respect to the weekday one. Corresponding average driving speeds, since significantly anti-correlated with traffic flows (Table 2), exhibit the lowest values (30–32 km/h) when traffic rush hours occur and the highest values (41–44 km/h) in the nighttime. Vehicle speed patterns are much smoother than those affecting traffic flows, as well as clearly lower the difference between weekdays and weekends.

The daily course of observed CO concentrations clearly exhibits a shape similar to the corresponding traffic flow daily course, both during the working days and in the weekends (Fig. 5). CO peak concentrations reflect the two morning and late afternoon traffic peaks, particularly during the weekdays: CO concentrations were confirmed to be a function of emissions from nearby CO sources (Horowitz, 1982).

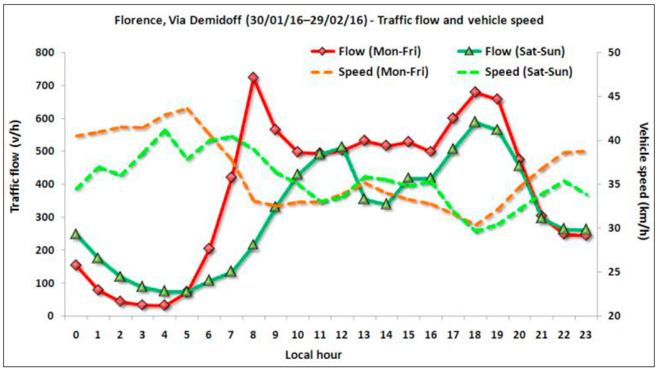


Fig. 4. Average daily course, sorted by weekdays/weekend, of 1-h traffic flows and average vehicle speeds observed by the IMP in Via della Villa Demidoff, Florence (30/01/2016–29/02/2016).

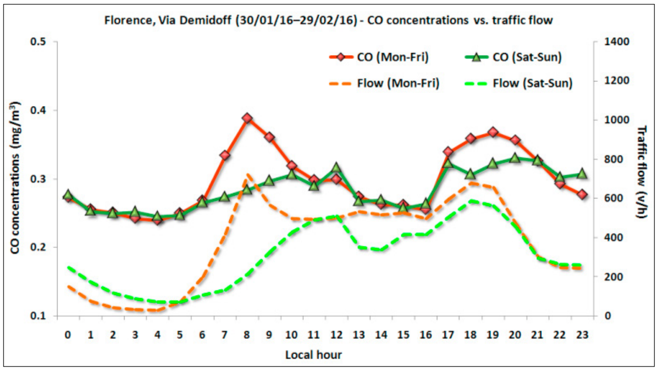


Fig. 5. Average daily course, sorted by weekdays/weekend, of 1-h CO concentrations and traffic flows observed by the IMP in Via della Villa Demidoff, Florence (30/01/2016–29/02/2016).

4.2. Estimated pollutant emissions

Based on 1-h traffic flow and vehicle speed measurements, the COPERT emission model has been applied by using the latest (2014) Florence-specific vehicle fleet data available from the Italian Automobile Association (ACI, 2016).

In Fig. 6 the daily course of COPERT-calculated CO and NO_x emissions along Via della Villa Demidoff are presented, along with overall measured local traffic flows used for comparison. The influence of traffic volumes on both CO and NO_x emissions is apparent throughout the day. The highest emissions levels are reached during the late afternoon traffic rush hours (h. 18:00–19:00): 560–590 g/h for CO, and 103–110 g/h for NO_x. Because of the so high r value resulting at daily scale between calculated CO emissions and observed traffic volumes (0.72), the same r value applies between observed CO concentrations and estimated CO emissions.

Traffic-related overall fuel consumptions may be also calculated by COPERT (Fig. 7) to achieve both total fuel consumed by all vehicles travelling the road (g/h), and corresponding total money cost (€/h). In particular, from this analysis the late afternoon traffic rush hours (h. 18:00–19:00) prove on average to be the most expensive ones, costing the 630–650 vehicles passing the road in an hour a total amount of 12 €/h consumed fuel. Averaging over the whole day, the working days are predictably the most costly (7.20 €/h), while the weekends are cheaper (5.70

€/h). Normalizing these figures by single passing vehicle, travelling the 350 m of Via della Villa Demidoff proves to cost on average 1.70 c€ consumed fuel, with peaks of 1.85 c€ across the late afternoon traffic rush hours. As apparent, this COPERT outcome would be particularly useful if the model could be applied over a significant number of road network links, as helping quick detect those road links less efficient from an economical (and thus energetic) point of view. Therefore, energy efficiency of an urban road network with respect to road traffic demand may be easily assessed through COPERT once both traffic flows and driving speeds are available.

