Final Report for

# Field Validation of Ventilation Troubleshooting Methods

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| $\rho$ | = | density |
| A | = | cross-sectional area normal to a duct |
| $A_{ROC}$ | = | area under the receiver-operator characteristic curve |
| D | = | duct diameter |
| Fen | = | coefficient reconciling pressures upstream of a junction fitting |
| ID | = | identification number assigned to ducts |
| idIVM | = | parameter computed for the idIVM method |
| FPR | = | false positive rate |
| LP | = | dissipated power |
| LogSP | = | parameter computed for the LogSP method |
| $P_{in,i}$ | = | power at upstream boundary "i" |
| Q | = | rate of airflow |
| SP | = | mean static pressure at a cross-section |
| $SPH_{one}$ | = | parameter computed for the $SPH_{one}$ method |
| $SPH_{two}$ | = | parameter computed for the $SPH_{two}$ method |
| $SPrat_{br}$ | = | parameter computed for the $SPrat_{br}$ method |
| $SPrat_{main}$ | = | parameter computed for the $SPrat_{main}$ method |
| TP | = | mean total pressure at a cross-section |
| V | = | mean velocity at a cross-section |
| VP | = | mean velocity pressure |
| $X_{duct}$ | = | parameter computed for the $X_{duct}$ method |

# Subscripts

subscripts to denote a time

| | | |
|---|---|---|
| c | = | "comparison" value (i.e., from current round of data) |
| o | = | "original" or baseline value (i.e., from previous round of data) |

subscripts to denote a point or cross-section

| | | |
|---|---|---|
| end | = | cross-section just upstream of the end of a duct |
| exit | = | cross-section at the exit of a volume |
| H | = | cross-section just downstream of a hood |
| in, i | = | cross-section at inlet "i" |
| main | = | cross-section in a duct downstream of the most downstream junction fitting |

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# SIGNIFICANT FINDINGS

In nearly every test, the performance of the proposed (Guffey, 1994) pressure ratio methods was substantially superior to the currently used methods, which involve direct comparisons of static pressures.

The most comprehensive test parameter used to evaluate the efficacy of the methods was the area ($A_{ROC}$) under a receiver operating characteristic curve, which is a plot of sensitivity versus false positive rate for a broad range of thresholds of action. Values of $A_{ROC}$ varied with the study conditions and with the method of troubleshooting. In summary, the results shows that:

1) For the great majority of conditions and systems tested, the values of $A_{ROC}$ were substantially higher for the proposed pressure ratio methods than for the traditional direct pressure comparison methods.

2) All methods performed substantially better under laboratory conditions than for field conditions.

3) Values of $A_{ROC}$ varied with the ventilation system, but the relative ranking of methods was consistent across systems.

4) For the laboratory studies pooled together as a single data set, the $X_{duct}$ and $SPrat_{br}$ methods were dramatically superior to the pressure comparison methods when the lower weight conditions were included. For one laboratory study (Colvin), all methods achieved extremely good results. All methods performed very well ($A_{ROC}$>0.95) in the laboratory studies if only the most important alterations were considered.

5) For the field studies no method could achieve near perfect sensitivity without incurring at least moderately high false positive rates when all weights of obstructions were included. Likewise, no method could achieve near perfect selectivity without sacrificing sensitivity. However, the pressure ratio methods generally produced substantially higher values of $A_{ROC}$ than the direct pressure comparison methods. Removing the lower weighted obstructions brought very high $A_{ROC}$ values (>0.90) for $X_{duct}$ and $SPrat_{br}$. The idIVM and $SPH_{one}$ methods performed extremely poorly for all conditions ($A_{ROC}$<0.4) — even when only the most profound obstructions were included. The $SPH_{two}$ method fared much better than idIVM and $SPH_{one}$ but not as well as $X_{duct}$ and $SPrat_{br}$.

6) Optimal thresholds for each troubleshooting method were determined for false positive rates of 10% and 20%. The combination of sensitivity and selectivity for the pressure ratio methods was superior to the combinations produced by the direct comparison methods.

7) The computation method and loss coefficients in *Industrial Ventilation* produced predicted values that were substantially different from observed values at the same airflows for two active industrial exhaust ventilation systems. Hence, since even an idealized form of the method performed very poorly under field conditions, the original method could be expected to perform poorly, indeed.

8) The mean velocity from a single Pitot traverse rarely deviated by more than 3% from the mean of two traverses if the pipe factor for the first traverse was less than unity. This provides a guideline to when a second perpendicular traverse should be taken.

9) Techniques were developed during the study that would greatly reduced the time necessary to monitor any system.

# USEFULNESS OF FINDINGS

The results of this study provide guidance to industrial hygienists and ventilation professionals as to what troubleshooting methodologies are most effective. Equipped with newer troubleshooting methods that produce much better sensitivity and far fewer false positives than they experienced with older methods, practitioners may be encouraged to monitor systems more closely and intervene before hood performance has deteriorated to levels that allow unacceptable exposures to workers.

The study provides substantial validation for new methods, and it provides substantial evidence that current methods are inadequate for general use. Using the proposed methods and suggested thresholds, ventilation practitioners should find that troubleshooting ventilation systems is far more reliable than when using the commonly used hood static pressure method or the commissioning method of *Industrial Ventilation* (1997). With fewer substantial obstructions overlooked, desired system airflows to hoods should be easier to maintain, making hoods more reliable in their protection of workers. With far fewer false positive indications, practitioners should find that far less of their time is wasted in fruitless searches for alterations that are actually elsewhere in the system. This should encourage them to do it frequently enough to reduce the long time lags that generally occur before a problem is discovered and fixed.

The P.I. has argued that no troubleshooting method will help if practitioners are unwilling to monitor systems (Guffey, 1994). In the P.I.'s experience, ventilation systems used to protect workers from high exposures outside of military bases and "high tech" are rarely monitored — other than occasional spot readings in response to sustained complaints. Although the specific aims of the study did not mention improving measurement methods, the study has produced a striking contribution to practice as a by-product of this research. In response to dire need in accomplishing this study, the P.I. developed techniques, procedures, and data acquisition software that dramatically reduce the time and effort required to collect, analyze, and interpret pressure and flow measurements for purposes of monitoring and troubleshooting. As an example: A system that routinely required 2 experienced individuals 10 hours to measure now requires an equally experienced individual less than 40 minutes to measure *alone* .

That time reduction is with standard Pitot tubes and is not due to learning of the system or to improving measurement stations. It does require a portable computer and a digital manometer than can send data to the computer. Furthermore, using the software, analysis and interpretation are done real-time as measurements are taken, eliminating the need for later data analysis and allowing on-the-spot checks of findings. The P.I. will submit a description of these techniques and procedures for inclusion in the Testing *and Measurement* chapter of *Industrial Ventilation* and in a submission for peer-reviewed publication.

Over time, one could reasonably hope that such dramatically reduced costs in time and effort would encourage far more frequent monitoring (and troubleshooting) than most systems now receive. The guidelines specifying when to take a second Pitot traverse also should improve velocity measurement accuracy to the degree that it encourages taking a second traverse when one is needed, and it should reduce wasted effort when it discourages an unnecessary second traverse.

# ABSTRACT

The purpose of this study was to determine the efficacy of current methods and methods proposed by the P.I. to "troubleshoot" industrial exhaust ventilation systems using measured pressures and flows. Exhaust ventilation systems for contaminant control often experience obstructions and other deleterious alterations to individual ducts. Those alterations can reduce airflow to hoods, reducing their reliability in controlling exposures to hazardous airborne contaminant. Since alterations often are hidden from sight inside opaque ducts, it is necessary to find them using indirect means, primarily by interpreting changes to observed airflows and pressures.

The most commonly used method ("$SPH_{one}$") assumes an obstruction has occurred if the magnitude of the hood static pressures ($SP_H$) has fallen. The second method ("$SPH_{two}$") was an obvious variation of the one-sided $SPH_{two}$ method wherein an obstruction was expected with a sufficiently large *increase or decrease* in $SP_H$. The "IVM" method compares the design value of $SP_H$ to the observed value. If $SP_H$ has fallen and the next downstream pressure ($SP_{end}$) has increased, it assumes that an obstruction has occurred. However, early tests quickly demonstrated that this method was unworkable for a long-installed system. For that reason, an idealized version ("idIVM") was employed in this study in which the "before" observed values were substituted for design pressures. The proposed methods each employ the ratios of pressures in an effort to normalize changes in pressures due to events external to the duct being tested. The "$X_{duct}$" method employs the ratio of the dissipated energy rate to the kinetic energy rate (which can be computed from measured pressures), the "$SPrat_{br}$" method employs the ratio of $SP_H$ to $SP_{end}$ for each branch duct, and the "$SPrat_{main}$" method employs the ratio of $SP_H$ to a common reference pressure in a main, SPref.

Six working systems in contaminant producing processes were challenged with combinations of serendipitous and deliberately inserted obstructions. For each round of measurements on a given system, hood static pressures ($SP_H$) and velocity pressures were measured for each branch, and the static pressure a few duct diameters upstream of a duct's terminus ($SP_{end}$) was measured for each branch and submain duct. All measurements were taken with standard Pitot tubes and a calibrated digital manometer. Custom written data acquisition software captured each measurement value from the manometer. Each troubleshooting method's value was computed from the appropriate measured values and compared to a range of thresholds for the test cases. If the method's value exceeded the threshold and an obstruction had been in that duct, the method was considered to be true positive for that duct, round of measurements, and threshold. False negatives, true negatives, and false positive also were assigned. The method with the highest value of $A_{ROC}$ was judged to be the most effective. In addition to the field data, data collected for other reasons in four ventilation laboratory studies was analyzed in the same manner.

From all of the cases of a particular data set, the sensitivity and false positive rate for that threshold and method were computed. The sensitivity was plotted against the false positive rate for each threshold for each method, and the area under the resulting "receiver operating characteristic curve" ($A_{ROC}$) was computed for each method. In addition, the thresholds that would achieve 10% and 20% false positive rates were determined for each method and the accompanying sensitivities compared.

The results showed that for the laboratory conditions $X_{duct}$ and $SPrat_{br}$ had nearly perfect detection of obstructions with nearly zero false positives ($A_{ROC}$=1). The values of $A_{ROC}$

for idIVM, $SPH_{one}$, and $SPH_{two}$ were substantially inferior. At the specific thresholds that would achieve either 10% or 20% false positive rates, the sensitivities for the traditional methods were substantially inferior to the those achieved by the proposed methods.

All methods performed substantially less well under field conditions than in the laboratory systems, probably due to the laboratories' excellent measurement conditions and to fewer misclassifications because of the higher degree of certainty of conditions in the laboratory. However, the results from the field studies showed even greater margins of superiority for the proposed methods in both $A_{ROC}$ values and in sensitivities achieved at 10% and 20% false positive rates. The idIVM and $SPH_{one}$ methods performed dismally in all tests, failing to detect 40% of profound obstructions and doing much worse on lesser obstructions. The SPHref_br, SPHref_main, and $X_{duct}$ methods were roughly equal. They each detected at least 90% of the "substantial" and "profound" obstructions but less than half of the very light and light obstructions. The $SPH_{two}$ method was inferior to the pressure ratio methods but far superior to the $SPH_{one}$ and idIVM methods.

At the threshold for $X_{duct}$ selected to achieve a 10% false positive rate, airflows would shift by 4% to 7% under most conditions of practical interest. The SPHref_br and SPHref_main methods should perform similarly at their recommended thresholds.

As one part of the study, observed equivalent loss coefficients for two woodworking systems were compared to values predicted using *Industrial Ventilation* loss coefficients and calculation method. The results were dismayingly poor. Only 30% of predictions had errors of less than 25%. Those results should be treated with caution since only two very similar systems were tested. Finally, analysis of data from nearly a thousand sets of perpendicular Pitot traverses collected for this study demonstrated that a second Pitot traverse seldom typically was needed to improve accuracy only if the ratio of the mean velocity to the centerline velocity of the first traverse exceeded unity.

The study provides substantial validation for new methods, and it provides substantial evidence that current methods are inadequate for general use. Using the proposed methods and suggested thresholds, ventilation practitioners should find that troubleshooting ventilation systems is more reliable than when traditional methods. With fewer substantial obstructions overlooked, desired system airflows to hoods should be easier to maintain, making hoods more reliable in their protection of workers. With fewer false positive indications, practitioners should find that far less of their time is wasted in fruitless searches for alterations that are actually elsewhere in the system. This should encourage them to monitor and troubleshoot systems frequently enough to reduce the long time lags that generally occur before a problem is discovered and fixed.

# BODY

## Background

Ventilation systems serve a vital purpose — they protect workers from potentially hazardous exposures. Like any other complex system, ventilation systems need to be monitored, evaluated, and maintained to ensure proper functioning.

*Current practice*

All too frequently ventilation troubleshooting consists of overly simplistic and qualitative approaches. Waiting for worker complaints or until visible emissions are noted at the hood identifies problems only after exposures have already become severe and already impacted worker health. Worse, if the escaping contaminants are poorly detected by the human senses, exposures could continue indefinitely. Relying on regular visual inspection of the system to identify any changes can permit many system alterations to go unnoticed because they occur within the opaque duct or in areas of poor accessibility.

