Smart Health Measurements on Urban Air for Smart Cities and Regions Matter

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1 ABSTRACT

In this article, we aim to present some of the possibilities for monitoring and quantifying the diverse influences of urban air (i.e. aerosoles, gases, and odors) in both indoor and outdoor spaces. These effects on citizens can also be monitored using unobtrusive methods. Based on literature, regulatory information and experiments, we present a somewhat fluid boundary between technologies that are already available on the market today, technologies that exist in principle in the scientific community but have not yet been incorporated into medically approved devices, and technologies that are expected to function within the next few years. We also do not claim to be exhaustive but rather aim to provide a selection of ways in which people's sense of well-being in relation to air quality in cities can be monitored, thus offering insights into potential manipulation.

Keywords: Smart City, Health Management, Urban Air, Measurement Technology, Sensor Networks

2 THE COMPONENTS OF URBAN AIR

Urban air is not a single “entitity”; vice versa, it is a dynamic complex mixture of suspended particles, liquid droplets, reactive and inert gases, and an immense variety of volatile organic compounds (VOCs). If one wants to monitor health-relevant external influences in cities – continuously, unobtrusively, and at scale – then particulate matter, aerosols, and gases are not optional topics but the measurement backbone. The technical challenge is not primarily that these quantities are unmeasurable. Rather it is that they vary rapidly in space and time, are driven by multiple intertwined sources, and require interpretation that is both physically sound and operationally useful for city management and indoor environments.

Particulate matter (PM) is commonly defined by its aerodynamic diameter and reported as PM10 and PM2.5 (and increasingly PM1). In cities, PM arises from combustion (traffic, heating), mechanical abrasion (tires, brakes, road wear), resuspension of deposited dust, construction activity, and secondary particle formation from gaseous precursors. The health relevance follows from deposition in the respiratory tract: PM2.5 can penetrate deeply into the alveolar region, and ultrafine particles (<0.1 µm) can, under certain conditions, cross biological barriers. For practical monitoring, it matters most that concentrations can change within seconds: for example, a cyclist leaving a congested arterial road for a side street may experience a pronounced step change in exposure, i.e., the “micro-geography” of exposure that regulatory stations, by design, can only approximate.

The European Union (EU) already provides a strong regulatory and analytical framework for PM. The EU Ambient Air Quality Directive sets binding limit values and introduces population-exposure concepts for PM2.5, explicitly shifting the discussion from point compliance to population-level exposure indicators (European Commission, 2008; EEA, 2008). The European Environment Agency (EEA) routinely assesses PM2.5 and other pollutants against both current EU limits and even stricter WHO guideline levels. In this context, the EEA’s recent “Air quality status” analyses underline that PM remains Europe’s largest environmental health risk despite long-term improvements (EEA, 2025a; EEA, 2025b). At the German level, the Umweltbundesamt (UBA) provides population-health indicators (e.g., DALYs attributable to PM2.5) and emission and exposure trend analyses that are directly usable for urban policy evaluation and for prioritizing interventions (UBA, 2023a; UBA, 2023b; UBA, 2023c).

Aerosols, in the strict physical sense, are suspensions of solid or liquid particles in a gas. The term becomes particularly consequential when we move from “ambient PM” to bioaerosols and respiratory aerosols. Human exhalation produces liquid droplets and droplet nuclei over a broad size spectrum, and these droplets can transport pathogens. The decisive point for monitoring is not a generic statement that “aerosols exist,” but that aerosol concentration, size distribution, and persistence depend on ventilation, humidity, room geometry, and human behavior. This is where small popularizations are not a stylistic luxury but an explanatory necessity: anyone who has entered a poorly ventilated meeting room and immediately noticed “stale air” has experienced the macroscopic correlate of microphysical processes – accumulating exhaled CO_2 and co-emitted respiratory aerosols. The scientific literature on indoor airborne transmission and mitigation strategies supports the view that minimizing indoor risk is primarily a question of ventilation, filtration, and time-dependent occupancy patterns (Morawska et al., 2020).

