Posting type	Informational
Subject	Universal calibration constants for flow rate calculation
Sites	All, following installation of Version 4 controllers
Period	2018 onward
Recommendation	N/A
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Supporting Information

The IMPROVE network has used site- and module-specific calibration constants to calculate flow rates since inception. These constants were determined in the field at the time of calibration against a flow rate transfer standard (Dwyer Magnahelic® in conjunction with a machined orifice). UC Davis maintains several transfer standards, and they are calibrated against a primary flow rate standard maintained at UC Davis, such as a Bios Definer 220®. Sampler flow rates were calibrated by comparing the pressure measurements recorded on the sampling module to the flow rates determined from the transfer standard, and new calibration constants were determined at every maintenance visit, as well as on an as-needed basis by site operators in the event of sampler malfunctions.

The flow rate calibration transfer standards are required to calibrate within 2% of a primary standard that is recalibrated regularly by the manufacturer. When checking multiple transfer standards or comparing multiple primary standards, it is possible to see a variation of up to 4%. Implementation of universal flow rate constants eliminates making adjustments to each site calibration during maintenance that may be caused by calibration device variability.

Flow rates for the $PM_{2.5}$ modules are based on pressure drop across the cyclone (ΔP_{cyc}), and flow rates for the PM_{10} modules are based on pressure upstream of the orifice (P_{ori}). The formulas for the flow rates are based on theory, and the constants in the equations encompass factors including the physical dimensions of sampler components where the flow rate is measured. The dimensions of the cyclone across which the $PM_{2.5}$ flow measurement is taken are consistent throughout the network. In 2015-2016, precision ruby orifices were added to the PM_{10} modules to improve the flow rate measurement and provide consistent flow geometry throughout the network. Given that the physical systems are the same at all sampling sites, universal flow rate equations are possible if the pressures are measured reliably and consistently throughout the network.

In the past, the flow rate calibration constants needed to be both site- and module-specific because the pressure transducers were not calibrated to measure pressure in absolute units. The old sampler electronics were analog (subject to noise), were not universally translatable to standard pressure units, were manually trimmed using potentiometers at calibration, and varied between units and with temperature changes.

Improvements in electronics now allow the use of universal constants for the entire network. The Version 4 electronics are digital, and the pressure transducers provide absolute measures of pressure in inches of H_2O for the cyclone transducer and pounds per square inch absolute (psia) for the orifice transducer. Quality control testing prior to deployment shows that the transducers are very consistent, with a full scale best fit straight line accuracy of 0.25% and a maximum total error band of ±2% full scale. Therefore, we implemented universal flow rate constants throughout the network.

$PM_{2.5}$ Flow Calculation

In 2018 and 2019, 128 IMPROVE sites equipped with V4 electronics were calibrated against the flow rate transfer standard per the normal 4-point calibration procedure, ranging from 23 lpm down to approximately 16 lpm. All the calibration data points were combined into a single data set, from which a universal slope and intercept were calculated (Figure 1).