Many texts discuss troubleshooting ventilation systems, but rely on visual inspection or give little guidance in interpreting changes in performance measures. *Handbook of Ventilation for Contaminant Control* (McDermott, 1995), for example, has one paragraph that addresses troubleshooting:

> Diagnose the problem by thoroughly inspecting the system and by taking pressure and velocity readings .... The visual inspection will reveal closed dampers, open inspection ports, damaged hoods, and ducts, and other common reasons for poor performance. The static pressure measurement at hoods, elbows, and on both sides of air cleaners will show the contribution of each to the overall pressure drop in the system. Static pressure measurements on both sides of the fan show how much pressure the fan is adding. If you know that the system ever operated correctly, try to compare current pressure readings with previous data. If no earlier data are available, try estimating where the pressure drop readings should be from the design tables in Chapter 8 or in the ACGIH *Industrial Ventilation Manual*. For new systems, pressure readings will help detect installation mistakes or blockages due to construction debris.

Notice that no guidance is given as to what percent change in what measures constitutes a substantive change. Without guidance, the reader may choose a low threshold for action, and as a result, waste long periods of time looking in locations where no alterations exist.

What is needed are effective screening tools, like medical screening tests, which indicate the "truth" with relatively little investment. Like medical screening tests, a good troubleshooting method should produce few false negatives. However, it is also important to avoid false positives. A medical screening test which identifies all of those that are diseased is not worthwhile if its false positives results in dangerous and unnecessary surgery. Ventilation troubleshooting is similar. Taking ductwork apart to remove obstructions is often time consuming and expensive. Fruitless searches can consume time, effort, money, and the credibility of the practitioners. A good troubleshooting method identifies where changes likely have occurred, but also reliably rejects cases where no change has occurred. For this study the analysis of troubleshooting methods draws on the use of receiver operating characteristic (ROC) curves developed for the analysis of medical screening tests (Baturin, 1972) to compare the overall effectiveness of different troubleshooting methods.

*Description of troubleshooting methods used in the study*

This section describes the troubleshooting methods or "screening tools" that are addressed in this study. The troubleshooting methods tested can be described mathematically as shown in Table I (Guffey, 1994). Stated briefly, the "$SPH_{one}$" method is a simple comparison of hood static pressures made under a limiting assumption: the hood static pressure ($SP_H$) will always fall in magnitude if a branch duct is obstructed (*Industrial Ventilation*, 1997). The "$SPH_{two}$" also compares $SP_H$ values, but with the assumption of falling values omitted as fallacious. The "idIVM" is an idealized version of the commissioning method described in *Industrial Ventilation*, which uses values of $SP_H$ and $SP_{end}$ predicted from published loss coefficients as the baseline condition. The method was idealized by the simple expedient of pretending that the baseline values actually observed were predicted perfectly from loss coefficients, thus excluding all possible errors due to incorrect or inappropriate loss coefficients.

The remaining three methods are all based on ratios of pressures. The $X_{duct}$ method compares so-called X-values, which for the simple case of branches can be reduced to ratios of total pressure at the end of the duct to the mean velocity pressure at the end of the duct. The $SPrat_{br}$ method compares ratios of $SP_H$ to $SP_{end}$ for branches. The $SPrat_{main}$ method normalizes $SP_H$ by a common reference pressure in a main duct.

In the P.I.'s experience, the "$SPH_{one}$" method is the only approach commonly employed in troubleshooting as of this writing. The "$SPH_{one}$" and "$SPH_{two}$" methods require the least effort since they use only values of $SP_H$. The "$SPrat_{main}$" method requires values of $SP_H$ plus a single static pressure reading in one main duct. The idIVM method require measurements of $SP_H$ plus measurements of $SP_{end}$ for any branch where $SP_H$ fell in value. Next in required information is the $SPrat_{br}$ method, which requires measurements of $SP_H$ and $SP_{end}$ for every branch duct tested. The X-value method requires determination of $SP_{end}$ and average velocity for each duct tested. The latter is substantially more time-consuming than measuring any single value of static pressure.

Each method is discussed in more detail below.

Table I: Computation of Method Values

| Method | Computation of value* |
|---|---|
| $SPH_{one}$ | $(SP_{HC} < SP_{Ho}) * \left(\frac{abs(SP_{HC} - SP_{Ho})}{SP_{Ho}}\right) * 100$ ... (1) |
| $SPH_{two}$ | $\left(\frac{abs(SP_{HC} - SP_{Ho})}{SP_{Ho}}\right) * 100$ ... (2) |
| idIVM | $(SP_{HC} < SP_{Ho}) * (SP_{endC} \geq SP_{endo}) * \left(\frac{abs(SP_{HC} - SP_{Ho})}{SP_{Ho}}\right) * 100$ ... (3) |
| $X_{duct}$ | $\left(\frac{abs(X_{ductc} - X_{ducto})}{X_{ducto}}\right) * 100$ ... (4) |
| $SPrat_{br}$ | $\left(\frac{abs\left(\frac{SP_{HC}}{SP_{endC}} - \frac{SP_{Ho}}{SP_{endo}}\right)}{\frac{SP_{Ho}}{SP_{endo}}}\right) * 100$ ... (5) |
| $SPrat_{main}$ | $\left(\frac{abs\left(\frac{SP_{HC}}{SPref_C} - \frac{SP_{Ho}}{SPref_o}\right)}{\frac{SP_{Ho}}{SPref_o}}\right) * 100$ ... (6) |
| LogSP | $abs\left(Log\left(\frac{\frac{SP_{Hc}}{SP_{endc}}}{\frac{SP_{Ho}}{SP_{end0}}}\right)\right) * 300$ ... (7) |

*Where o= previous round and C= this round
$SP_H$ = hood static pressure
$SP_{end}$ = pressure at end of the duct
$SP_{ref}$ = common reference pressure measured in a main duct

Hood Static Pressure Method — $SPH_{one}$

The most commonly used troubleshooting methodology in the field and the most frequently described in the ventilation texts is what is called here the "one-sided SPH" or the "$SPH_{one}$" hood static pressure method (Alden, 1982; Burton, 1982). Here, the hood static pressure is compared to a previous value. If the hood static pressure has decreased, an obstruction is suspected in the branch or a downstream submain. An increase in $SP_H$ is ignored; hence, the "one-sided" appellation.

There are several shortcomings of this method. First, there are no published and tested guidelines as to what constitutes a significant change in hood static pressure. Second, any change in air resistance at any point in the ventilation system will cause shifts in airflow throughout the system and change the hood static pressures. Thus, hood static pressure values will change even when there are no alterations downstream in the branch due to such things as changes in fan rotation rates and alterations in other ducts. Hood static pressures are sensitive to shifts in airflow, but are very non-specific, leading to a large number of false positives if the Threshold(%) is low. Third, this method may be able to identify only obstructions that occur downstream of the hood measurement location. It is common, however, for obstructions to occur upstream of the $SP_H$ location. As mentioned previously, it is frequently necessary to locate the $SP_H$ location well downstream of the hood opening because of access and measurement quality issues. This frequently leaves an inaccessible length of duct where obstructions can occur.

Industrial Ventilation Method

Probably the most widely published troubleshooting methodology is that described in *Industrial Ventilation* (ACGIH, 1994). It calls for comparisons of observed static pressures to design values. A summary of this procedure follows (changed slightly from original for brevity):

1. Check fan performance against plan, include flow rate, fan static pressure, fan size, inlet and outlet diameters against plan, and the fan speed and direction against design.
2. If fan Inlet static pressure is greater (more negative) than calculated in the design, proceed to Step 3. If fan outlet static pressure is greater (more positive) than design, proceed to Step 7.
3. Measure hood static pressure on each hood and check against design. If correct, go to Step 9; otherwise, continue. Check size and design of hoods and slots against plan, and examine each hood for obstructions [emphasis added].
4. After all hood construction errors and obstructions have been corrected, if hood static pressures are correct, return to Step 1; if too low, proceed to Step 5.
5. Isolate within the duct where the obstruction is located as follows. Measure junction static pressure of the duct and compare with design calculations. If too high at the junction, proceed upstream in the branch until static pressures are too low and isolate the obstruction [emphasis added]. In an area where the loss exceeds design, check the following: angle of junction entries, radii of elbow curvature, duct diameters, and duct obstructions. [Reworded based on personal communication with the section's main author (William Cleary, 1996)]
6. After correcting all construction details which deviate from specifications, return to Step 1.
7. Measure pressure differential across air cleaning device and check against manufacturer's data. If loss is excessive, make necessary corrections and return to Step 1. If loss is less than anticipated, proceed. Check ducts, elbows and entries as in Step 5, and check system discharge type and dimensions against plans.

8. If errors are found, correct and return to Step 1. If no errors can be detected, recheck design against plan, recalculate, and return to Step 1 with new expected design parameters.
9. Measure control velocities at all hoods where possible. If control is inadequate, redesign or modify hood.
10. The above process should be repeated until all defects are corrected and hood static pressures and control velocities are in reasonable agreement with design. The actual hood static pressures should then be recorded for use in periodic system checks.
11. For all of the above measurements, agreement is acceptable if within ±10%.

The IVM procedures cover the fan and air cleaner as well as the duct system. The focus of this study is on steps 1 through 5 as these address the identification of obstructions in the ventilation system branches.

The IVM method assumes that the ventilation system can be accurately characterized using published loss coefficients. However, this is problematic for older systems with dents, leaks, wear, or settling. There is no published data in the literature to support the assumption that loss coefficients correctly model newly installed systems, much less much older systems. There is some evidence that published loss coefficients are unreliable even with relatively new systems. Hoppe (1995) showed that the observed sum of loss coefficients for 87% of the branches of a three year old system deviated from predicted values by more than ±16%. This is not surprising when one considers the variability in the recommended loss coefficients with different sources. For example, up until 1995 IVM recommended using a loss coefficient of 0.27 while ASHRAE Fundamentals (1995) recommended 0.19 for a common elbow geometry (radius/diameter = 2, 5 section). IVM later adopted the ASHRAE values, but ASHRAE soon embraced still new values.

In addition, hoods used for a variety of tools do not have published loss coefficients. Without loss coefficients for the elements in a branch, it is not possible to accurately calculate expected losses, static pressures, and flows for the entire system. The IVM method acknowledges this and even states, "It is intended as an initial verification of the design computations and contractor's construction in new systems [commissioning], but it may be used also for existing systems when design calculations are available or can be recomputed." (ACGIH, 1995). In addition it is common that design data, which is used as the basis for comparison, is frequently lost within a few years of installation.

Step 3 requires that if one hood static pressure differs from expected, then all the hoods need to be inspected to ensure that there are no obstructions and that the hoods are installed as designed. This process has the potential for being excessively time-consuming, especially when inspection involves more than a quick visual check with a flashlight. The hoods of some tools require the hood static pressure measurement to be made well downstream of the hood opening, often with several bends in the duct which prevent inspection by flashlight. An ideal troubleshooting method would not require that all hoods be cleaned out before measurements are made on the ducts, but instead would indicate which of the hoods have undergone some type of change that warrants a visual inspection.

Furthermore, the IVM method provides little guidance as to what changes should be considered significant. It states that, "For all … measurements, agreement is acceptable within ±10%." However, if the fan rotation rate is set 8% high, then, following the fan laws, total pressure at the fan is going to be 16% high and the total flow rate will be 8% high. In this case, strict interpretation of the IVM method would require all hoods and branches to be inspected for obstructions.

Like the one-sided $SP_H$ method, the IVM method identifies only alterations that produce a *decrease* in hood static pressure. Ignoring increased $SP_H$ may not be prudent.

### Idealized IVM Method — idIVM

The efficacy of the IVM method depends on both the accuracy of published loss coefficients and the specific use of pressures as indicators. Conceivably, some day practitioners could have perfect knowledge of loss coefficients. However, in analyzing the IVM method, it should not be penalized because current loss coefficients are less than perfectly accurate or, for some components, do not exist. Therefore, we will use the ideal case where the loss coefficients exactly predict the behavior of the original system in every particular way. In other words the predicted static pressure equals the measured static pressure in a clean system. This modification focuses the analysis on errors due to the method itself. The idealized IVM method is as follows:

1. Measure hood and end static pressures three duct diameters downstream of the hood and three duct diameters upstream of junction, respectively, if feasible. Otherwise, take the best location possible. Record these values as baseline values for later comparison.
2. In future monitoring, if $SP_H$ has fallen from its baseline by some threshold percent, SPH-Threshold(%), and $SP_{end}$ has increased by any amount, assume that there is an obstruction in the duct. If both of these conditions are not met, assume no change has occurred.

### Hood Static Pressure Method — $SPH_{two}$

This variation on the one-sided hood static pressure method addresses one problem discussed above — the one-sided SPH method's inability to detect obstructions upstream of the hood measurement point. By investigating increases in hood static pressure as well as decreases (hence, "two-sided"), it should be possible to reduce the number of false negatives and improve sensitivity.

