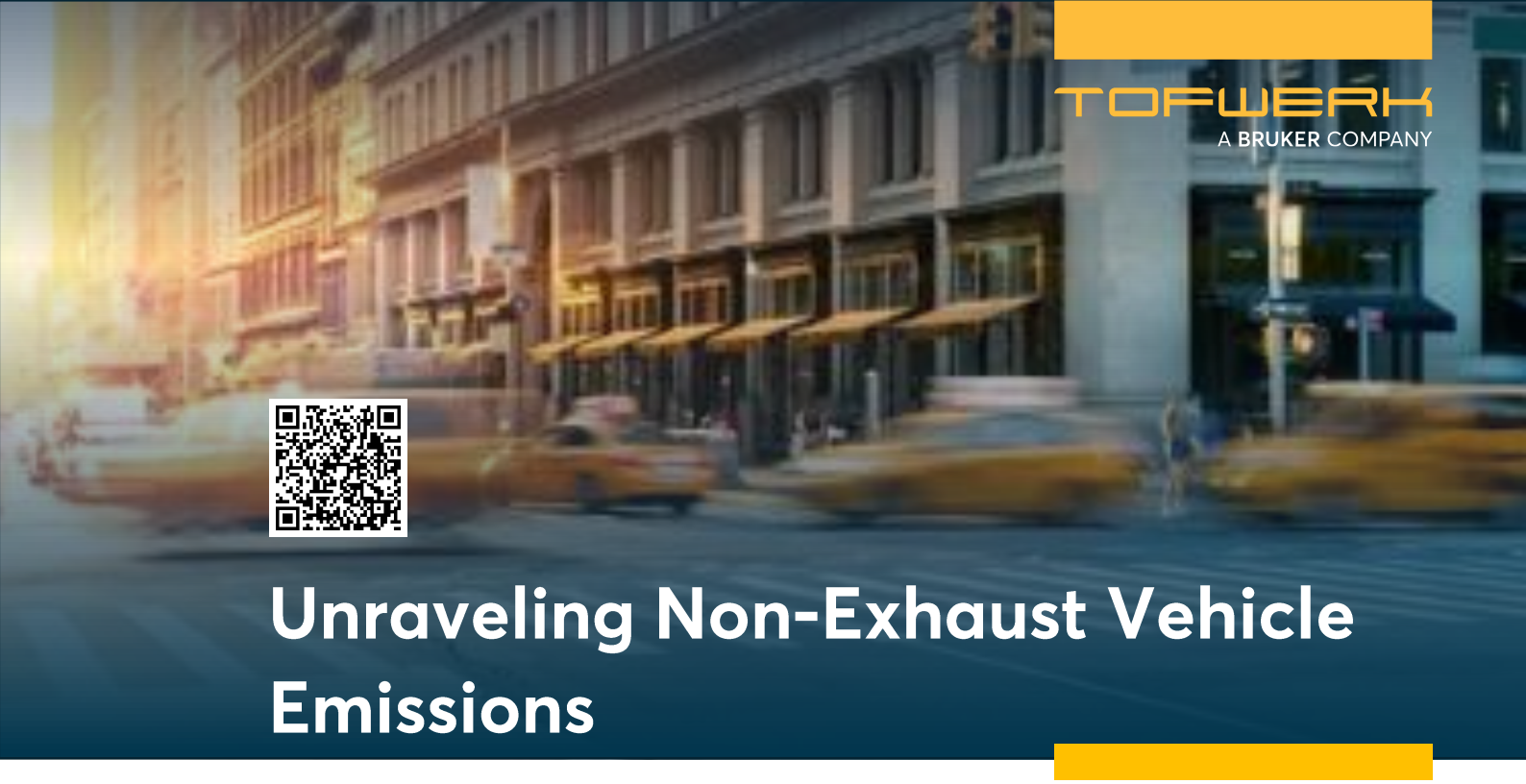

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Unraveling Non-Exhaust Vehicle Emissions

Lorenz Gfeller[1], Alexander Gndlach-Graham[1], Jay Slowik[2], André Prevot[2] and Martin Tanner[1]
[1] TOFWERK, Thun, Switzerland
[2] Paul Scherrer Institute, Villigen, Switzerland

High Time Resolution Mobile Aerosol Monitoring

Road traffic generates diverse aerosols, spanning from gaseous species to fine particulate matter, including polymeric, and metallic particles. Beyond combustion byproducts from fuel and lubricants, motorized transport also produces non-exhaust vehicle emissions. These arise from mechanical abrasion of brakes and tires, road surface erosion and resuspension of accumulated dust. Each source releases metals with distinct chemical signatures: road wear is characterized by crustal elements (Si, Al, Mg, Ca) [1], tire wear is dominated by Zn, a key vulcanization additive [2]; and brake wear exhibits a complex metallic profile typically containing Ba, Sb, Cr, Mn, Fe, Cu and Sn [3, 4]. Non-exhaust vehicle emissions are therefore a significant and underexplored source of urban particulate pollution.

