$PM_{2.5}$ instrumental uncertainties aboard the Google Street View cars in London

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1 Overview

As part of the Breathe London project, two instrumented Google Street View cars performed mobile measurements of $PM_{2.5}$ between September 2018 and October 2019. These instruments record data at 1 Hz sampling rate, which can be beneficial for high-spatial-resolution mapping. However, at this high frequency sampling rate, instrument precision must be characterized. In this report, we summarize assessments of instrument uncertainty in the Breathe London mobile PM measurements performed using the Palas Fidas 100 optical $PM_{2.5}$ sensor.

Table 1: Summary of minimum detection limit (MDL) and precision characterized in this report for the Palas Fidas 100. MDL is defined as 3× standard deviation of $PM_{2.5}$ measured while sampling particle-filtered air. Precision is expressed in two forms, defined based on whether $PM_{2.5}$ is higher or lower than a nominal 10 μg m^{-3} cut-off. For a continuously variable uncertainty, please refer to Table 2.

Data period	**MDL [μg m^{-3}]**	**Uncertainty**
Before 14 April 2019	0	0.5 μg m^{-3} or 6%, whichever greater
After 14 April 2019	0	2.2 μg m^{-3} or 17%, whichever greater

2 Methods

Two Google cars (vehicle IDs 27522 and 27533, herein referred to as car #1 and #2, respectively) measured $PM_{2.5}$ using the "Palas FIDAS-100" size-resolved optical particle counter. $PM_{2.5}$ measurements were also made with a separate instrument (Thermo-Fisher pDR 100) on both cars, and uncertainties associated with this instrument will be summarized in a separate document. When not driving, the cars continued to make measurements for extended periods while parked in the National Physical Laboratory (NPL) parking lot in the Teddington suburb of London. During these periods, the Google cars were collocated 20 m from an identical $PM_{2.5}$ instrument operated by NPL. The Fidas in both Google cars was operated at 1 Hz time resolution, while the one in NPL was operated at 2 minute resolution. Further, all measurements aboard the Google cars were recorded with a 10-second smoothing filter until this filter was disabled on April 14, 2019.

To characterize instrument precision, we applied the following algorithm:

1. Break the entire 13-month time-series of NPL's $PM_{2.5}$ measurements into 12 minute segments (12 minute duration chosen arbitrarily). Assuming the NPL Fidas was running continuously during all segments, each 12 minute segment should contain 6 data points, each 2 minutes apart.

2. Calculate standard deviation within each 12 minute segment. Identify segments as either "stable" ($\sigma < 0.1\mu$g m^{-3}) or "unstable" ($\sigma > 0.1\mu$g m^{-3}). The threshold of 0.1 μg m^{-3} is arbitrary, and results in 2% of the 12 minute segments being classified as stable (Figure 1).

3. Download 1 Hz GSV PM$_{2.5}$ data for all 12-minute stable periods identified as "stable". Assuming the GSV data were recorded continuously, all segments should have 720 data points (12 min × 60 seconds/minute). Compute standard deviation of 1 Hz GSV data for each stable segment.

4. These standard deviations of 1 Hz data can be used as instrument precision around a stable reading. They can either be reported in absolute units, or normalized to the NPL PM$_{2.5}$ concentration to report uncertainty as a % of concentration. It is worth noting that the instrument precision calculated this way is subject to a slight overestimation, given that variations in ambient PM$_{2.5}$, albeit $< 0.1\mu$g m^{-3}, would also get lumped with instrument precision.

5. Lastly, if stable segments are identified over a wide range of absolute PM$_{2.5}$ concentrations, any possible linearity (i.e., concentration dependence) in instrument precision can be characterized.