### Power Loss Coefficient Method — $X_{duct}$

In troubleshooting ventilation systems, it would be useful to have a value conceptually similar to a resistance which does not change with varying airflow. If an obstruction is in the duct, the "resistance" would increase from baseline. Power loss coefficients, or "X-values", serve this purpose. (Guffey 1994, 1993b; Colvin 1993; Spann, 1993) Changes in X-values from baseline are indicative of changes to the system — larger X-value increases indicate more significant obstructions.

An X-value is a ratio of the lost power (energy dissipated as heat) to the kinetic power at the "exit" point for any continuous portion of the ventilation system. This is represented as:

$$X = \frac{\left(\sum_i P_{in,i}\right) - P_{exit}}{Q_{exit} VP_{exit}} \tag{8}$$

where: $P_{in,i}$ = power at upstream boundary "i" = $Q_{in,i}$*$TP_{in,i}$

$P_{exit}$ = power at exit = $Q_{exit}$*$TP_{exit}$

$Q_{exit}$ = airflow at exit

$VP_{exit}$ = velocity pressure at exit

TP = Total pressure

X-values can be used to calculate a resistance for any continuous portion of a ventilation system, but for the purposes of this study they are only used on branches. In this case, $\Sigma Q_{in} = Q_{exit}$ and $\Sigma TP_{in} = 0$ (atmospheric pressure), and the X-value for the whole branch up to the "end" measurement point is:

$$X_{end} = \frac{\sum TP_{in,i} - TP_{end}}{VP} = -\frac{TP_{end}}{VP} \tag{9a}$$

Given that TP is the sum of VP and static pressure (SP), then Equation 9a can be restated for branches as:

$$X_{duct} = -\frac{SP_{end} + VP}{VP} \tag{9b}$$

If baseline X-values have been established, the location of a significant alteration can be determined through a sequential search of the system.

Static Pressure Branch Ratio Method — $SPrat_{br}$

Calculation of X-values requires time-consuming Pitot traverses to determine velocity pressures. A better method would be one that avoids this, such as the proposed static pressure ratio method. The tradeoff over X-values is that this can only be done on branches; changes to submains cannot be detected with this method as it is used. It is a fairly straight forward derivation (Guffey, 1994) to show that for any branch:

$$\frac{X_H+1}{X_{end}+1} = \frac{SP_H}{SP_{end}} \tag{10}$$

Thus, the static pressure ratio cannot vary unless $X_{hood}$, $X_{end}$, or both change. As with X-values, a change in this ratio indicates that a change has occurred somewhere in the branch upstream of the $SP_{end}$ measurement location.

$$SPrat_{br} = \frac{SP_H}{SP_{end}} \tag{11}$$

where: $SP_H$ = hood static pressure

$SP_{end}$ = static pressure at the end of the branch duct

Note that an increase in $X_H$ would also increase $X_{end}$. Thus, as $X_H$ becomes increasing large, $SP_H/SP_{end}$ approaches unity if the velocity pressures are the same at H and end. Conversely, an increasingly large obstruction downstream of H would drive $SP_H/SP_{end}$ increasingly to zero. If the ratio is already near unity, even a very large obstruction upstream of H could produce only small changes in $SP_H/SP_{end}$. Likewise, if the ratio is already nearly zero, even a very large new obstruction downstream of H could have very little effect on the ratio.

### Static Pressure Main Duct Ratio Method ($SPrat_{main}$)

Calculation of $SPrat_{br}$ requires two pressure measurements for each duct ($SP_H$ and $SP_{end}$). Since the $SP_{end}$ measurement generally requires use of a ladder, it would be convenient if a single pressure taken at one location could serve as the normalizing pressure for every branch duct. The $SPrat_{main}$ method tries just that approach.

As with $SPrat_{br}$, a change in this ratio indicates that a change has occurred somewhere in the branch (Guffey, 1994). Since SP

$$SPrat_{main} = \frac{SP_H}{SP_{main}} \tag{12}$$

where: $SP_H$ = hood static pressure

$SP_{main}$ = common reference static pressure in a main duct

### Log Transformed Static Pressure Branch Ratio Method — LogSP

The linear static pressure ratio method is not very sensitive when the hood accounts for most of a branch's resistance (i.e., the $SPrat_{br}$ approaches unity). Getting a deviation greater than a 10 percent threshold over a baseline of 0.95 is impossible. For that reason, a method that is more sensitive at the higher static pressure ratios was also analyzed. This was done by taking the log transform of one minus the static pressure ratio and using that as the troubleshooting indicator variable. This is equivalent to making the threshold a moving threshold so that it is smaller at the higher values of $SPrat_{br}$; thus, smaller differences can be more significant. This is shown in Equation 13 below:

$$LogSP = Log\left(\frac{\text{larger SPratio}}{\text{smaller SPratio}}\right) * 300 \tag{13}$$

Where: larger SPratio = larger of $\frac{SP_{Hc}}{SP_{endc}}$ and $\frac{SP_{Ho}}{SP_{end0}}$

smaller SPratio = smaller of $\frac{SP_{Hc}}{SP_{endc}}$ and $\frac{SP_{Ho}}{SP_{end0}}$

This log transform method is potentially more sensitive when the $SPrat_{br}$ is high. In this case, the hood accounted for most of the pressure loss because it consisted of a 2 inch diameter opening which then expanded to 3 inches. In addition, there was a blockage of 50% of the duct at the 2 inch opening.

*Relating shifts in airflow to troubleshooting parameters*

In this section, the relationship between airflow distribution and values of X is demonstrated (see Figure 1), beginning with the equation that defines the relationship between two flows converging in a junction fitting (Guffey, 1991):

$$SP_q - F_{enq} VP_q = SP_d - F_{end} VP_d \quad .... (14)$$

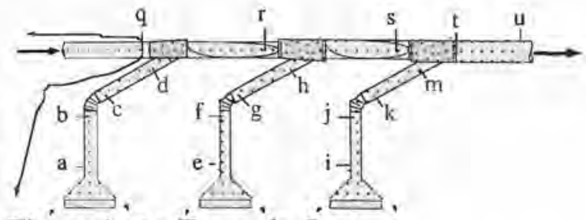


Figure 1: An Example System

Where $F_{enq}$ and $F_{end}$ are functions solely of junction geometry and do not vary with Q or VP (see reference 9)

Since SP=TP-VP and, from Equation 9a, $X_q = -TP_q / VP_q$ and $X_d = -TP_d / VP_d$, Equation 14 can be restated as:

$$-\left(1 + X_q + F_{enq}\right) VP_q = -\left(1 + X_d + F_{end}\right) VP_d \quad .................(15)$$

Since velocity pressure (VP) is proportional to density ($\rho$) and airflow squared ($Q^2$) and inversely proportional to area squared ($A^2$), Equation 15 can be manipulated algebraically to produce:

$$\frac{Q_d}{Q_q} = \left(\frac{A_d}{A_q}\right)\left(\frac{\rho_q}{\rho_d}\right)^{0.5}\left(\frac{1 + X_q + F_{enq}}{1 + X_d + F_{end}}\right)^{0.5} \quad (16)$$

Values of $A_q$ and $A_d$ are fixed if ducts are not replaced, and $F_{enq}$ and $F_{end}$ are constants if the junction fitting is not altered.[9] For simplicity of presentation, let us assume that $\rho_q / \rho_d$ and $A_d/A_q$ do not vary significantly. From Equation 16, one can see that airflow distribution must change with changes in relative resistances to flow. Conversely, if the density ratio is unchanged and neither $X_q$ nor $X_d$ has changed, then the airflow distribution cannot change.

Table II: Shift in Airflow Distribution Between Two Adjacent Ducts

| Initial conditions | | %Change in Xq required for change in Qq/Qd of | |
|---|---|---|---|
| Xd | (Xq/Xd) | 5% | 10% |
| 1 | 0.5 | 33 | 69 |
| 2 | 0.5 | 22 | 45 |
| 4 | 0.5 | 16 | 33 |
| 8 | 0.5 | 13 | 27 |
| 0.5 | 1 | 33 | 69 |
| 1 | 1 | 22 | 45 |
| 2 | 1 | 16 | 33 |
| 4 | 1 | 13 | 27 |
| 0.5 | 2 | 22 | 45 |
| 1 | 2 | 16 | 33 |
| 2 | 2 | 13 | 27 |
| 4 | 2 | 12 | 24 |

Equation 16 is extremely useful, also, in that it allows one to predict the expected effect of a change in an X value on airflow distribution. As shown on Table II, the change in X required to shift airflows by some percentage varies with the absolute level of the initial values of X for the two ducts. A 5% shift in airflow can occur with a change in X of less than 12%, or it could take more than a 33% change in X value. Likewise, a 10% shift in airflow could require a change in X of more than 69% or less than 24%, depending on initial X values in both joining ducts.

Note that a 10% shift in the ratio of the two airflows usually will include a decrease in one duct's airflow and a smaller increase in the other duct's airflow. The proportions in each direction would depend on the X values for all of the other ducts in the system and the location of the altered duct within the system. Conservative practice would be to assume that the shift is entirely accounted for by a decrease in one duct's airflow.

Of course, a duct system usually has far more than two ducts joining at junction fittings. The actual shift in airflows among all of the branches of a system would depend on the initial constellation of X values in the system and which specific duct experienced the alteration. If more than one duct were altered, the shifts in airflow would be still more complex. For that reason, it is more useful to select a range based on a set of two ducts, only.

Based on Table II and the typical values of X observed in working ventilation systems, the P.I. would select a goal of detecting a 20% change in X values to keep typical declines in airflows to hoods to about 5%. The P.I. knows of no practical method to develop similar quidelines for troubleshooting parameters other than X-values. They alone can be directly related to shifts in airflow.

*Considerations in assigning true and false*

Ideally, the condition detected in a sensitivity study is either present or not, making "truth tables" easy to develop. For a troubleshooting study, that would require an obstruction that either blocked flow completely or not at all. For troubleshooting such simplicity would be of little value since an obstruction that completely blocks flow is obvious without using *any* quantitative indicators. The quantitative troubleshooting methods are useful for cases where the obstruction or alteration is not obvious. For that reason, only conditions of partial blockage were used in the study.

However, unlike complete obstruction, "partially obstructed" implies degrees of obstruction. As a practical matter, the lowest degrees of obstruction may be of little or no interest in troubleshooting, which, after all, is done to determine when and where active intervention (maintenance) is necessary. For example, virtually all ducts in systems serving dusty operations will show some degree of settling or coating. However, one would rarely go to the trouble to clean out a duct unless its degree of obstruction was sufficient to deleteriously affect the level or distribution of airflow.

Distribution of airflow in a system is governed by relative resistances to flow for each pathway. An obstruction adds resistance to flow for the pathway it obstructs, shifting airflow to other pathways and reducing its own share. Hence, the goal of troubleshooting should be to detect alterations that alter relative resistances enough to produce substantial shifts in airflow distribution. Of the methods studied, only the X-method directly determines change in resistance, but other methods may be good indicators of significant changes in resistance.

For this study, judging whether a given obstruction or other alteration actually changed resistance enough to warrant the time and cost of removing it is not a simple matter. It is certainly not intuitive obvious how much an observed obstruction would change resistance to flow. Resistance to flow varies with size, shape, texture, and orientation of the obstruction, and it varies with the distance of the obstruction from hood openings, elbows, etc. Hence it is unlikely that the resistance of a given obstructions could be reliably determined without empirical test — an impracticable approach in working systems. For that reason, a field study is likely to have at least some misclassifications, which would reduce the sensitivities and inflate the false positive rates for every method. However, unless there is a serious bias against a given method in the classification scheme, a method that performs much better than another is probably a much better method.

Each of the alternative methods of judging whether a given obstruction warrants classification as "positive" (i.e., should be removed) presented difficulties:

1. Visual appearance. Given the difficulty of estimating the resistance of an observed object, it is quite likely some visually apparent objects are more impressive to the beholder than to the ventilation system. Even relative rankings would be problematic, especially when the observations are widely separated in time or background conditions are radically different. Hence, one would expect subjective rankings of degrees of obstruction to produce misclassifications, especially in making anything but the coarsest distinctions. On the other hand, observations are independent of any method that employs measurements.

2. Measurement of obstruction parameters. This is a difficult proposition. Two complex obstructions with the same cross-sectional areas or lengths or any other measurable parameter could have radically different resistances to flow. Even identical objects can produce quite different resistances if they are oriented differently to the flow. It is also moot, since gaining the quality of access needed to measure the dimensions of an obstruction was seldom possible.

3. Determine actual resistance before removing the obstruction. To the naive, it might seem possible to measure the pressure differential across an obstruction and compute the velocity pressure coefficient for the obstruction using that information. However, determining the true contribution of the obstruction would require taking measurements substantial distances from the obstruction and from elbows. In most cases, one would end up using the before and after resistance determined at the end of the duct. Since the "X-method" is a measure of resistance at the end of the duct, use of resistance as a "gold standard" would beg the question.

To provide an independent determination of the resistance of the obstruction in situ, one would need the degree of control and the measurement conditions found only in a ventilation laboratory. For that reason, this report include just such an analysis done for data collected in both our former and our current ventilation laboratory's test systems.