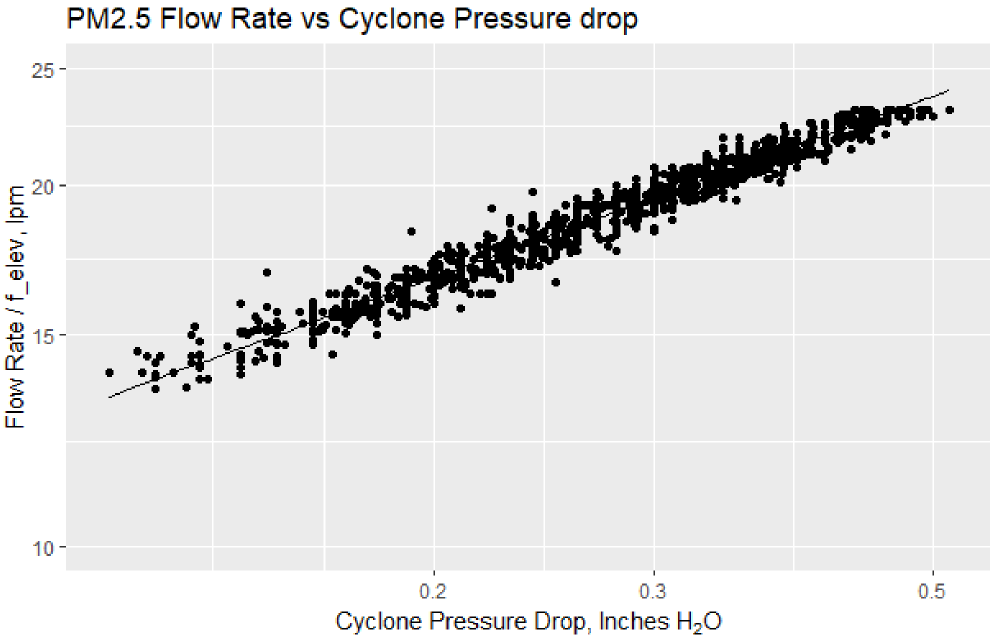

Figure 1. Flow rate versus cyclone pressure drop measurements for $PM_{2.5}$ modules at 128 IMPROVE sites.

Data from these calibrations were used to determine universal intercept and slope (A and B) constants. Calibration flow rate data from each site was normalized for barometric pressure, reducing the $PM_{2.5}$ flow equation to

$$Log_{10}(Flow) = A + B * Log_{10}(\Delta P_{Cyc})$$

where A = intercept constant = 1.489

B = slope constant = 0.3797

ΔP_{Cyc} = Pressure drop across the cyclone (inches H_2O), measured by the cyclone transducer.

The resulting constants for the $PM_{2.5}$ module are shown in the variable definitions above, and the correlation coefficient (r^2) is 0.964. Comparing the flow calculated using universal constants to the field calibration device yields an error standard deviation of 0.43 lpm, or 2.4%. The distribution of errors is shown below (Figure 2).

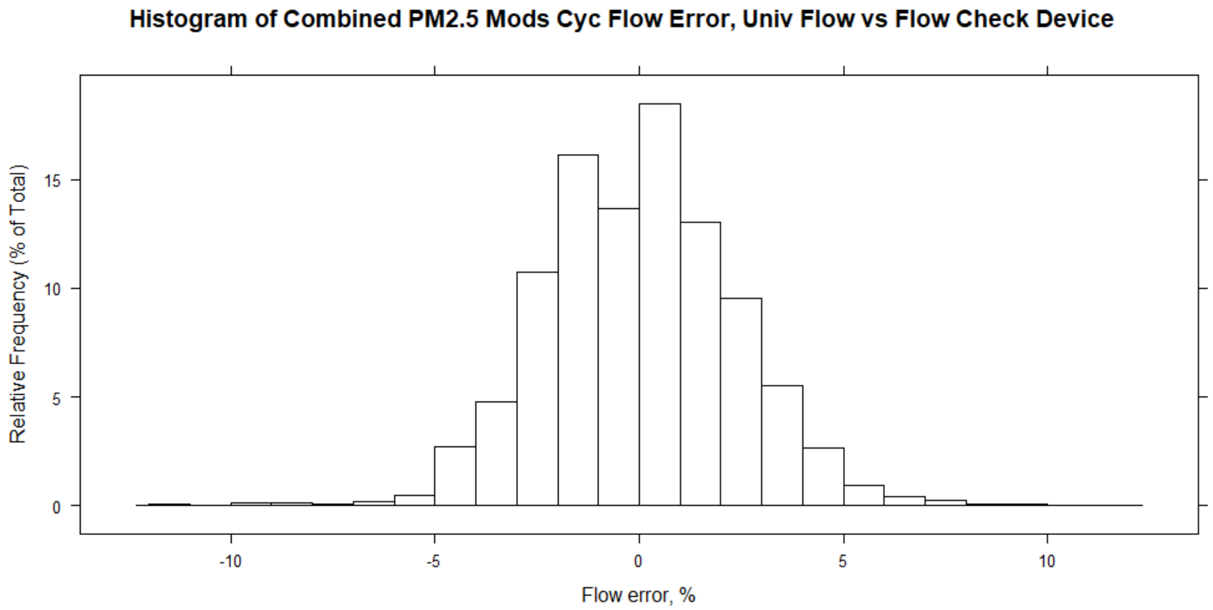

Figure 2. Error histogram for $PM_{2.5}$ module flow rates measured by the calibration device versus calculated using universal constants