3 Results

3.1 Identification of stable segments

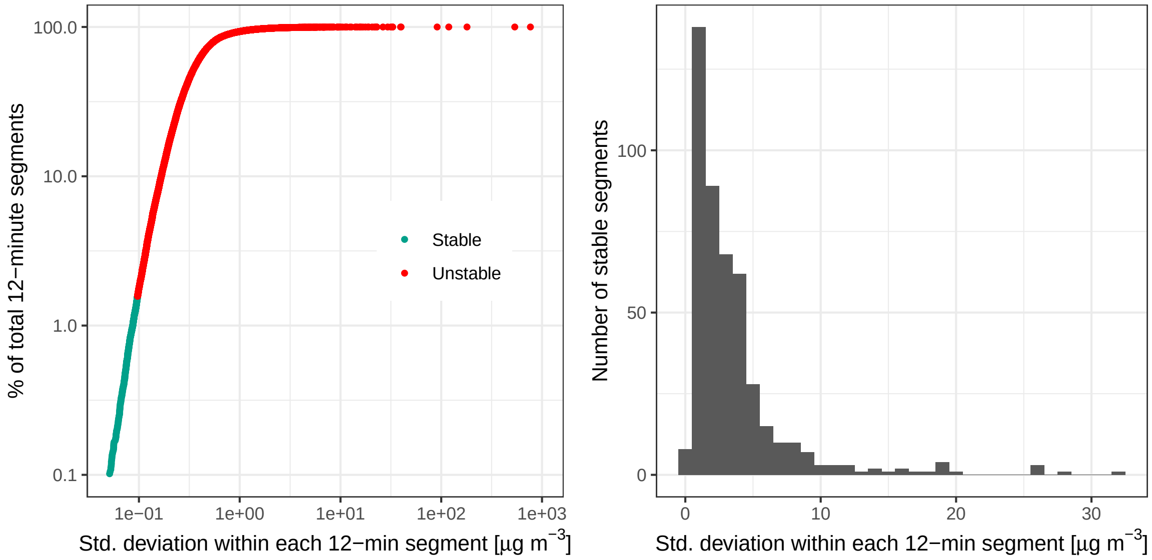

Figure 1: *left:* cumulative distribution of all 12-min segments of NPL Fidas PM$_{2.5}$ time series. Segments are classified into "stable" and "unstable" using an arbitrary $\sigma < 0.1\mu$g m^{-3}. *right:* distribution of mean PM$_{2.5}$ concentrations during stable segments.

Figure 1 shows all 12-min segments of NPL Fidas PM$_{2.5}$ data. There are a total of 29494 segments. The non-zero standard deviations of PM$_{2.5}$ measurements within each segment range from 0.08 μg m^{-3} (1$^{\text{st}}$ percentile) to 2.91 μg m^{-3} (99.9$^{\text{th}}$ percentile), with outliers as high as 700 μg m^{-3}. Arranged in increasing order of standard deviations, the lowest 2 percentile segments (about 600) are categorized as "stable", and all the rest are categorized as "unstable". Stable segments have standard deviations as high as 0.1 μg m^{-3}.

Mean PM$_{2.5}$ concentrations during these stable segments are low (< 10 μg m^{-3}), with very few segments having concentrations between 10 and 30 μg m^{-3}. It is not surprising that most stable segments occur during low PM$_{2.5}$ conditions (e.g., night-time and other typical low-emission periods).

3.2 GSV Fidas precision during stable segments

Figure 2 shows standard deviations of all 1 Hz PM$_{2.5}$ data recorded by the GSV Fidas (both cars) during stable segments identified in Figure 1. A time series of these standard deviations are shown in Figure 4. On both cars' Fidas instruments, a 10-second rolling average was applied during measurements before April 14, 2019. As evident, this rolling average results in dampening of instrument precision.

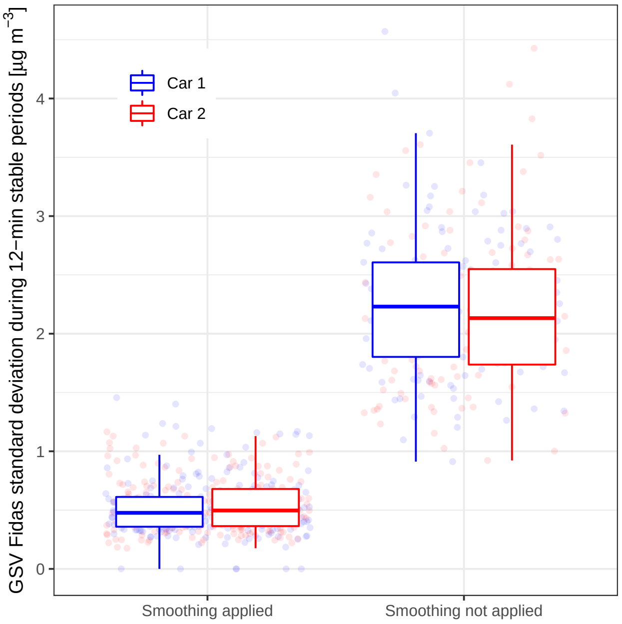

Figure 2: GSV Fidas standard deviations during stable segments identified in Figure 1. Data are grouped by vehicles, and by application of a 10-second smoothing filter applied during data collection. The filter was enabled on all days before April 14, 2019, at which point it was disabled permanently.