4. Observe the change to airflow. The airflow to a branch duct can change for many reasons, including an obstruction or leak in it, an alteration to other ducts (especially those nearby), changes to resistance at an air-cleaning device, and anything that affects fan performance. It is quite possible for a combination of effects elsewhere to mask the effects of an alteration to a branch duct. Hence, airflow through the duct is a poor "gold standard" to judge how substantial an observed obstruction really is. Furthermore, since each value used in the X-method are computed from an observed velocity, errors in determining velocity produce matching errors in X-values.

5. Observe the change to airflow *distribution*. As mentioned in the original proposal, it would be desirable if methods reliably discriminated between obstructions that could substantially affect airflow distribution (i.e., fraction of airflow drawn through each branch duct). However, it is not clear that one should employ changes to distribution as an indicator of whether an obstruction is real and substantial. The effects of multiple changes to the system can present complex changes to distribution that have poor correspondence to individual obstructions or alterations. Furthermore, as with use of airflow values, errors in measuring airflow will produce corresponding errors in both airflow distribution and X-values.

We selected visual observations and subjective classification of relative weight as the "gold standard". Despite the near certainty of some misclassifications, visual observation had two compelling virtues: 1) it was feasible, and 2) it was independent of any the methods tested.

## Specific aims

*Original specific aims*

The specific aims of the proposed longitudinal field study were to evaluate and compare four methods for detecting alterations and specifying in which ducts they are located ("troubleshooting") for five working industrial exhaust ventilation systems for contaminant control. The four troubleshooting methods are as follows:

1. A proposed method based on observed changes to two troubleshooting variables, power loss coefficients (X) and static pressure ratios ($SPrat_{br}$).
2. A method based on comparison of pressures predicted from published velocity pressure coefficients and measured static pressures, as described in *Industrial Ventilation* (IVM).
3. A method based on changes to hood static pressures ($SP_H$), a commonly used approach.

The success of each method in specifying which system ducts have been altered were to be discussed in terms of sensitivity and specificity (i.e., probabilities of true positives and false negatives). The tradeoffs between selection criteria and specificity and sensitivity were to be explored for all three approaches using receiver operating characteristic curves. It also should be possible to determine the minimum change in airflow distribution that can be reliably detected using each approach.

*Achievement of specific aims*

The study not only achieved all of the original aims, it went considerably beyond them both in intensity of effort and scope. The original proposal called for study of 4 competing troubleshooting methods: two pressure ratio methods proposed by the P.I., the commissioning method of *Industrial Ventilation*, and the traditional use of hood static pressures. In addition to comparing those methods, we added two additional variants: a modified hood static pressure method and a third pressure ratio method. As was discussed in competing renewal applications and in a following section, we also modified the commissioning method of *Industrial Ventilation* make it more appropriate to troubleshooting long-installed systems and to give it a much better chance of success.

Although the study proposal called for studies of 5 field systems, we actually collected data on 9 systems, of which 6 were selected for continued inclusion in the study. In addition, we analyzed data collected in 4 previous studies of two systems in ventilation laboratories. The laboratory studies were helpful because they represent ideal conditions in two ways: 1) measurement conditions were ideal, and 2) no alterations in the ducts or changes to fan performance could have occurred without the active intervention of the experimenters. Unlike the field studies, there should have been few, if any, classification errors.

The original study proposal called for at least 4 rounds of data collection on 5 systems, with the data to be collected by the Boeing Company personnel. Instead, the P.I. and his students collected 14 to 20 usable rounds of observations on each of 6 systems in the field. Those figures do not include any of the data collected in the first year and a quarter on the original 5 ventilation systems, a time when no reliable means of verification of obstructions existed.

As stated in the specific aims of the study, the study reports on the comparative success of each troubleshooting method in terms of sensitivity and specificity (i.e., probabilities of true positives and false negatives). The tradeoffs between selection criteria and specificity and sensitivity also are explored for all approaches using receiver operating characteristic curves. Finally, the last sections of this Report will discuss the minimum change in airflow distribution that can be reliably detected using each approach.

*Difficulties encountered and overcome*

There were three main difficulties encountered and overcome in this study: 1) much greater than expected difficulty in accessing and verifying obstructions in ducts, 2) poor quality of initial measurements made by the Boeing personnel, and 3) difficulty in classifying degree of obstruction. The first problem was overcome in the second year by use of a borescope and by substituting more accessible systems from other companies. The second problem was overcome by taking all measurements ourselves. The third problem was overcome by use of a borescope, creating and using a subjective classification scheme for degree of obstruction, deliberately inserting highly diverse "obstructions" into some ducts, and increasing the number of rounds of data collection.

The original proposal was based on the assumption that we would analyze and verify measurement data collected as part of on-going routine by the Boeing Company. In addition, the Company would install access ports on ducts to allow verification and removal of obstructions where convenient access was not possible by disconnecting the ducts. However, the Company experienced a business contraction at the beginning of the study that lead to sharp reductions in the resources applied to monitoring systems. The scope and time allowed for ventilation measurements was reduced, and no inspection panels were installed. As a result, the P.I. and his students began taking all measurements on all of the original five systems while attempting to find alternate ways to verify or refute presence of obstructions and other alterations. The data collected during the first year established that the proposed pressure ratio methods agreed with each other but frequently disagreed with the established pressure direct comparison methods. Lack of access precluded verifying which methods were correct and which were wrong in most instances.

Purchase and use of a borescope in the second year provided enough visual access for adequate certainty in declaring presence or absence of an obstruction. It did not resolve the more complex issue of declaring true and false positives and negatives, a difficult issue discussed in a following section.

Since judgments of the degree of obstruction were unavoidably subjective and imprecise, we increased the power of the study by collecting far more rounds of observations than were originally proposed. We also dropped 4 of the 5 Boeing systems from the study and replaced them with 5 more accessible systems used in other contaminant producing operations.

For the laboratory studies there were objective, quantifiable independent bases (e.g., damper insertion depth, target damper loss coefficient, or an independently determined loss coefficient for a deliberately inserted obstruction) for assigning weights to alterations.

## Apparatus

*Ventilation Systems*

For the purposes of this study, the ventilation system needed to: 1) be part of an organization that would allow access to the system(s) for the length of the project; 2) be in heavy use such that a variety alterations would likely be observed over the course of the study; 3) have hoods that are not manipulated during the day such that air is redistributed in the system; 4) have convenient measurement locations; and 5) be located close to the University of Washington. Nine systems were used at different times in the system, but three were dropped from the study due to difficulty of accessing the inside of the ducts to confirm the presence or absence of obstructions. The six remaining systems was measured in detail, including duct diameters, length of runs, location and orientation of elbows, and junction angles. Measurement locations for all branches and submains were noted hand-made drawings at the beginning of the study. The systems are described briefly below.

The Bandsaw and Drysaw systems ventilated a metal band saws and circular saws sharpening process. The two ventilation systems were used to control exposures in both metal grinding and brazing operations. The branch ducts in the Dry Saw system ducts varied in diameter from 3-4 inches. The velocities ranged from 1000 to 4500 ft/min. The Bandsaw system contained 5 to 6 inch duct diameter branches whose velocities varied from 500 to 3700 ft/min. Both systems plugged frequently, providing many opportunities to detect obstructions and other alterations.

Model Shop, Cabinet Shop, MezEast, and MezWest all controlled dust from typical woodworking operations, including joining, planing, various types of sanders, and cut-off saws. The Model Shop consisted of branches that ranged in velocity between 500 and 3700 ft/min. The branches were made of 5 and 6 inch duct diameters. The Cabinet Shop velocities varied from 400 to 6500 ft/min and contained branch ducts that varied between 4-8 inches in duct diameter. MezEast contained branch ducts between 4 and 6 inches in diameter. These branches ranged in velocity from 2000-5200 ft/min. The MezWest system branches ranged in velocity from 2000-6500 ft/min. MezWest contained branch ducts between 4 and 6 inches in diameter. None of the three systems plugged frequently.

In one preliminary study using the Model Shop (Pinsky, 1995), characterization was hampered by changes in the positioning of flexible ducts and adjustable dampers as this alters the airflow and pressures in that branch and throughout the system. In the cases where flex duct positioning was as issue, pictures were taken for precise repositioning. However, it remained extremely difficult to ascertain whether small repositions occurred. In the other systems, most flexible ducts were fixed more tightly in place.

*Measurement Equipment*

Pressure measurements were made with the Alnor CompuFlow ElectroManometer, Model 8530D-I (Skokie, IL) or a TSI DP-Calc, Model 8702 , both with an accuracy of ±1% after zeroing. In the field, the digital manometers were frequently re-zeroed to insure accurate readings and minimal zero drift.

Static and velocity pressures were taken using Dwyer® stainless steel Pitot tubes (model 167, 1/8 inch diameter, 6 inch insertion depth, 1.5 inch lead tube, Michigan City, IN) which comply with AMCA and ASHRAE specifications (Dwyer Instruments, 1992). Two different tubes were used: one marked for ten-point velocity traverses of 3 inch diameter ducts and the other marked for 4 inch ducts. The duct was divided up into ten equal annular areas, and the traverse points were not positioned in the center of that area, but so that each point represented the mean velocity of that annular area. This log-linear method is considered to be a more accurate traverse method (Ower and Pankhurst, 1977). Each traverse point on the Pitot tubes was scored with a file and marked with indelible ink. During use, static pressure and total pressure holes of the Pitot tube were cleaned when needed. If cleaning was necessary while measuring a branch, all measurements on that branch would be redone. Velocity traverses were done by hand as were all static pressure measurements. The Pitot tubes were connected to the manometer using 1/4 inch internal diameter, 1/16 inch wall thickness Tygon® tubing.

Wet and dry bulb temps were measured using a battery-powered psychrometer (Cole-Parmer Psychro-Dyne) to determine humidity and air density. Temperatures were taken at the start of a sampling day and then repeated when temperature changes were noticed to be potentially significant. Temperatures were assumed to be the same for all hood openings. Note that slight errors in humidity measurements would have very little effect on the air density. Barometric pressures were not taken as they traditionally have minimal effect on the air density.

*Calibration*

The digital manometers were calibrated against a 4-inch Meriam Wall-Mounted Inclined Manometer (model No. 40HE35WM) and a Dwyer Hook Gage (series 1425, Michigan City, IN) with 0.001 in.w.g. resolution. These instruments were connected using a valved manifold setup which was then connected to a Meriam hand pump (model B34348). Pressures were set with the hand pump at approximately the following calibration levels (in.w.g.): 0.5, 1, 2, 3, 4.

*Data Acquisition and Software*

To facilitate data collection, a digital manometer readings were entered directly into a computer program designed for ventilation measurements (Guffey, 1997). Three different palmtop or laptop computers were employed. This direct data-logging procedure should have drastically decreased the number of transcription errors that may have occurred in many ventilation studies (Hoppe 1995, Pinsky 1996).

Pressures, wet/dry bulb temperatures, and all comments were input directly into HV_Meas ventilation software developed by Guffey (1997). HV_Meas then calculated air flows, static pressure ratios, and X-values for all branches and submains for which the data was input. HV-Meas also allowed the user to compare pressure and troubleshooting variables to previous values and, thus, check the new data as it is being entered to ensure that the data is entered in the appropriate cell. Substantial upgrades to this software were made over the course of the study to expand its capabilities, speed, and ease of use. After collection, data from HV_Meas was exported into a spreadsheet and statistical programs for analysis, organization, and formatting.

Statistical analyses were done using Data Desk, version 5.0 (Data Description, Inc., Ithaca, NY), SPSS (SPSS, Inc., Chicago, IL), and Microsoft Excel, Version 7 (Microsoft Corp., Redmond, WA).

## Procedures

*Characterizing the Systems*

Each component of both systems was thoroughly described at the beginning of the study with the following procedure:

1. Identification of each run of duct and assignment of an integer ID number for reference. A new number designated a different branch or submain, or a change in diameter of the same branch or submain. For example, if a branch had a taper within it, the ducts upstream and downstream of the taper were assigned different branch ID numbers.
2. Measurement of the length of duct for every branch from hood to centerline of the junction and from the hood static pressure measurement location to the "end" pressure measurement location.
3. Measurement of nominal duct diameters with a steel tape and with a micrometer, where accessible.
4. Count of elbows per run, and determination of turning angles and radius of curvature for each elbow.
5. Determination of taper angles, where present.
6. Measurement and calculation of slot areas for hoods with slot openings.

*System Preparation*

Measurements were not taken until the fan had run for at least 30 minutes, allowing it time to achieve steady operation. While the system warmed up, all dampers were opened fully and secured in that position with a sheet metal screw. Endcaps were removed from some branches to create additional branches that should be clean ducts.

Where possible the systems were measured when the shop was not in use to avoid interference with shop activities and to minimize alterations during the taking of measurements.

Static pressure measurement locations consisted of 1/8 inch x 1/4 inch oblong holes. All measurement locations were labeled on the duct with indelible ink and the holes covered with tape to prevent airflow leaks.