Gases complete the picture and, in practice, often provide the most actionable signals. CO_2 is not toxic at typical indoor concentrations, but it is an excellent surrogate for ventilation quality, occupancy, and the dilution capacity of a room. Elevated CO_2 levels are usually the earliest quantitative sign that an indoor environment is drifting into a regime where exhaled aerosol accumulation becomes plausible. CO, in contrast, is directly toxic even at low concentrations and indicates incomplete combustion. NO_2 and O_3 are key oxidants, with pronounced diurnal cycles and strong coupling to traffic and photochemistry. VOCs are a heterogeneous class that ranges from innocuous metabolic emissions to compounds of toxicological concern; importantly, VOC mixtures are central to what humans perceive as odors.

2.1 Measurement technology and validation: From reference methods to scalable sensor networks

A technically defensible monitoring concept must separate three layers: (i) reference measurement for comparability and legal robustness, (ii) dense indicative sensing for spatial/temporal resolution, and (iii) data fusion and interpretation for decision support.

For particulate matter, the reference anchor in Europe is gravimetric sampling with standardized inlet characteristics and filter weighing. EN 12341:2014 specifies the standard gravimetric method for PM10 and PM2.5 mass concentrations (CEN, 2014). Whilst these methods are slow (typically 24-hour sampling), they provide traceability. In contrast, most compact low-cost PM sensors rely on optical scattering. They infer particle number and size proxies from scattered light and convert these signals into mass concentrations using assumptions about particle density and refractive index. This is not “wrong” and a different measurement model with known limitations. It is well suited to mapping variability and detecting events when properly calibrated, quality-controlled, and interpreted with humility about absolute accuracy.

Aerosol measurement overlaps technically with PM sensing but often shifts the objective: relevant metrics include number concentration, size-resolved dynamics, and – particularly for infection-relevant contexts – the ability to distinguish liquid respiratory aerosols from predominantly solid ambient particles. The ProxiCube® NX3 provides a representative example of an applied research-to-product trajectory in this domain. The device integrates two optical particle counters within a single housing. One particle counter measures the total particle population, while the second samples air that is guided through a heating element. This heating step evaporates liquid aerosols, so that only solid particles remain. By evaluating the differential signal between both particle counters, liquid and solid particle fractions can be distinguished within one device. This concept addresses a central ambiguity in indoor monitoring: elevated particle counts may arise from harmless dust resuspension or from human-generated liquid aerosols that are relevant for infection risk. While uncertainty is not eliminated, interpretability is significantly improved compared to a single undifferentiated particle metric (Westphal, 2021; Westphal et al., 2022).

For gases, sensor choice depends on the target compound and the required confidence level. Nondispersive infrared (NDIR) sensors provide robust CO_2 measurements and are a practical baseline for occupancy/ventilation inference. Electrochemical sensors cover CO, NO_2, and O_3 with good sensitivity but require attention to cross-sensitivities and sensor aging. Metal-oxide semiconductor (MOS) sensors provide broad VOC responsiveness (often reported as TVOC) but are, by nature, non-specific and strongly influenced by humidity and temperature. The key engineering point is that multi-sensor fusion – CO_2 plus particles plus TVOC plus humidity/temperature/pressure – often outperform any single “hero sensor”, because it constrains interpretation.

Indoor “problem detection” is a specific, high-value use case. Mold, for instance, is rarely detected directly by a single gas sensor. Instead, risk emerges as a pattern: persistently high relative humidity, poor ventilation (CO_2), temperature profiles that enable condensation, and the appearance of characteristic odor signatures or elevated microbial VOCs. German guidance documents on mold prevention, investigation, and evaluation highlight the necessity of combining building physics, hygiene, and measurement – an approach aligned with smart monitoring as an early-warning system rather than a single-parameter alarm (UBA, 2017). A similar logic applies to spoiled food or decomposition: what is measured are VOC patterns and secondary indicators; confirmation then requires targeted inspection or sampling.

Any sensor network worth deploying in a city or region must address comparability and quality assurance. Practical approaches include co-location with reference stations for calibration transfer, drift monitoring, plausibility checks (e.g., CO_2 should correlate with occupancy), and transparent uncertainty reporting. The air-pollution monitoring community has long emphasized the paradigm shift (Snyder et al., 2013) from sparse, highly accurate stations to hybrid systems that combine reference methods with dense indicative sensing (Morawska et al., 2020).