These metals are released predominantly as airborne fine particulate matter ranging from 0.01 to 10 µm which is able to enter the respiratory tract [5]. Upon penetration into lung tissue, these fine metal containing particles can interact with metal-binding proteins, inducing oxidative stress [6]. This renders non-exhaust vehicle emissions an important public health concern, particularly in densely populated urban environments. Recognizing these health implications, the European Union introduced the EURO7 standard (Regulation 2024/1257). EURO7 marks a paradigm shift as the first framework to explicitly regulate vehicles. Non-exhaust vehicle emissions, enforcing limits on metallic and particulate emissions from brake- and tire wear. This regulatory evolution raises the

urgent need for appropriate, high-time-resolution methods to assess the metal content in airborne fine particles in real-world environments.

Common methods for measuring airborne metals rely on trapping particles on filters over periods of typically several hours [7]. However, such long averaging times fail to capture time dependent concentrations of non-exhaust vehicle emissions in the field. Like this, rapid fluctuations in traffic conditions at key emission sources, such as intersections, steep slopes, and tunnels, which vary by time of day, weather, and other environmental conditions cannot be documented.

Here, we report the use of the microwave inductively coupled plasma time-of-flight mass spectrometer (mipTOF) for real-time mobile quantification of trace airborne metals in Bern, Switzerland. The instrument was integrated into the MOSQUITA mobile laboratory (Paul Scherrer Institute, Switzerland) and prepared for continuous sampling while driving through downtown Bern, Switzerland. Our measurements captured distinct, localized emission plumes of metals associated with non-exhaust vehicle emissions, particularly those from brake wear. Notably, these plumes peaked within a sloped motorway access tunnel, where specific metals (e.g. Fe) concentrations reached up to 1000 times background levels.

Instrument Description and Experimental Setup

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The mipTOF is first commercial high-power nitrogen plasma driven time-of-flight mass spectrometer. It consists of a microwave induced plasma source (MICAP , Radom Corp., USA) coupled to TOFWERKs mass spectrometer featuring ion optics to guide the ion beam and remove neutral species, a notch filter to selectively remove ions of defined mass-to-charge ratio (m/Q) and an orthogonally accelerating time-of-flight (TOF) mass analyzer to acquire full mass spectra at high time resolution. The mipTOF's plasma is sustained with nitrogen (N_2), operates with power ranging from 800 to 1500 W, and reaches a gas temperature of >5000 K. These conditions facilitate vaporization, atomization and ionization of aerosols directly injected into the plasma.

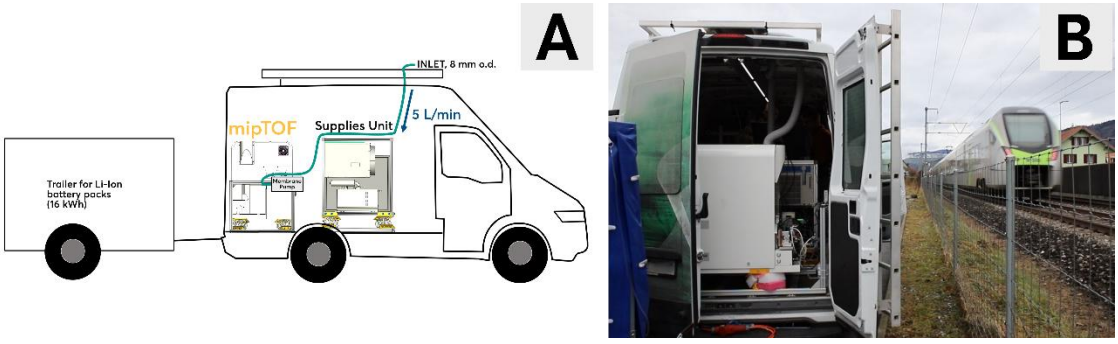

Figure 1. (A) mipTOF setup in MOSQUITA Car. Air sampled at 5 L/min via 8 mm polymer tubing, routed directly or through HEPA filter. (B) Field photo of the equipped vehicle near train tracks.