Measurement positions were chosen pursuant with *Industrial Ventilation* recommendations as much as possible — that is, at least seven duct diameters downstream and two duct diameters upstream of elbows, hoods, expansions, contractions, and other components. This was not always possible because of duct geometry; in these cases, the best available location was chosen. Poor measurement conditions can lead to highly variable and inaccurate data and potentially erroneous conclusions regarding pressures and flows

*Measurement Procedure*

For the majority of the static pressure data that was collected, the digital manometer was set with a long time constant (e.g., 4 seconds) to ensure stable readings. A shorter time constant (1 to 2 seconds) was considered acceptable for individual velocity pressure measurements since errors in individual measurements would tend to balance out over the ten or twenty-point average.

The measurement process initially required two people to collect the data. To insure consistent positioning of the Pitot tube between different branches and rounds, placement of the tube was always done by a highly experienced investigator. With improvements to the software and to measurement technique eventually a single investigator (the P.I. or his students) could do it alone.

In general, a "round" of pressures was taken starting at the most upstream branch and working from hood static pressure to end static pressure. Sometimes this order was broken to save time in ladder movement and preparation. When one round of measurements for the ventilation system were completed, at least one more round was done to help characterize measurement variability. Because it was necessary to do repeat measurements on the system, each system was done in two parts to allow many repeats on one part of the system. It was assumed that the distribution of the airflow between the two halves of each system was constant over repeated rounds. This was a reasonable assumption because it was difficult for the workers to disrupt airflow during routine work. Even if one hood was changed slightly on the part of the system that was not being measured, the effect on the other part of the system should have been minimal given that they were separated by large distances.

Once a set of measurement rounds on the system were done, the system was inspected for alterations which may have affected air flow. The inside of the ducts were inspected for clogging, settling, and other alterations with a periscope-like instrument called a borescope (Series 5, Olympus America, Melville, NY). This allowed visual identification of obstructions. The location of each obstruction relative to both geometry and measurement positions was noted on diagrams and in the computer software. In addition, the size of the obstruction and a qualitative estimation of its significance were noted. Later, an obstruction classification code was assigned to each of the noted obstructions (see Table 3).

## Methods

*Analytical procedure*

The data analyses was complex and involved hundreds of thousands of computations. In the steps listed below, the computations in step B were executed using Hv_Meas, computer programs specially written by the P.I. to do both data acquisition and troubleshooting computations. Steps C through E were done using software specially written by the P.I. to do those operations for this study. The following overall steps were included:

A. For each case in this study it was necessary to do the following:

1. Determine whether a positive event had occurred, and if so what subjective weighting should be given. This was done before other analyses.
2. Determine whether a case should be rejected due to obvious errors in measurements (e.g., velocity profile consistent with plugging of one port of the Pitot tube) or because of failure to subjectively weight the conditions inside the duct.
3. Determine whether a case should be omitted from analyses involving a specific troubleshooting method because of obvious inapplicability for that method (e.g., missing traverse for $X_{duct}$ method, missing SPH for all but $X_{duct}$ method).

B. For the remaining cases for each of 350 thresholds from 0 to 2000% for each of the troubleshooting methods:

1. Pair rounds of data from the same system to provide baseline and "comparison" data to maximize the time lapse between compared rounds
2. Compute the method-values appropriate for each data-pair for each method (see Table I),
3. Assign true-positive if the method value exceeded the threshold if a subjectively judged positive event had occurred and assign false positive if no event had occurred,
4. Assign true and false negatives if the method was less than the threshold

C. With the truth status determined for each threshold for each case for each method, create different subsets of data by filter the data to include or not include combinations of different weighted events (i.e., ignore cases where the positive event was deemed trivial, modest, or moderate). For each data subset:

1. Compute sensitivity, selectivity, and false positive ratio for each threshold across all cases for each method,
2. Plot sensitivity as the dependent variable against false positive ratio for all thresholds for each method and compute the areas under the resulting curve ($A_{ROC}$)

D. For each data subset created in step C, randomly select from cases (with replacement) a number of times equal to the number of cases to create a new data set with some cases repeated more than once and others omitted, then repeat steps 4 and 5.

E. Repeat step E thirty times and combine the results into one data set.

F. Filter the resulting data set in Step E to create different subsets (e.g., all systems together, specific ventilation systems, specific weights included or not included, etc.), and for each data subset:

1. Compute the "boot-strap" variability for $A_{ROC}$ for each method
2. Analyze $A_{ROC}$ for dependence on important independent variables (e.g., method, vent system, weights included)

G. For all field data and all laboratory data considered separately,

1. Find the two thresholds for each method that will produce a false positive rate of 10% and 20%, respectively
2. Determine the sensitivity for each method at each of the pair of thresholds determined above.

As noted in Step B1, the rounds of measurement were sorted to provide the maximum difference in time between successive rounds for each ventilation system. Each round was treated as the baseline (o) for the next round (c). If the difference in weight between the compared conditions was greater than zero, the condition was considered positive. If the method-value (see Table I) exceeded a given threshold then method was considered to indicate positive for that threshold and method. If a condition was positive and the method indicated positive, then that method was considered true positive. False positives, false negatives, and true negatives were assigned similarly.

Table III: Weight Classifications for field study

| Weight | Description | %Obstructed | Illustrative examples |
|---|---|---|---|
| 0 | very light | 1-5 | surface layer of dust or extremely clean |
| 1 | very light | 1-5 | thin wood strip in duct<br>damper inserted 10%<br>dusting of sawdust or metal shavings |
| 2 | light | 6-15 | wood strips inside duct blocking 15%<br>small clumps of metal shavings obstructing 10%<br>small change in position of flexible duct and hood opening adjustment<br>damper inserted 20% |
| 3 | moderate | 16-40 | 3x5 in brick in 6in. diameter duct<br>lead weight blocking 20% of duct<br>damper inserted 30% to 40%<br>strips of tape covering 30% of hood |
| 4 | heavy | 41-75 | 50% of hood opening covered with wood<br>damper inserted 60% of diameter |
| 5 | gross | 76-90 | damper inserted 80% of diameter<br>hood covered 80% |
| 6 | nearly plugged | 91-100 | duct nearly completely filled with woodshavings |
| 7 | plugged | 100 | completely filled with settled material |

The weight classification scheme was based on the subjective judgment of the effect of an obstruction or alteration on resistance to flow. As discussed elsewhere, such subjective classifications are likely to produce frequent misclassifications. An observer might place a given alteration in the very light category one time and in the light or even moderate category the next. This is especially likely if the observations are done on different systems or many months apart. In addition, the lightest classifications may have little or no effect on ventilation performance, making success in detecting them of dubious importance.

Finally, as noted in the step-by-step procedure, some cases were omitted as being obvious by any method. Examples included ducts that were completely blocked or plugged, permitting trivial duct velocities (i.e., both compared velocities less than 900 ft/min) in otherwise high velocity systems. In addition, cases were omitted if the $SP_H$ and $SP_{end}$ measurement locations were so close together that $SP_H$ and $SP_{end}$ were nearly identical when the duct was clean (i.e., both comparison values of $SPHrat_{br}$. greater than 0.97).

*Description of each laboratory study*

As in the field studies, all measurements were taken with a digital manometer (the TSI DP-Calc 8702) and standard hemi-spherical head Pitot tubes. Unlike the field studies, Pitot tube traverses were done using a holding device (Guffey, 1990) which provided optimal control over probe orientation and insertion depth.

The Carrel (1993), Spann (1993), and Colvin (1997) studies were done on the same five-branch duct system in the University of Washington "Union Bay" ventilation lab (Guffey and Curran, 1993). Branch duct diameters ranged from 4 to 7 inches in diameter. Branch ducts were ten to twenty feet in length and had zero or one elbow for each branch. Duct velocities ranged from 2900 to 5500 ft/min for each study.

The Geiger study (1997) was done at the University of Washington "Northlake" ventilation laboratory, the successor to the Union Bay facility. The duct system included 8 branches having duct diameters ranging from 4 to 6 inches in diameter. Branch ducts were 20 to 35 feet in length and included one to three elbows for each branch duct. Duct velocities ranged from approximately 2900 ft/min to 5500 ft/min.

Fan output varied only because of changed resistance in the branches for all studies except that of Spann, who varied fan speed to change airflows by 50% for some rounds of data collection.

Carrel study

The Carrel study of the Union Bay five-branch system had no obstructions. Instead, at least one branch was sealed tight for each experimental round. Eight rounds of data were collected.

Even casual inspection would reveal when a branch has no airflow, so the "obstructed" branches were not included in the analysis. Thus the study contributed no positive cases to the pooled data. Without positive cases, the sensitivity is always zero, making $A_{ROC}$ zero as well.

Colvin study

The Colvin study of the Union Bay five-branch duct system employed various specially made obstructions whose actual velocity pressure coefficient of resistance was independently determined, allowing completely objective assignments of weights for obstructions. Different combinations of two to three branch ducts were partially obstructed with one of 5 obstructions for 10 rounds of data collection.

Spann study

The Spann study of the Union Bay five-branch duct system employed slide-gate dampers as obstructions. The expected resistance of the damper for each branch for each round was used to weight the degree of obstruction for this analysis. For 10 rounds three or four branch ducts were partially obstructed. For three other rounds, no ducts were obstructed.

Geiger study

The Geiger study was conducted on the eight-branch Northlake laboratory duct system. The obstructions were slide-gate dampers inserted to measured insertion depths. The weight rankings were based on the unobstructed area of the damper divided by the duct cross-section. All dampers were downstream of the $SP_H$ measurement location. For half of the 16 rounds no duct was obstructed. For the other half, 5 to 7 of the branches had diverse degrees of obstructions.

## Results of laboratory studies

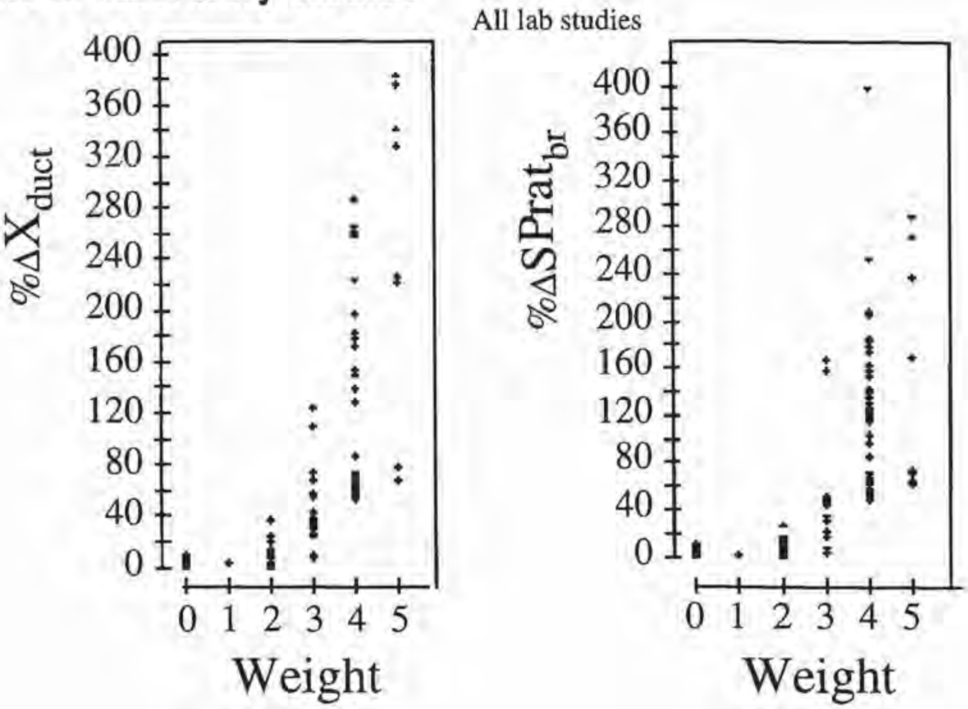


Figure 2: Separation by weight for pooled laboratory studies data

For the laboratory-based studies we re-analyzed data collected for other purposes. In each study, the obstructions were both known (see Table IV for prevalence rates) and relatively easy to rank by degree of obstruction. As shown on Figure 2, the variability of $X_{duct}$ values for clean conditions was very low, and the values of $X_{duct}$ and $SPrat_{br}$ for weights above category 1 were clearly higher than the spread of values for clean conditions. Although there is a great deal of overlap between weights 3, 4, and 5, the crucial issue is the distinction between "clean" and obstructed enough to shift airflows by 5% of more (i.e.., change in $X_{duct}$ of more than about 20%. The range of "clean" conditions did not exceed 20% for $X_{duct}$. All but one case with a weight of 3 or more did exceed 20%, building confidence in the classification of weights. Roughly half of the weight 2 conditions exceeded 20% change in $X_{duct}$, making that weight category a test of the resolution of the various methods.

Since few, if any, positives could be misclassified as negatives, one might expect all troubleshooting methods to show performances superior to those found in the field studies. Indeed that was the case. However, misclassification of negatives could still have occurred for cases where one condition was incorrectly given a higher obstruction weighting than another or two conditions were incorrectly given the same weighting. For those cases, the false-positive rate would be inflated for all methods.

Finally, no obstructions were placed upstream of the $SP_H$ measurement location H, a condition some methods may detect better than others. In particular, idIVM and 1-Sided would have performed less well if upstream obstructions were included.