Figure 3 shows the relative GSV Fidas precision, or relative standard deviation (= absolute standard deviation normalized to mean PM$_{2.5}$ concentration, i.e., σ/μ), versus PM$_{2.5}$ concentrations during various stable segments, with/without 10-second rolling average (smoothing) applied during data collection. In all cases, the precision is higher during lower PM$_{2.5}$ concentrations (< 10 μg m^{-3}), and stabilizes with concentrations $>$ 10 μg m^{-3}. When the 10-second rolling average was applied (upper panels in Figure 3), the precision stabilizes at 6%. Without the filter, the precision stabilizes at 17%.

While the stable precision values of 6% (smoothing applied) and 17% (smoothing not applied) may be appropriate for PM$_{2.5}$ > 10 μg m^{-3}, histograms of on-road PM$_{2.5}$

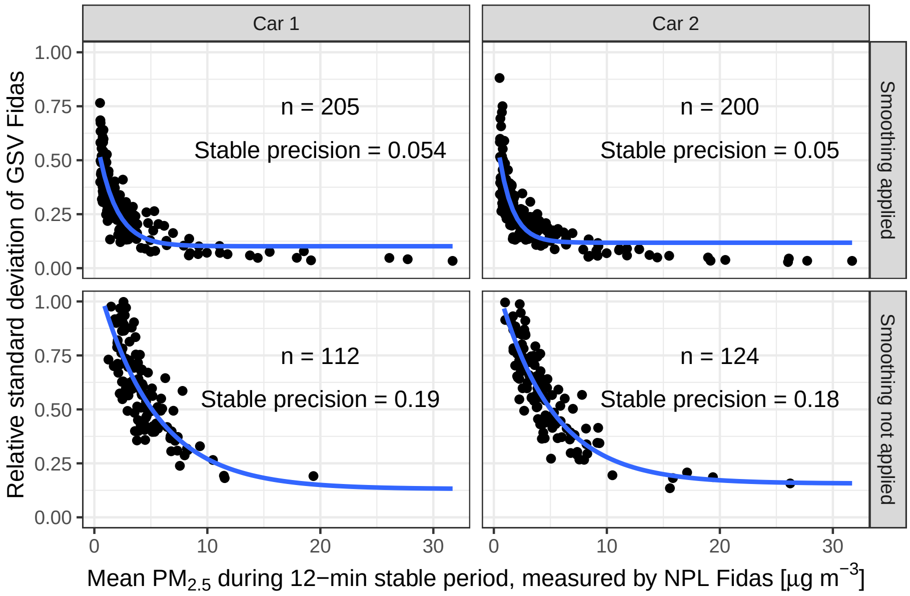

Figure 3: Decay of GSV Fidas precision with increasing absolute $PM_{2.5}$ concentrations, for both cars, with and without application of 10-second smoothing during data collection. *Note:* the blue curves are exponential fits, discussed further in Table 2. The stable precision estimated for each panel is the average relative standard deviation of all data points > 10 μg m^{-3}.

measurements indicate that a majority of the values are < 10 μg m^{-3} (see Figure 5). Hence, to avoid underestimating the instrumental precision in this range, one may use an absolute precision of 0.5 μg m^{-3} (before 14 April 2019), and 2.2 μg m^{-3} (after April 14 2019). These are average absolute standard deviations when $PM_{2.5}$ is below 10 μg m^{-3} (see Figure 6). One may also apply a variable, concentration-dependent instrumental precision function. This dependence is parameterized in Table 2.

Table 2: Dependence of instrumental precision on $PM_{2.5}$ concentration: $n(c) = \alpha + \beta \cdot \exp(c/\gamma)$, where $n(c)$ is the concentration-dependent instrumental precision (i.e., one relative sigma; unitless), c is the $PM_{2.5}$ concentration, and α, β, and γ are empirically-determined parameters. This exponential model is derived based on the assumption that the instrumental precision is highly sensitive to $PM_{2.5}$ when $PM_{2.5}$ concentrations are low (this sensitivity is indicated by β), but decays with increasing $PM_{2.5}$ (rate of decay indicated by γ).