Only a few data points exceed 5% error; most exceeding 5% were found at low flow rate positions (below 20 lpm) – none were at the full-flow 23 lpm calibration position and three were the second highest calibration position, approximately 21 lpm. These high differences may result from operator error, damage to the transfer standard, or variable atmospheric conditions (e.g., high winds), which are all motivating factors for switching to universal constants. In lower flow positions (approximately 17 and 19 lpm), a larger percent error is seen per lpm of difference in flow, and small errors in pressure reading result in relatively larger errors in flow calculation.

Local ambient temperature and pressure correction factors must be applied to calculate volumetric flow during sampling. This calculation remains the same as before, with the flow at local conditions ($F_{2.5,vol}$) calculated as follows:

$$F_{2.5,vol} = 10^{A} * \Delta P_{Cyc}{}^{B} * \sqrt{\frac{P_0}{P}} \sqrt{\frac{T + 273.15}{T_0}}$$

where P_0 = reference pressure = 14.7 psia

P = ambient pressure (psia)

T = ambient temperature (°C)

T_0 = reference temperature = $293.15K$

PM_{10} Flow Calculation

Similarly, field calibrations from the 128 sites visited during the 2018 and 2019 maintenance seasons were used to determine universal flow rate calibration constants for the PM_{10} modules (Figure 3).

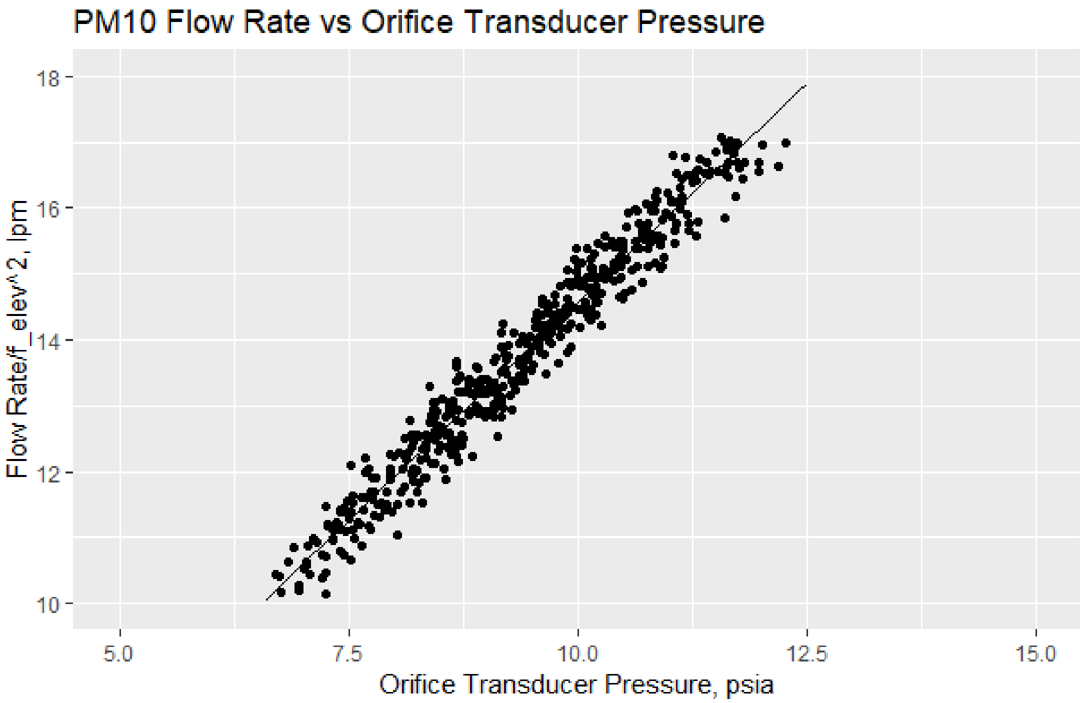

Figure 3. PM_{10} Pressure-Flow Relationship

After normalizing for barometric pressure, the PM_{10} module flow equation reduces to

$$Flow = C + D * P_{Ori}.$$

where C = intercept constant = 1.320

D = slope constant = 1.325.