*Table IV: Laboratory studies prevalence rates for obstructions of each weight*

| Ducts | Method | No. Cases | all | very light | light | mod-erat | heavy, subst-antial | gross | nearly plugged |
|---|---|---|---|---|---|---|---|---|---|
| branches | $SPH_{one}$, $SPH_{two}$ idIVM, $SPrat_{main}$ | 132 | 33 | 1 | 5 | 8 | 14 | 5 | 0 |
| | $X_{duct}$ | 182 | 53 | 1 | 9 | 12 | 25 | 5 | 0 |
| | $SPrat_{br}$ | 184 | 52 | 1 | 9 | 12 | 25 | 5 | 0 |
| | | | | | | | | | |
| submain | $X_{duct}$ | | 1 | 0 | 0 | 1 | 0 | 0 | 0 |

Table V: Areas under the curve for laboratory studies

| | | | Percentage of cases with weight | | | | Direct Pressure Comp. Methods | | | Ratio Methods | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System Name | WtDiffs Excl. | Total Cases | very light | light | mod erat | subs tant | SPH one | SPH two | ideal IVM | X duct | SP ref_br | SPrat main |
| All lab | none | 264 | 6 | 14 | 9 | 26 | 0.69 | 0.78 | 0.70 | 0.96 | 0.97 | 0.91 |
| | 1 | 247 | 0 | 15 | 9 | 28 | 0.69 | 0.78 | 0.73 | 0.97 | 0.98 | 0.91 |
| | 1,2 | 209 | 0 | 0 | 11 | 33 | 0.81 | 0.81 | 0.85 | 1.00 | 1.00 | 0.95 |
| | 1,2,3 | 186 | 0 | 0 | 0 | 37 | 0.95 | 0.95 | 0.98 | 1.00 | 1.00 | 1.00 |
| Carrel | all clean | 30 | 0 | 0 | 0 | 17 | N/A | N/A | N/A | N/A | N/A | N/A |
| Colvin study | none | 45 | 11 | 9 | 16 | 4 | 0.95 | 0.95 | 0.94 | 1.00 | 1.00 | 0.95 |
| | 1 | 40 | 0 | 10 | 18 | 5 | 0.93 | 0.93 | 0.92 | 0.99 | 1.00 | 0.92 |
| | 1,2 | 36 | 0 | 0 | 19 | 6 | 0.97 | 0.97 | 1.00 | 1.00 | 1.00 | 0.97 |
| Geiger | none | 96 | 2 | 13 | 13 | 55 | 0.61 | 0.62 | 0.72 | 0.95 | 0.97 | 0.69 |
| | 1 | 94 | 0 | 13 | 13 | 56 | 0.63 | 0.64 | 0.74 | 0.96 | 0.98 | 0.70 |
| Spann | none | 60 | 5 | 2 | 5 | 2 | 0.77 | 0.78 | 0.00 | 0.96 | 0.89 | 0.88 |
| | 1 | 58 | | 2 | 5 | 2 | 0.99 | 0.99 | 0.00 | 1.00 | 1.00 | 0.99 |

*Table VI: Geometric standard deviation of areas under the curve for all lab studies*

| | | Direct Pressure Comp. Methods | | | Ratio Methods | | | |
|---|---|---|---|---|---|---|---|---|
| System Name | WtDiffs Excl. | SPH one | SPH two | ideal IVM | X duct | SP ref_br | Log SP | SPrat main |
| All lab pooled | none | 1.07 | 1.06 | 1.09 | 1.02 | 1.02 | 1.03 | 1.03 |
| | 1 | 1.06 | 1.04 | 1.09 | 1.02 | 1.02 | 1.04 | 1.03 |
| | 1,2 | 1.07 | 1.05 | 1.10 | 1.01 | 1.01 | 1.05 | 1.02 |
| | 1,2,3 | 1.03 | 1.02 | 1.04 | 1.01 | 1.01 | 1.04 | 1.01 |
| Colvin study | none | 1.03 | 1.03 | 1.05 | 1.01 | 1.00 | 1.00 | 1.03 |
| | 1 | 1.05 | 1.05 | 1.14 | 1.01 | 1.00 | 1.00 | 1.05 |
| | 1,2 | 1.03 | 1.03 | 1.00 | 1.00 | 1.00 | 1.00 | 1.02 |
| Geiger | none | 1.10 | 1.10 | 1.08 | 1.03 | 1.01 | 1.01 | 1.08 |
| | 1 | 1.07 | 1.07 | 1.07 | 1.02 | 1.01 | 1.01 | 1.07 |
| Spann | 1 | 1.31 | 1.27 | 1.00 | 1.06 | 1.16 | 1.16 | 1.17 |

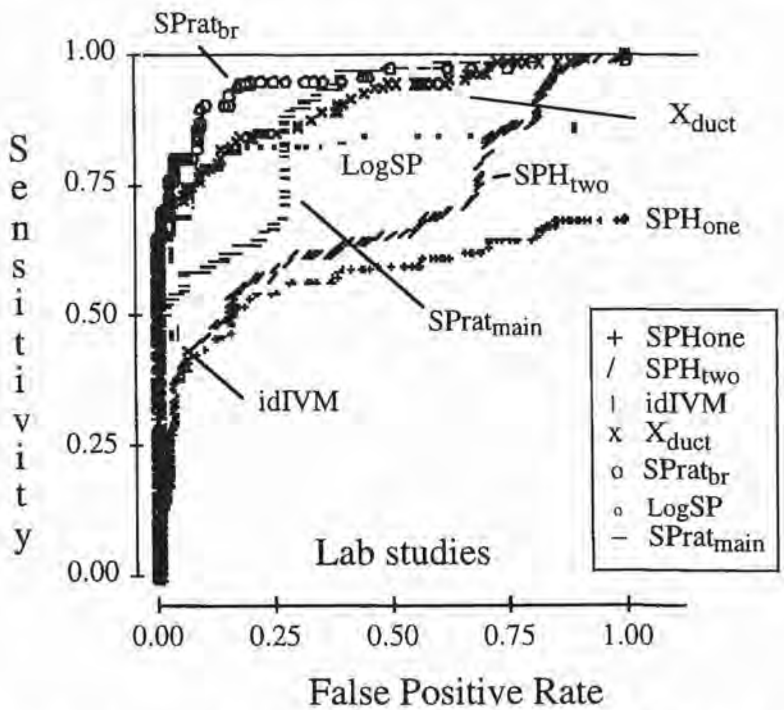


Figure 3: Receiver-operating characteristic curve for all pooled data from laboratory studies

Note in Table V and Figure 3 that when all weights of obstructions were included the values of $A_{ROC}$ for the pressure ratio methods ($X_{duct}$, $SPrat_{br}$, and $SPrat_{main}$) were substantially higher than the values for the simple pressure comparison methods ($SPH_{one}$, $SPH_{two}$, and idIVM). The $X_{duct}$ and $SPrat_{br}$ methods were very nearly perfect ($A_{ROC}$>0.96). As might be expected, excluding lower classifications of obstructions increased the efficacy of the methods somewhat, but it did not change the order of the relative rankings substantially. When individual laboratory studies were considered alone, the values of $A_{ROC}$ were more variable. The results from each analysis are discussed below.

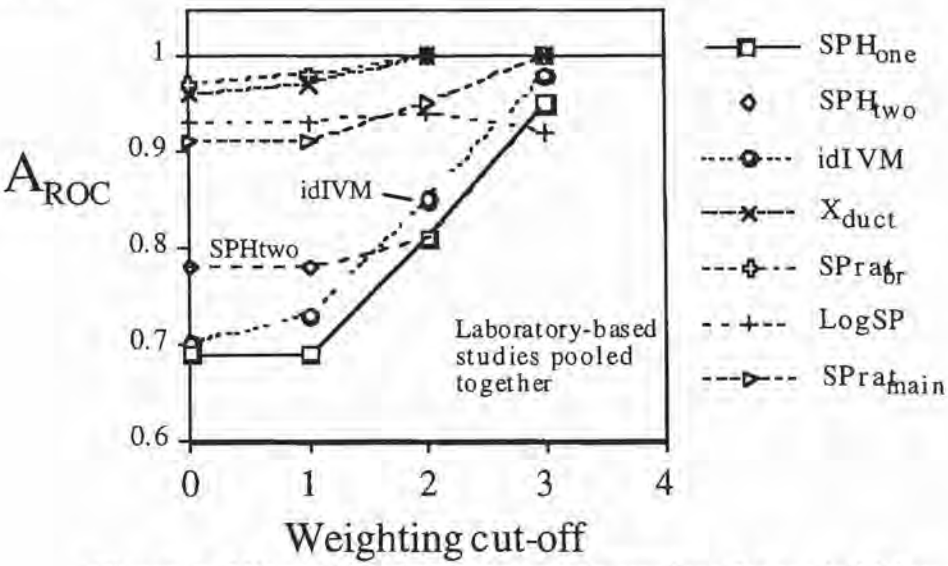


Figure 4: Effects of excluding lesser obstructions for pooled laboratory data

*Pooled data*

When the data were pooled for all laboratory studies and included all obstruction weightings, values of $SPrat_{br}$ (0.97) were 1% higher than $X_{duct}$ (0.96). LogSP and $SPrat_{main}$ values were both somewhat lower (0.93 and 0.91, respectively), but both were substantially higher than $SPH_{two}$ (0.78), $SPH_{one}$ (0.69), and idIVM (0.70).

Removing the lower-weighted obstructions generally improved the values of $A_{ROC}$ for each method, except for LogSP. As shown in Table V and Figure 4, the values of $A_{ROC}$ increased quickly to perfection for $SPrat_{br}$ and $X_{duct}$. $SPrat_{main}$ improved gradually, reaching perfection only when all but the most profound obstructions were removed from the analysis. The values for $SPH_{two}$ improved started off substantially higher than $SPH_{one}$ and idIVM, but became indistinguishable from $SPH_{one}$ when the lightest weight of obstructions was removed. When only the most profound obstructions remained, idIVM approached perfection and $SPH_{one}$ and $SPH_{two}$ reached 0.95.

*Results by study*

The Carrel study served only to add negative cases, so its areas under the curve were all zero. All methods did extremely well for the Colvin study, but the Geiger and Spann studies presented more of a challenge. The $X_{duct}$ method did extremely well on all studies, and $SPrat_{br}$ was extremely high for all but the relatively low value of 0.89 for the Spann study. The idIVM, $SPH_{one}$ and $SPH_{two}$ values were much lower for all but the Colvin study. $SPrat_{main}$ fell well-below $X_{duct}$ for all but the Colvin study.

For the Spann study the value of $A_{ROC}$ for idIVM was zero because it failed to detect any obstructions, probably because of the interactions between the low prevalence of substantial changes (7%), and its apparently over-restrictive rules for identifying positive cases.

## Discussion of laboratory-based results

As was discussed earlier, misclassification and measurement errors inevitably loom larger in a field study than in the well-controlled conditions of a ventilation laboratory. Both types of errors would tend to deflate sensitivities and inflate false positive rates. Studies of laboratory-based ventilation systems can be helpful in determining whether differences in efficacy would be greater or lesser if those errors were reduced.

These four laboratory studies suggest that the $X_{duct}$ and the $SPrat_{br}$ methods have the potential to be extremely precise in detecting and locating alterations. The LogSP method required the same information as the $SPrat_{br}$, but performed less well. For that reason there is little point in considering the LogSP method further. The remaining methods performed relatively poorly compared to $X_{duct}$ and $SPrat_{br}$, but they continue to have the compensating attraction of requiring somewhat less information.

*Analysis for significance of $A_{ROC}$ results*

The issue of dependence of results on a few observations can be addressed quantitatively by data re-sampling (i.e., "boot-strap" methods). To that end, $A_{ROC}$ values were determined from randomly selected (with replacement) observations from each study. Thirty iterations were performed with the number of randomized re-samples equal to the number of observations in each case. As shown in Table VI, when all studies were considered at once the overall geometric standard deviations were extremely low for $X_{duct}$, $SPrat_{br}$, and $SPrat_{main}$ (Gstd=1.01) and were very low for $SPH_{two}$ (1.03) and $SPH_{one}$ (1.14). When paired pooled t-tests for each combination of methods were performed, the difference in mean areas were significantly different ($p<0.001$), except for two combinations whose differences were not significant ($p>0.10$): LogSP versus $SPrat_{main}$, and $SPrat_{br}$ versus $X_{duct}$.

Another issue worth considering is whether the differences in efficacy could be due to inclusion of relatively minor obstructions as positive events. To analyze for that effect, the values of $A_{ROC}$ were re-computed for each method with the lesser alterations omitted from the analyses (i.e., ignoring cases where the subjectively assigned "weighting" differed by only one or two). As shown in Table V, for the case when all study data were considered together, omitting the lesser changes in resistance made little difference in the results and none in the rank order of $A_{ROC}$.