Unlike any conventional ICP-MS, the mipTOF can analyze aerosol particles directly without the need for external gas-exchange or dilution devices [8].

Ambient air is drawn into the MICAP through a concentric pneumatic nebulizer (ARG 07 US6, Glass Expansion, Australia) operated as a Venturi pump. Before measurements, the sampling gas flow was calibrated with a DryCal Defender 520 (MeasLabs, USA). Ambient air is introduced into the central channel of the N_2 plasma at a flow rate of ~120 cm^3/min.

During analysis, average mass spectra are produced every 5 ms from 167 individual TOF extractions. Capturing complete spectra enables accurate peak identification and deconvolution of isobaric species. Integrated mass peaks across the full elemental mass-to-charge range allow following analyte time trends in real time. Elemental concentrations of the particulate matter in the measured aerosol were calculated based on liquid multi-element standards, standard Ag-nanoparticles and a gas blank from filtered air. The required transport efficiency parameter was determined daily using the 'particle-size method' [9, 10]. Instrument parameters are detailed in Table 1.

Table 1. Instrument parameters.

Gas Sampling Rate	120 cm^3/min
MICAP Power	1.45 kW
Plasma Sampling Depth	3 mm
Spectral Generation Rate	200 Hz

For the mipTOF installation in the MOSQUITA vehicle (Paul Scherrer Institute, Switzerland), the main and supply units were mounted on vibration-dampening wire-loop isolators (Fig. 1), with base frames secured directly to the vehicle floor. Power was supplied by two 8 kWh Lithium-ion battery packs (EcoPowerTrolley, EcoVolta, Switzerland) housed in a trailer, enabling ~3 hours of operation per charge.

The air-sampling inlet was positioned above the front window. Air entered via an 8 mm OD polymer tubing (PEN 8x1.25, Festo) at 5 L/min. Sampled air was routed either directly to the mipTOF or through a HEPA filter (Low Pressure Drop HEPA, TSI, USA) using shut-off valves. A subsample of air was then introduced into the instrument at 120 cm^3/min. Polymer tubing and non-full-bore valves likely limited large particle transport efficiency, though this cutoff was not characterized.

Results

The mipTOF analyzes airborne metals with high time resolution. This provides spatial and temporal detail currently unavailable with alternative technologies. Figures 2 and 3 demonstrate the value of this high-resolution data, enabling users to pinpoint emission sources or capture fast transient signals that are typically lost due to wider time-interval integration.

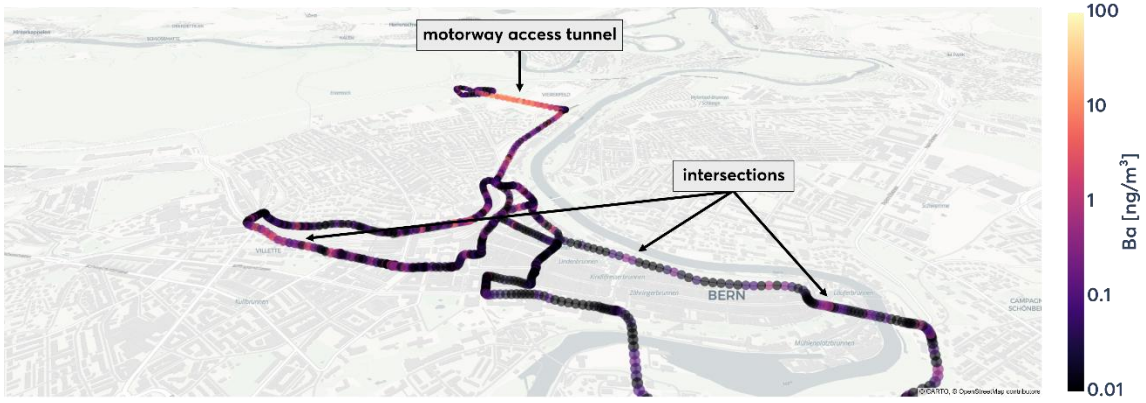

Figure 2. High-resolution mobile trace of airborne barium (Ba) concentrations across Bern, Switzerland. Data points represent 3-second integrated averages. Elevated concentrations are highly localized, occurring primarily at major intersections and within the Neufeld motorway access tunnel (marked on map).

Figure 2 presents the quantified time trace of airborne Ba concentrations recorded during a MOSQUITA vehicle ride through the city of Bern. The data points represent average concentrations calculated over 3-second intervals, providing a high-resolution view of aerosol dynamics. During this measurement campaign, the vehicle traversed several intersections and passed through the Neufeld motorway access tunnel located in northern Bern.