The resulting constants for the PM_{10} modules are shown in the variable definitions above, and the correlation coefficient (r^2) is 0.964. Comparing the flow calculated using universal constants to the field calibration device yields an error standard deviation of 0.36 lpm, or 2.5%. The distribution of errors is shown below (Figure 4).

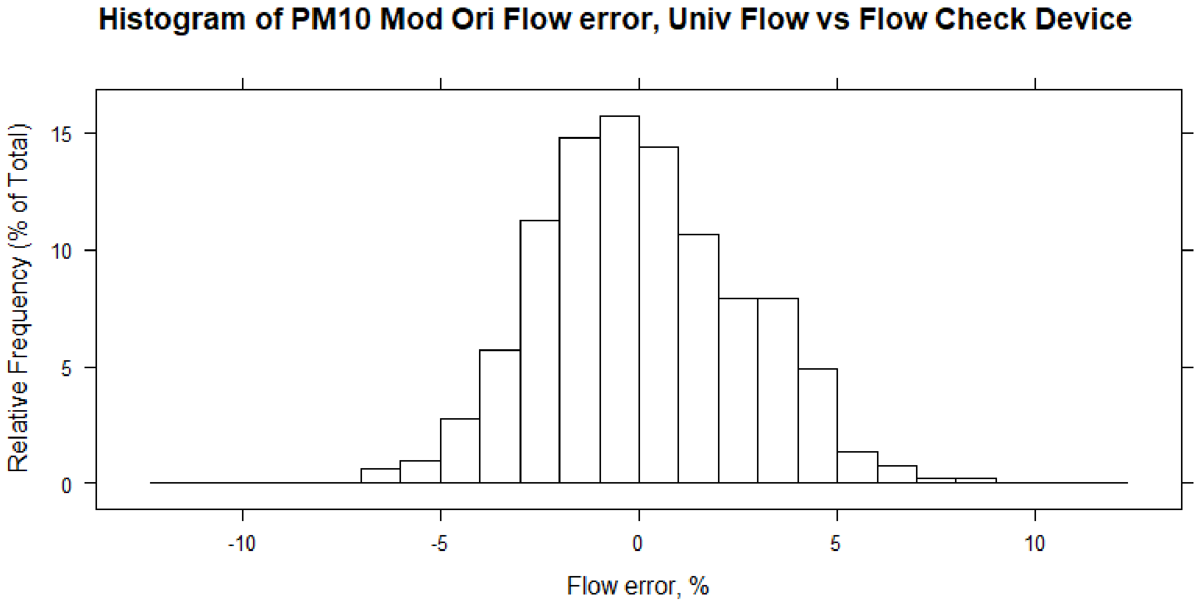

Figure 4. Error histogram for PM_{10} module flow rates measured by the calibration device versus calculated using universal constants

As with $PM_{2.5}$ flow rate measurement, temperature and pressure corrections must be applied to calculate PM_{10} module volumetric flow ($F_{10,vol}$) during sampling:

$$F_{10,Vol} = (C + D * P_{Ori}) * \frac{P_0}{P}\sqrt{\frac{T + 273.15}{T_0}}$$

It is important to note that the pressure correction factor is different between the $PM_{2.5}$ and PM_{10} module flow rate equations. Previous versions of the orifice flow equation incorrectly used the same pressure correction factor, $\sqrt{\frac{P_0}{P}}$, as the cyclone-based $PM_{2.5}$ equation. This error did not ultimately result in miscalculation of PM_{10} flow rates when using site-specific constants, as the difference was compensated by the slope constant calculated for each module. However, correction of this factor is necessary for the application of universal constants.

The universal constants described above are intended to characterize the entire network, provided that standard equipment is used at each site. Flow constants will not change with each site maintenance visit – rather, equipment will be checked during maintenance to ensure that flow calculation is within spec. If it is out of spec, the maintenance team will seek to determine the cause of the discrepancy and make repairs as necessary.