Table VII: Significance of Method and Vent System for Laboratory Systems with all obstructions included

**Laboratory systems data**, Dependent Variable: Area under the curve, $A_{ROC}$

| Source | df | Sums of Sq. | Mean Square | F-ratio | Probability |
|---|---|---|---|---|---|
| Const | 1 | 434.689 | 434.689 | 75133 | ≤ 0.0001 |
| Vent study | 2 | 6.40639 | 3.20320 | 553.65 | ≤ 0.0001 |
| Method name | 6 | 11.4993 | 1.91655 | 331.27 | ≤ 0.0001 |
| Study*Method | 12 | 13.4177 | 1.11814 | 193.26 | ≤ 0.0001 |
| Error | 609 | 3.52340 | 0.005786 | | |
| Total | 629 | 34.8468 | | | |

Table VIII: Scheffe for Linear Model with Different Weight Included

| Study | WtDiffs Excl | $SPH_{one}$ | $SPH_{two}$ | X duct | SP ref_br | Log SP | SP ref_main |
|---|---|---|---|---|---|---|---|
| All lumped | 1, 1&2 | p>0.10 | p<0.001 | p<0.001 | p<0.001 | p>0.10 | p<0.001 |
| All lumped | none, 1 | p>0.10 | p>0.10 | p<0.001 | p<0.001 | p<0.007 | p>0.10 |
| All lumped | none, 1&2 | p>0.10 | p<0.001 | p<0.001 | p<0.001 | p>0.10 | p<0.001 |
| Colvin | none, 1 | p>0.10 | p>0.10 | p>0.10 | perfect | perfect | p>0.10 |
| Holly | none, 1 | p>0.10 | p>0.10 | p>0.10 | p<0.002 | p<0.002 | p>0.10 |
| Spann | none, 1 | p<0.001 | p<0.001 | p<0.001 | p<0.001 | p<0.001 | p<0.001 |

As shown in Table VII, General Linear Model Analysis of data associated with specific studies (Datadesk of Princeton, NJ) found that the area under the curve was significantly related to study and to which troubleshooting method was employed. As shown on Table IX, Scheffe Post Hoc Tests for Method showed no significant differences (p>0.2) among the areas for $X_{duct}$, LogSP and $SPrat_{br}$ or between areas for $SPH_{one}$ and $SPH_{two}$. All other comparisons were highly significant (p<0.001). If the lowest weighted obstructions were removed from the analysis, the differences between $SPrat_{main}$ and idIVM became insignificant (p>0.10).

When the data was pooled so that there was a common prevalence among all systems (see Table VII), all method differences were significant except $X_{duct}$ and $SPrat_{main}$ (P>0.10). If the lowest weighted obstructions were removed, then all comparisons were significant (p<0.05) except $X_{duct}$ and $SPrat_{br}$. When the next lowest ("moderate") obstructions were removed, the significance of the differences among areas remain unchanged.

Table IX: Suggested Thresholds and Their Efficacies in Lab Studies for Branch Ducts

| Method | %Thresh-old | No. Cases | Prev-ance | %False Pos. | %Sensitivity for each weight: all | very light | light | mod-erat | heavy, substantial | gross, near plug |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| $SPH_{one}$ | 34 | 132 | 33 | 11 | 55 | 0 | 0 | 9 | 89 | 100 |
| $SPH_{one}$ | 36 | 132 | 33 | 5 | 50 | 0 | 0 | 0 | 84 | 100 |
| | | | | | | | | | | |
| $SPH_{two}$ | 40 | 184 | 52 | 11 | 57 | 0 | 0 | 18 | 89 | 100 |
| $SPH_{two}$ | 50 | 184 | 52 | 8 | 50 | 0 | 0 | 14 | 76 | 100 |
| | | | | | | | | | | |
| idIVM | 0 | 132 | 33 | 3 | 75 | 0 | 14 | 64 | 100 | 100 |
| idIVM | 5 | 132 | 33 | 1 | 73 | 0 | 14 | 55 | 100 | 100 |
| | | | | | | | | | | |
| $X_{duct}$ | 10 | 182 | 53 | 2 | 85 | 0 | 38 | 91 | 100 | 100 |
| $X_{duct}$ | 12 | 182 | 53 | 0 | 85 | 0 | 38 | 91 | 100 | 100 |
| | | | | | | | | | | |
| $SPrat_{br}$ | 10 | 184 | 52 | 1 | 86 | 0 | 44 | 91 | 100 | 100 |
| $SPrat_{br}$ | 15 | 184 | 52 | 0 | 81 | 0 | 13 | 91 | 100 | 100 |
| | | | | | | | | | | |
| $SPrat_{main}$ | 20 | 184 | 52 | 19 | 72 | 0 | 6 | 55 | 100 | 100 |
| $SPrat_{main}$ | 40 | 184 | 52 | 6 | 60 | 0 | 0 | 18 | 96 | 100 |

*Selection of thresholds for troubleshooting the laboratory-based systems*

Table IX represents thresholds selected for optimal results for each method under the ideal conditions of the laboratory studies. On the assumption that the false positive rates for the field studies would be considerably higher than those found at the same thresholds in the lab study, the thresholds were selected to keep false positive rates as low as possible without reducing sensitivities to uselessly low levels, especially for the three categories representing the most substantial obstructions (i.e., weight differences greater than 2).

Note, however, that even at 11% false positive rates both $SPH_{one}$ and $SPH_{two}$ could detect less than a fifth of the Weight 3 obstructions and less than 90% of the Weight 4 obstructions. The idIVM method was much better, mainly because it almost never produced false positives even with a threshold of zero. The $X_{duct}$ and $SPrat_{br}$ methods had much better sensitivities than idIVM with similarly trivial false positive rates. The $SPrat_{main}$ method was not as good as idIVM but was much better than $SPH_{one}$ and $SPH_{two}$.

## Results of field studies

*Repeatability of measurements*

Measurement error was determined in the MezEast and MezWest systems by taking the percent difference of measurements repeated on the same day on ducts that were supposedly clean during both sets of measurements systems (see Table X and Figure 5). Each system had one branch with unusually large variations in measurements. One was a 4 inch diameter duct containing an orifice with a 2 inch opening.

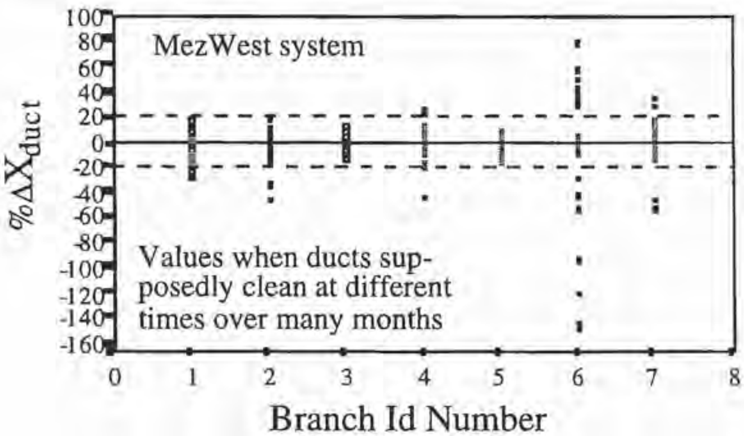


Figure 5: Variability of $X_{duct}$ when ducts are clean

Table X: Percentage Deviation of Paired Observations When Ducts were Presumed Clean

| Parameter | %Deviation |
|---|---|
| Velocity | 5.45 |
| Velocity* | 2.32 |
| SPH | 2.87 |
| SPend | 1.65 |
| SPref | 1.24 |
| SPH/SPref | 2.55 |
| SPH/SPend | 1.98 |
| $X_{duct}$ | 11.3 |
| $X_{duct}$* | 3.88 |

*without 2 highly variable brancl

*Table XI: Field studies prevalence rates for obstructions of each weight*

| Ducts | Method | No. Cases | all | very light | light | mod-erat | heavy, subst-antial | gross | nearly plugged |
|---|---|---|---|---|---|---|---|---|---|
| br | $SPH_{one}$, $SPH_{two}$, idlVM | 543 | 32.2 | 3.1 | 10.1 | 11.0 | 6.4 | 0.0 | 1.5 |
| | | | | | | | | | |
| | $X_{duct}$ | 560 | 30.0 | 3.4 | 8.8 | 10.5 | 6.3 | 0.0 | 1.1 |
| | $SPrat_{br}$ | 560 | 32.2 | 3.1 | 10.1 | 11.0 | 6.4 | 0.0 | 1.5 |
| | $SPrat_{main}$ | 459 | 29.8 | 3.4 | 8.8 | 10.4 | 6.3 | 0.0 | 0.9 |
| | | | | | | | | | |
| sub | $X_{duct}$ | | 7.3 | 0.0 | 2.0 | 4.9 | 0.0 | 0.0 | 0.0 |