The data reveals that elevated Ba concentrations were highly localized, occurring almost exclusively at these specific intersections and within the tunnel. These observations clearly reflect the spatial variability of non-exhaust vehicle emissions in real-world traffic conditions. To investigate the chemical composition of these hotspots further, Figure 3 displays time traces for a broader suite of elements during the tunnel transect. This detailed view documents how vehicle emissions are concentrated in the confined tunnel space and allow a distinct clustering of these metals, including Ba, Sb, Cr, Mn, Fe, Cu, and Sn. These specific elements strongly indicate that the observed vehicle emissions are dominated by non-exhaust emissions, commonly associated with brake wear [3, 4]. Overall, the measured concentrations allow to quantify the acute exposure of car passengers, road workers, and pedestrians to potentially health affecting metals in absolute mass per volume (ng/m^3). Further, the mipTOF allows to assess metal content per particle information in (fg/particle). Another new parameter for exposure studies which can be linked e.g. to particle size data from complementary methods.

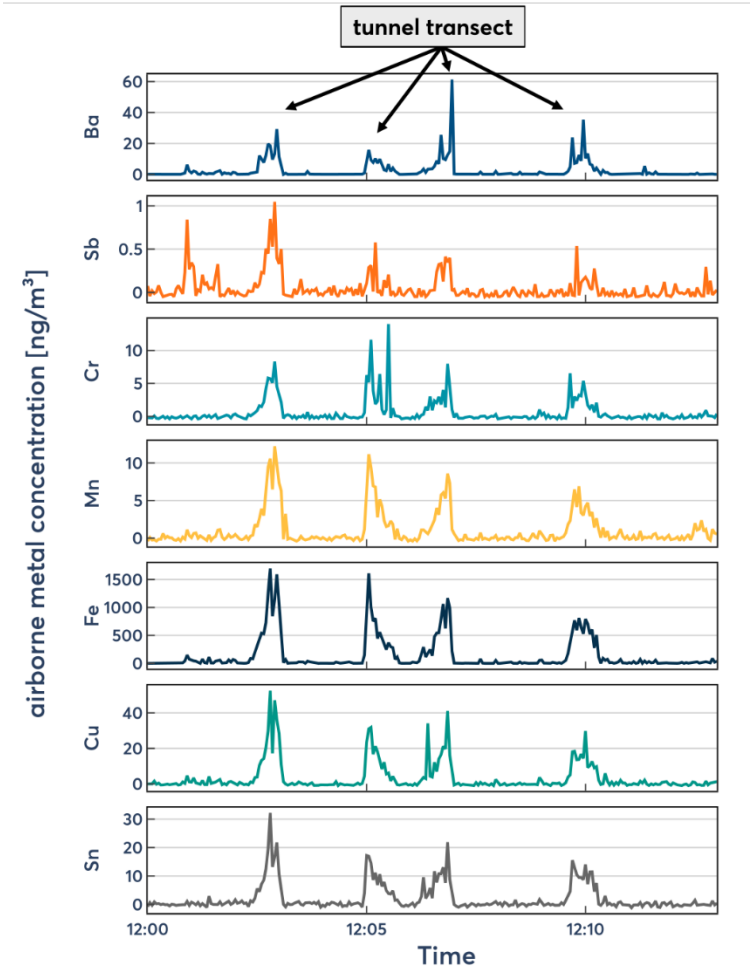

Figure 3. Time traces of airborne metal concentrations across the Neufeld tunnel transect, showing simultaneous spikes in Ba, Sb, Cr, Mn, Fe, Cu, and Sn. The co-occurrence of these specific elements within the tunnel points to non-exhaust emissions driven by brake wear abrasion as the source of the aerosol plume.

Conclusion

The mipTOF is a field-deployable, mobile mass spectrometer specifically engineered for direct, rapid elemental analysis of ambient air pollutants. This instrument delivers exceptional sensitivity coupled with high temporal resolution, enabling precise characterization of airborne trace metals. We demonstrate mipTOF's unique capabilities through continuous, real-time measurements of vehicle emissions collected during a mobile laboratory vehicle ride-through campaign across an urban area. Such real-time metal aerosol detection empowers researchers to rapidly identify and screen transient, highly localized emission sources with spatial detail. In this specific study, we successfully pinpointed distinct non-exhaust vehicle emissions arising from everyday traffic patterns. Such measurements facilitate improved understanding of acute exposure risks and the dynamic behavior of non-exhaust vehicle emissions and other metal emissions in urban environments.

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