Data period	α	β	γ
Before 14 April 2019	0.11	0.59	-1.38
After 14 April 2019	0.12	0.87	-5.51

The spec sheet for this instrument[1] does not mention a minimum detection limit (MDL), but reports a $PM_{2.5}$ measurement range of 0 to 1500 μg m^{-3}. Routine checks in London show that the instrument indeed records absolute 0 μg m^{-3} while measuring particle-filtered air (see Figure 7). Hence, using an MDL of 0 μg m^{-3} for the Fidas is appropriate.

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[1] `https://www.ecotech.com/wp-content/uploads/2015/03/Product-Brochure-Fidas-100.pdf`

Supplemental information

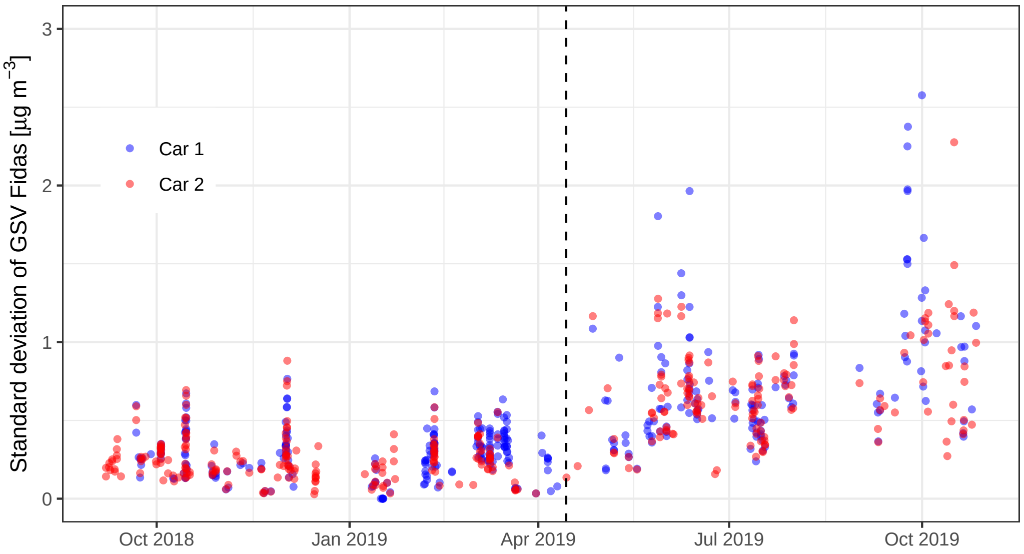

Figure 4: Time series of GSV Fidas standard deviations during stable segments identified in Figure 1. The vertical dashed line indicates when a 10-second smoothing was disabled during data collection.

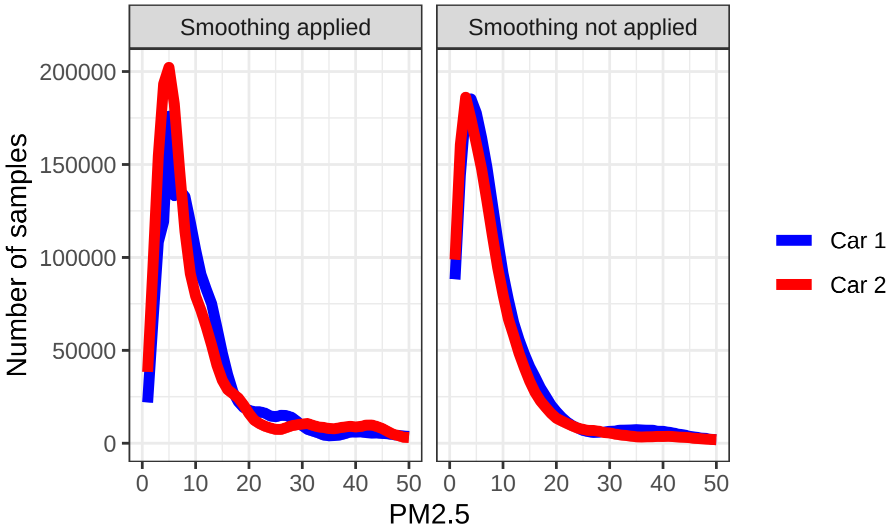

Figure 5: Histograms of on-road $PM_{2.5}$ values measured by the GSV Fidas. The x-axis is in units of μg m^{-3}. These histograms are prepared using $PM_{2.5}$ data corrected for sampling losses (characterized in separate document). Given that the correction factors were $\sim$ 1.1 for the two cars, if one were to prepare these histograms for uncorrected data, the distributions would essentially shift towards the left by about 10% along the x-axis.