2.1.1 Cutaneous and Transcutaneous Measurements

A currently developing air related area of concern is transcutaneous skin measurement. Here, sensors monitor the skin's surface without penetrating it (without pricking). This allows for the detection of oxygen deprivation or subsequent, incipient damage caused by oxygen deprivation, particularly in endurance sports. Diseases such as kidney failure or impairment, as well as liver malfunction, can also be monitored using transcutaneous sensors. In our increasingly aging population, age-related illnesses and the effects of improper behavior on bodily functions are becoming ever more significant.

A promising approach for the precise recording and successive optimization of the health status of an urban population lies in the implementation of large-scale, public monitoring stations based on cutaneous and transcutaneous diagnostics. The term "cutaneous" (derived from the Latin "cutis" for skin) refers to methods that directly examine the condition of the epidermis. In contrast, transcutaneous measurement methods refer to those non-invasive procedures in which physiological parameters are detected within or below the skin layers without violating the anatomical integrity of the tissue through penetration. Detrimental cutaneous effects of air quality are reflected, for example, in deteriorating values as to inflammation, oxidative stress, skin barriers, or microvascular changes. Detrimental transcutaneous effects , i.e. via lungs or blood circulation, triggered by air polution are reflected by worsening oxygen or carbon dioxide related values. Various transcutaneous technologies are already used in current clinical practice and everyday life:

Infrared thermometry: The non-contact measurement of thermal radiation to determine core body temperature.

Pulse oximetry: The optical determination of arterial oxygen saturation (µ) using light absorption in a photometric method (often implemented as a “finger clip”).

In modern medical technology, there is a significant drive to replace conventional, invasive blood analyses with innovative transcutaneous measurement methods. While the laboratory analysis of blood samples is methodologically standardized and relatively easy to validate scientifically, every invasive sampling procedure – due to the risk of infection and tissue trauma – represents a burden for the subject. Transcutaneous methods, on the other hand, are characterized by a minimal risk profile. This lack of risk makes them ideal for use in public spaces to generate large-scale datasets. By correlating and algorithmically calculating this biometric data with other environmental factors, a valid picture of urban health can be generated.

2.1.2 The role of Raman spectroscopy – an experiment

Raman spectroscopy, an analytical technique used to identify and possibly quantify air pollutants, is a technologically highly potent method that has not yet been sufficiently used for public screening. This method, the fundamentals of which were already discussed in the relevant specialist literature for transcutaneous diagnostics at the beginning of the 21st century (around 2001), is based on the inelastic scattering of light on molecules.

While Raman spectroscopy in combination with light microscopy is already a gold standard in modern laboratory analysis, its transfer to the public sphere has so far proved complex. The primary challenge lies in the use of laser radiation as an excitation source. However, the associated safety concerns regarding eye protection and skin exposure have been largely resolved through advanced technical protective measures and the development of lower-class laser systems (with the same sensitivity). Raman spectroscopy is thus on the verge of being used as a precise, non-invasive tool for real-time biochemical analysis in urban areas.

Raman is a method for obtaining chemical information. This allows molecule-specific information to be obtained. Three very promising analytes are urea, lactate, and bicarbonate. These have specific peaks in the Raman spectrum and are present in the skin and blood. To evaluate the validity of transcutaneous Raman spectroscopy under controlled conditions, measurements were performed on skin phantoms in experimental series. The aim of these investigations was to simulate the determination of urea concentrations depending on different dermatological tissue properties.

The construction of these phantoms was based on a complex matrix of water and gelatin, which was supplemented by a specific scattering medium in order to realistically replicate the optical properties of human dermis (light scattering and absorption). Within the various phantoms, both the concentration of the analyte (urea) and the melanin content were systematically varied. The variation in melanin content is of crucial importance here in order to ensure the transferability of the method to different skin types (phenotypes), as pigmentation has a significant influence on the optical penetration depth and the signal-to-noise ratio.