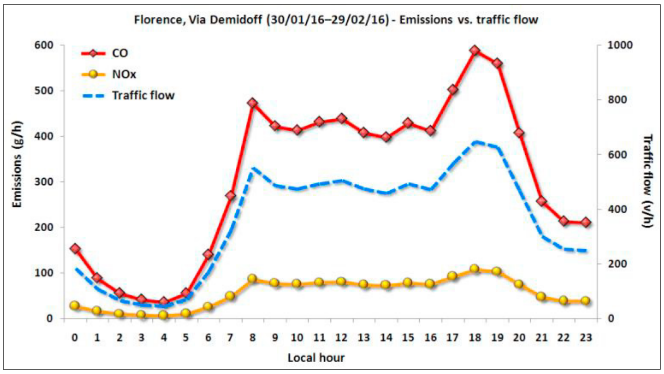


Fig. 6. Average daily course of 1-h CO and NOx overall emissions estimated by the COPERT model vs. traffic flows observed by the IMP in Via della Villa Demidoff, Florence (30/01/2016–29/02/2016).

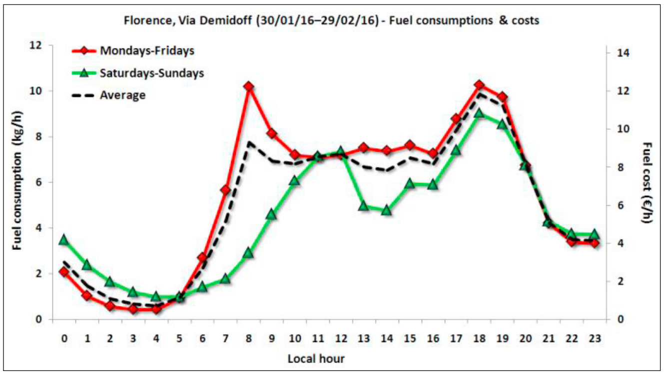


Fig. 7. Average daily course, sorted by weekdays/weekend, of 1-h fuel consumptions and costs estimated by the COPERT model in Via della Villa Demidoff, Florence (30/01/2016–29/02/2016).

5. Conclusions and perspectives

Developed for real-time combined monitoring of traffic flows and air pollution in urban areas, the IMP was tested through a 1-month campaign at a road site in Florence (Italy). Concentrations of CO, NO_2 and CO_2 were measured, thus providing indicative air quality measurements to supplement fixed measurements collected by the official urban monitoring network. Moreover, the online web application provides an excellent means for fast and transparent dissemination of measurements. The COPERT emission model was also applied to calculate pollutant emissions and fuel consumptions due to local road traffic. Monitoring performed through the IMP proved to be a sustainable approach towards a novel generation of smart mobility solutions designed by leveraging on the infrastructure made of smart citizens, as well as on the capabilities of inexpensive devices equipped with modern software technology. The IMP actually proved to be a low-cost solution, as its total cost is below 1000 €. Furthermore, as a portable device, the IMP can be installed over a number of key roads of the urban area so as to create not only an efficient network of low-cost and easy-to-be-managed "supplementing" air quality stations, but also of traffic monitoring devices particularly helpful in those cases when traffic regulation actions at urban-scale (e.g. traffic restrictions, odd-even days, etc.) are adopted. In a future perspective of implementing European citizen science (Serrano Sanz et al., 2014), the IMP will be also a valid means to support research activities by which citizens could be more directly involved in participatory environment monitoring and city management.

Because of IMP's open-source modular structure, various upgrades are foreseen in the near future, e.g. integration of further air pollutant sensors, or improvement in the traffic analysis software. In the latter case, a vehicle fleet apportionment will be performed matching the COPERT main category classification on a 1-h time scale, which will enable time-varying estimation of pollutant emissions from each COPERT vehicle category.

Acknowledgements

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