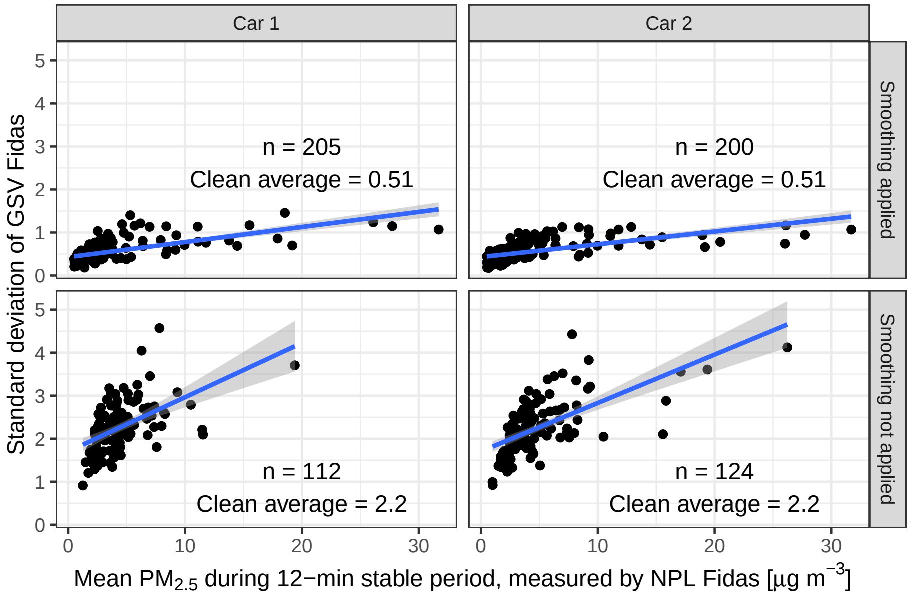

Figure 6: Increase in GSV Fidas precision with increasing absolute $PM_{2.5}$ concentrations, for both cars, with and without application of 10-second smoothing during data collection. The "clean average" for each panel is the average standard deviation of all data points < 10 μg m^{-3}.

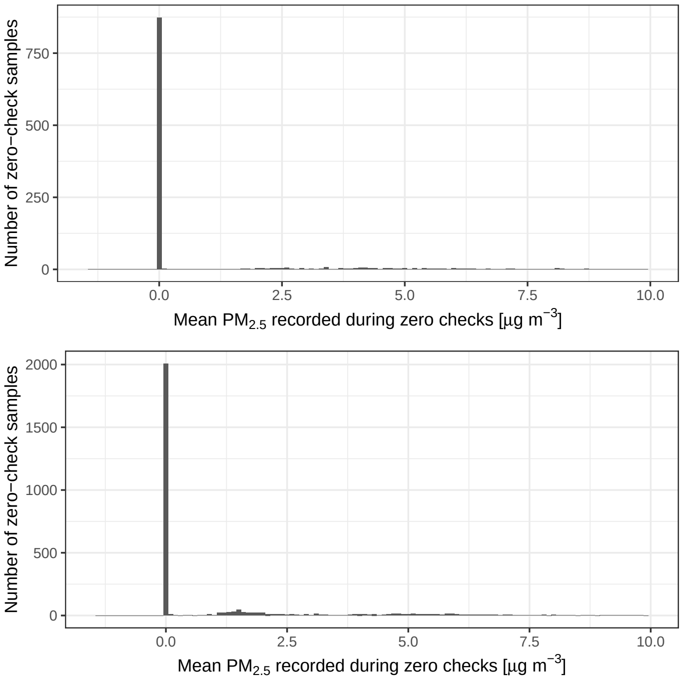

Figure 7: Histogram of GSV Fidas data while measuring particle-filtered air during routine maintenance checks. Upper panel is for Car # 1 (27522) and lower panel is for Car # 2 (27533).