2.1.3 Production of the phantoms

First, the solid ingredients are weighed on an analytical balance and mixed. After everything has been ground in a mortar until no titanium oxide lumps are visible, the mixture is transferred to a 50 ml beaker. The water is weighed into a 100 ml beaker and heated to approximately 60°C on a hot plate. Once the water has reached the desired temperature, add the solid ingredients while stirring with a flat spatula. Continue stirring until there are no more gelatin crumbs visible and the mixture has a homogeneous consistency. It had to be made sure that the mixture does not burn. The mixture is then poured into a silicone mold and sonicated in an ultrasonic bath for 10 minutes. After sonication, the mold can be removed from the ultrasonic bath. The molds are covered with aluminum foil to allow them to harden completely and stored in the refrigerator until measurement. The measuring head shown in figure 1 is designed as a compact optical setup for Raman spectroscopy with an excitation wavelength of 785 nm and integrates beam guidance, sample excitation, and detection in a coaxial geometry. The monoch 1 romatic excitation laser is first collimated and coupled into the optical path via a suitable beam shaping element. The laser radiation then hits a dichroic beam splitter, which is highly reflective for the excitation wavelength, while exhibiting high transmission for longer wavelengths. This deflects the laser beam toward the focusing optics and focuses it on the sample, generating a sufficiently high power density on the measurement sample to excite Raman scattering.

The scattered light emitted by the sample, consisting of elastically scattered Rayleigh component and inelastically scattered Raman component, is collected by the same focusing optics and returned along the original excitation path. Due to the spectral properties of the dichroic beam splitter, the returning scattered light with wavelengths greater than 785 nm is transmitted and coupled out of the excitation beam path.

To effectively suppress intense Rayleigh scattering, a spectral blocking filter is integrated into the detection path, which strongly attenuates the laser line (here: spectral line, not geometric line) and allows only the Raman-shifted wavelengths to pass through.

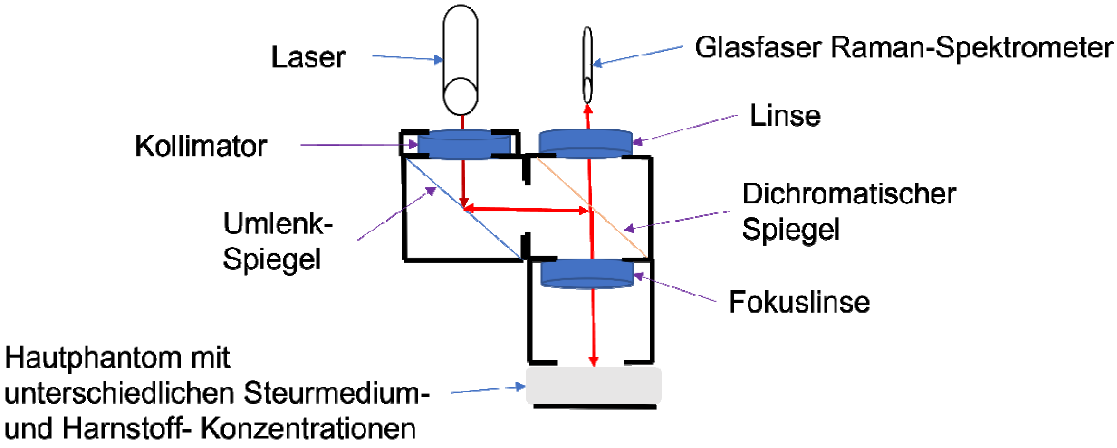

Figure 1: Illustration of Raman Spectroscopy Experiment

The filtered Raman light is then focused onto the entrance to an optical fiber via a further imaging optic. The geometric arrangement of the optical elements ensures that excitation and detection overlap spatially and that high collection and coupling efficiency is achieved. Overall, the design shown allows for stable, backscatter-based Raman measurement with good suppression of the background signal and is particularly suitable for compact, fiber-coupled measurement systems in the near-infrared excitation range.

Figure 2 clearly shows a linear relationship between the Raman peak at 1050 cm^{-1} and urea content. The two lines show the signals for two different skin types.

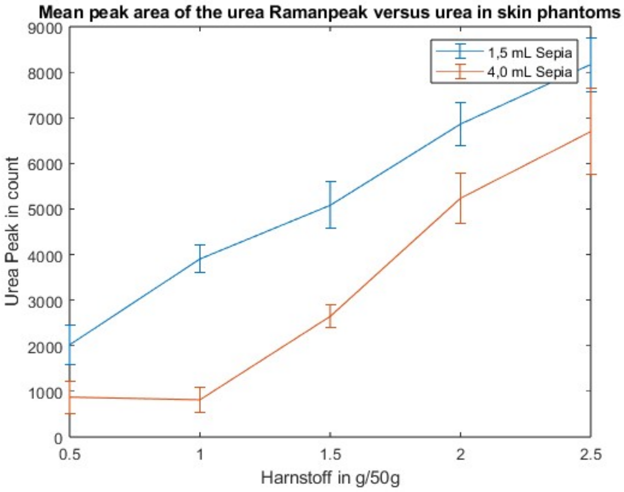

Figure 2: Ramanpeak versus Skin Phantoms

3 SMART-CITY AND SMART-HEALTH INTEGRATION AND CITIZENS' INCLUSION

Air-quality measurement data become infrastructure intelligence by being operationally integrated. "Smart Health Measurements" is not the act of producing numbers; it is the creation of feedback loops that connect environment, behavior, and interventions, at multiple scales.

At the city scale, dense PM and NO_2 data can support adaptive traffic management, evaluation of low-emission zones, and targeted enforcement or incentives. At the neighborhood scale, identifying exposure corridors (e.g., school routes, cycling networks) allows urban design to reduce chronic exposure without requiring citizens to change behavior. At the building scale, CO_2 and aerosol metrics can control ventilation and filtration in real time – demand-driven rather than schedule-driven – thereby achieving both health protection and energy efficiency. Latter city scenarios are illustrated by an experiment with the aforementioned ProxiCube® NX3 applied at five parallel outdoor measurement points of the city of Mannheim at a high data rate (Kaufmann et al., 2023).

Standards and professional guidelines in the German-speaking context explicitly target healthy indoor environments and the hygiene requirements of ventilation and air-conditioning systems (e.g., VDI 6022) and the broader European framework (e.g., DIN EN 16798-3 replacing the older EN 13779) (VDI, 2018; DIN, 2017).

Two operational principles are worth stating plainly. First, resolution beats averages for many health-relevant questions: a 24-hour mean PM2.5 value is important for epidemiology, but it does not tell a citizen or a facility manager whether an indoor space is currently drifting toward an avoidable risk regime. Second, interpretability beats raw sensor count: a smart city does not need "more sensors" as an end in itself. It needs measurement designs that map to actions – ventilate, filter, reroute, warn, investigate – and that provide auditable rationales.

This domain is also comparatively favorable regarding privacy and ethics. Environmental sensing can be designed as passive, non-invasive observation: the city and the building are measured, not the individual. Exposure assessment can then be personalized only if the citizen opts in, while public policy can act on aggregate patterns.

In the context of a concerted smart city stakeholder inclusion, a bridge must be created between science, economy and society. This is the mission of the TransforMA project, a joint endeavor of the Mannheim

University of Applied Sciences and the University of Mannheim (https://www.hs-mannheim.de/die-hochschule/forschung-und-transfer/transforma.html). Technologies from the fields of AI, sensor technology, and robotics are presented, designed to make otherwise complex topics more accessible. The project is structured into five areas of action: “Communication”, “Cooperation”, “Technology”, “Impact and Responsibility” and “Cooperation and Evaluation”. The sub-project "Communication" aims to establish channels, for example in the area of social media, and thereby promote the transparent exchange of information between science and society. In the area of cooperation, networks with a wide variety of institutions are being established and expanded to foster stronger collaboration within the region. Additionally, events are being organized within this framework, inviting people from diverse backgrounds to engage in dialogue. The technology component of TranforMA involves the Technical University and the University jointly presenting various technologies to the public in the context of demonstrators. Technologies from the fields of AI, sensor technology, and robotics will be showcased, making otherwise complex topics more accessible.

4 CONCLUSION

Particulate matter, aerosols, gases, and odors form a technically coherent measurement domain that connects directly to smart-city operation and smart-health outcomes. The required technologies already exist – from EN-standardized reference methods to integrated devices such as the ProxiCube® NX3 or increasingly transcutaneuous measurements. The order of the day is to deploy, validate, interpret and communicate measurement data as part of an intelligent control loop, information and communication system. In terms of the impact on humans, the first possibilities for contactless, continuous monitoring are emerging through image analysis methods additionally evaluated by AI and novel methods of spectroscopy. Even if there is still a long way to go, with the required detection limit not yet being achieved or cross-sensitivities heavily influencing or falsely altering the results, the technological path has been laid out and will lead to commercial and affordable devices in the coming years. Finally, awareness building and inclusion of citizens is recommended to come to the fore.

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