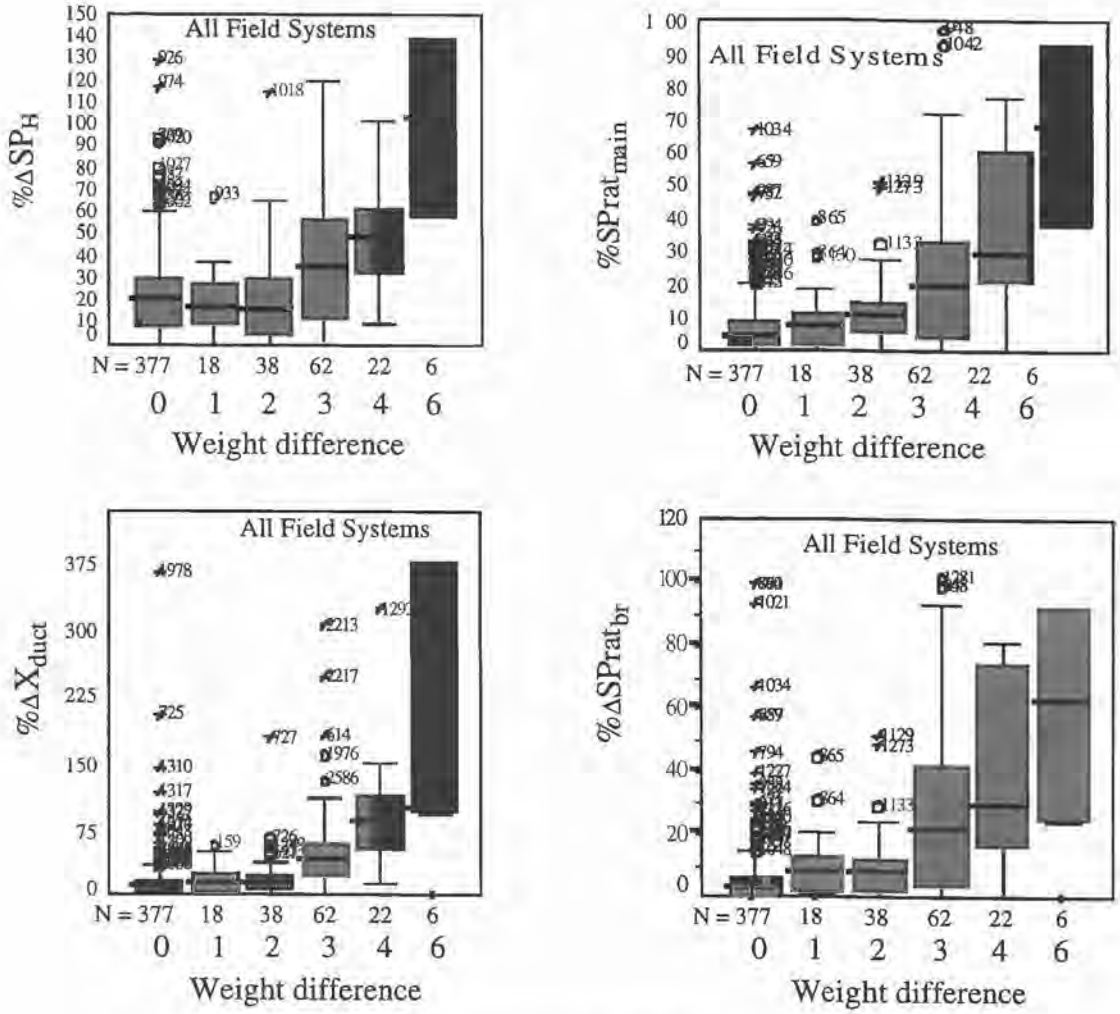


Figure 6: Variability of Parameters for Different Weights

Table XII: Areas under the curve for field studies

| | | | | Percentage of cases with weight | | | | Direct Pressure Comp. Methods | | | Ratio Methods | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System Name | WtDiffs Excl. | Omit Branc | Total Cases | very light | light | moderat | substant | $SPH_o$ne | SPH two | ideal IVM | X duct | SP ref_br | Log SP | SPrat main |
| All field pooled | none | | 704 | 4 | 9 | 12 | 8 | 0.40 | 0.64 | 0.17 | 0.76 | 0.79 | 0.68 | 0.75 |
| | 1 | | 677 | 0 | 10 | 13 | 9 | 0.40 | 0.66 | 0.18 | 0.79 | 0.81 | 0.69 | 0.76 |
| | 1,2 | | 612 | 0 | 0 | 14 | 9 | 0.43 | 0.70 | 0.22 | 0.88 | 0.90 | 0.73 | 0.79 |
| | 1,2,3 | | 525 | 0 | 0 | 0 | 11 | 0.40 | 0.78 | 0.24 | 0.92 | 0.91 | 0.79 | 0.85 |
| | 1,2,3,4 | | 525 | 0 | 0 | 0 | 11 | 0.40 | 0.78 | 0.24 | 0.92 | 0.91 | 0.79 | 0.85 |
| Bandsaw | none | | 75 | 9 | 16 | 16 | 17 | 0.20 | 0.66 | N/A | 0.78 | 0.76 | 0.74 | 0.84 |
| | 1 | | 68 | 0 | 18 | 18 | 19 | 0.18 | 0.70 | 0.11 | 0.83 | 0.82 | 0.82 | 0.85 |
| | 1,2 | | 56 | 0 | 0 | 21 | 23 | 0.19 | 0.77 | 0.16 | 0.98 | 0.93 | 0.93 | 0.91 |
| | 1,2,3 | | 44 | 0 | 0 | 0 | 30 | 0.31 | 0.97 | 0.31 | 1.00 | 1.00 | 1.00 | 1.00 |
| DrySaw | 1 | | 107 | 0 | 4 | 9 | 4 | 0.35 | 0.70 | 0.11 | 0.93 | 0.88 | 0.88 | 1.00 |
| | 1,2 | | 107 | 0 | 4 | 9 | 4 | 0.35 | 0.70 | 0.11 | 0.93 | 0.88 | 0.88 | 1.00 |
| | 1,2,3 | | 103 | 0 | 0 | 10 | 4 | 0.27 | 0.70 | 0.14 | 0.97 | 0.92 | 0.92 | 1.00 |
| Cabinet Shop | 1 | | 139 | 0 | 4 | 20 | 4 | 0.40 | 0.57 | 0.26 | 0.75 | 0.77 | 0.45 | 0.61 |
| | 1,2 | | 133 | 0 | 0 | 21 | 4 | 0.43 | 0.58 | 0.28 | 0.75 | 0.81 | 0.40 | 0.58 |
| | 1,2,3 | | 105 | 0 | 0 | 0 | 5 | 0.02 | 0.27 | 0.00 | 0.85 | 0.56 | 0.12 | 0.44 |
| | 0 | 5 | 120 | 2 | 5 | 14 | 1 | 0.41 | 0.59 | 0.49 | 0.76 | 0.78 | 0.74 | 0.80 |
| | 2 | 5 | 112 | 0 | 0 | 15 | 1 | 0.45 | 0.60 | 0.55 | 0.74 | 0.81 | 0.73 | 0.82 |
| MezEast | none | | 110 | 2 | 8 | 15 | 10 | 0.49 | 0.68 | 0.11 | 0.77 | 0.75 | 0.67 | 0.75 |
| | 1 | | 108 | 0 | 8 | 15 | 10 | 0.48 | 0.68 | 0.11 | 0.76 | 0.78 | 0.68 | 0.78 |
| | 1,2 | | 99 | 0 | 0 | 16 | 11 | 0.56 | 0.77 | N/A | 0.86 | 0.87 | 0.76 | 0.83 |
| Model Shop | none | | 78 | 15 | 32 | 10 | 13 | 0.42 | 0.58 | N/A | 0.60 | 0.72 | 0.62 | 0.79 |
| | 1 | | 66 | 0 | 38 | 12 | 15 | 0.48 | 0.64 | 0.10 | 0.61 | 0.74 | 0.60 | 0.82 |
| | 1,2 | | 41 | 0 | 0 | 20 | 24 | 0.69 | 0.81 | 0.18 | 0.80 | 0.88 | 0.57 | 0.91 |
| MezWest | none | | 193 | 2 | 5 | 7 | 8 | 0.56 | 0.70 | 0.29 | 0.80 | 0.86 | 0.85 | 0.82 |
| | 1 | | 189 | 0 | 5 | 7 | 8 | 0.57 | 0.71 | 0.32 | 0.85 | 0.89 | 0.88 | 0.87 |
| | 1,2 | | 180 | 0 | 0 | 7 | 8 | 0.53 | 0.70 | 0.39 | 0.88 | 0.95 | 0.93 | 0.91 |
| | 1,2,3 | | 167 | 0 | 0 | 0 | 9 | 0.53 | 0.80 | 0.53 | 0.90 | 0.97 | 0.98 | 0.98 |

*pooled field data*

As shown for $X_{duct}$ on Figure 5, there was significant variability in troubleshooting parameter values when supposedly clean ducts were re-measured at different times over many months. Note that values for Branch 6 were substantially more variable than other ducts, probably because of the very poor measurement conditions produced by an orifice welded inside the duct. As might be expected, many of the same measurements produced false positives in all methods. Note also that several values from other ducts exceeded the

20% threshold associated with 5% shifts in airflow, suggesting that detecting alterations just capable of producing 5% percent shifts in airflow may be difficult.

One would hope that the subjective classification scheme would produce distinct populations with as little overlap as possible. As shown on Figure 6, the lower weights may have required a higher degree of precision and resolution than subjective classification could deliver. For the more substantial weight classifications $X_{duct}$ and SPHref_br appeared to produce the least overlap with clean condition (weight=0) values. However, none of the parameters produced clear separations between clean conditions and the lower three weight classifications. This may indicate that the investigators were unable to make precise distinctions among less substantial obstructions and that the less substantial obstructions were unimportant. It is interesting to note that the median $X_{duct}$ values for weights 1 and 2 were below the 20% threshold that is associated with a roughly 5% shift in airflows.

Compared to laboratory study results, the values of $A_{ROC}$ found in the field studies were substantially lower for all methods and restrictions (see Table XII). However, the superiority of the $X_{duct}$ and $SPrat_{br}$ methods for these data was just as apparent. Removing lesser alterations from the analysis substantially improved performance for all methods except for idIVM and $SPH_{one}$ (see Table XII).

Even the best performing methods were much less than perfect (i.e., $A_{ROC}$=1) for the lower weight classes. As shown on Table XII, the values of $A_{ROC}$ for $X_{duct}$ and $SPrat_{br}$ exceeded 0.90 only when all but the most substantial alterations were excluded. However, the superiority of the pressure ratio methods was striking. $SPrat_{br}$ and $X_{duct}$ had values of $A_{ROC}$ that were consistently higher than those for other methods — and the advantage increased as lower weighted obstructions were removed from the mix. The $SPrat_{main}$ values were slightly to somewhat lower than $SPrat_{br}$ and $X_{duct}$ for each group of weights considered and were always substantially higher than $SPH_{two}$, the next highest ranking method. $SPH_{two}$ was far superior to $SPH_{one}$ and idIVM. The latter was abysmally lower, never exceeding 0.24 even when only the most profound obstructions were included in the analysis.

LogSP was inferior to $SPrat_{br}$. Since it require the same information as $SPrat_{br}$, it offered no advantage and was dropped from further consideration.

*individual duct systems*

The results were similar when each system was analyzed separately (see Table XII). The idIVM and $SPH_{one}$ methods values of $A_{ROC}$ never exceeded 0.60 and generally were much lower, in some cases in the single digits. With the exception of the ModelShop, $SPH_{two}$ was generally much lower than $SPrat_{main}$, $X_{duct}$ , or $SPrat_{br}$. The $SPrat_{br}$ method was sometimes somewhat higher than $X_{duct}$ and $SPrat_{main}$, but more often the three methods performed about the same.

Table XIII: Geometric standard deviation of areas under the curve for all field studies

| | | | | Direct Pressure Comp. Methods | | | Ratio Methods | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| System Name | WtDiffs Excl. | Omit Branc | Total Cases | SPHone | SPH two | ideal IVM | X duct | SP ref_br | Log SP | SPratmain |
| All field pooled | none | | 704 | 1.08 | 1.04 | 1.15 | 1.04 | 1.03 | 1.04 | 1.04 |
| | 1 | | 677 | 1.08 | 1.04 | 1.14 | 1.03 | 1.03 | 1.04 | 1.03 |
| | 1,2 | | 612 | 1.08 | 1.04 | 1.21 | 1.03 | 1.02 | 1.05 | 1.05 |
| | 1,2,3 | | 525 | 1.16 | 1.05 | 1.26 | 1.03 | 1.03 | 1.06 | 1.04 |
| | 1,2,3,4 | | 525 | 1.18 | 1.06 | 1.40 | 1.03 | 1.04 | 1.06 | 1.06 |
| Bandsaw | none | | 75 | 1.27 | 1.11 | 1.19 | 1.07 | 1.09 | 1.09 | 1.08 |
| | 1 | | 68 | 1.32 | 1.11 | 1.68 | 1.06 | 1.06 | 1.06 | 1.06 |
| | 1,2 | | 56 | 1.38 | 1.08 | 1.42 | 1.02 | 1.04 | 1.04 | 1.07 |
| | 1,2,3 | | 44 | 1.54 | 1.03 | 1.44 | 1.00 | 1.00 | 1.00 | 1.00 |
| DrySaw | 1 | | 107 | 1.27 | 1.17 | 1.62 | 1.03 | 1.06 | 1.06 | 1.00 |
| | 1,2 | | 107 | 1.26 | 1.15 | 1.67 | 1.04 | 1.06 | 1.06 | 1.00 |
| | 1,2,3 | | 103 | 1.63 | 1.17 | 1.52 | 1.02 | 1.04 | 1.03 | 1.00 |
| Cabinet Shop | 1 | | 139 | 1.15 | 1.08 | 1.28 | 1.07 | 1.09 | 1.18 | 1.08 |
| | 1,2 | | 133 | 1.18 | 1.12 | 1.31 | 1.06 | 1.12 | 1.30 | 1.11 |
| | 1,2,3 | | 105 | 1.19 | 1.09 | 1.30 | 1.14 | 1.10 | 1.43 | 1.22 |
| | 0 | 5 | 120 | 1.19 | 1.09 | 1.30 | 1.08 | 1.08 | 1.11 | 1.05 |
| | 2 | 5 | 112 | 1.15 | 1.11 | 1.26 | 1.10 | 1.09 | 1.11 | 1.05 |
| MezEast | none | | 110 | 1.16 | 1.10 | 1.27 | 1.09 | 1.08 | 1.09 | 1.06 |
| | 1 | | 108 | 1.18 | 1.09 | 1.43 | 1.09 | 1.10 | 1.12 | 1.06 |
| | 1,2 | | 99 | 1.13 | 1.07 | 1.38 | 1.05 | 1.04 | 1.07 | 1.07 |
| Model Shop | none | | 78 | 1.15 | 1.13 | 1.23 | 1.27 | 1.11 | 1.13 | 1.07 |
| | 1 | | 66 | 1.18 | 1.10 | 1.33 | 1.15 | 1.10 | 1.11 | 1.08 |
| | 1,2 | | 41 | 1.19 | 1.11 | 1.49 | 1.14 | 1.11 | 1.27 | 1.06 |
| MezWest | none | | 193 | 1.10 | 1.06 | 1.29 | 1.03 | 1.06 | 1.06 | 1.06 |
| | 1 | | 189 | 1.12 | 1.07 | 1.26 | 1.04 | 1.03 | 1.04 | 1.04 |
| | 1,2 | | 180 | 1.13 | 1.10 | 1.27 | 1.03 | 1.02 | 1.05 | 1.04 |
| | 1,2,3 | | 167 | 1.23 | 1.09 | 1.29 | 1.04 | 1.01 | 1.01 | 1.01 |

## Discussion of field studies

As expected, values of $A_{ROC}$ were substantially lower for the field conditions than for the laboratory conditions. As discussed in earlier sections, under field conditions one could expect more misclassification errors, especially in mistakenly assigning a negative condition when an alteration was simply not observed. Thus one could also expect deflated sensitivities and inflated false positive rates for all methods. Higher measurement errors also could reduce differences in $A_{ROC}$ values for different methods. For example, in the Laboratory studies $X_{duct}$ and $SPrat_{br}$ were far superior to other methods in detecting the lesser alterations. With higher measurement errors, all methods would have more difficulty in distinguishing small changes. The methods that were very successful in detecting less changes under good measurement conditions would be disproportionately affected by reduced resolution when compared to methods that already did poorly.

Table XIV: Significance of method and vent system for field systems with all obstructions included

**Field systems data**, Dependent Variable: Area under the curve, $A_{ROC}$

| Source | df | Sums of Sq. | Mean Square | F-ratio | Probability |
|---|---|---|---|---|---|
| Const | 1 | 672.779 | 672.779 | 171668 | ≤ 0.0001 |
| Vent study | 5 | 4.96916 | 0.993831 | 253.59 | ≤ 0.0001 |
| Method name | 6 | 73.4423 | 12.2404 | 3123.3 | ≤ 0.0001 |
| Study*Method | 30 | 10.2613 | 0.342043 | 87.276 | ≤ 0.0001 |
| Error | 1638 | 6.41944 | 0.003919 | | |
| Total | 1679 | 117.323 | | | |

The interesting finding was that the $SPH_{one}$ and idIVM methods suffered disproportionate declines in $A_{ROC}$ when compared to the other methods. As might be expected when $A_{ROC}$ values were very low, the low-scoring $SPH_{one}$ and idIVM had substantially higher $A_{ROC}$ variability than the higher scoring methods when cases were randomly selected in "bootstrap" determinations of the variability for each method (see Table XIII).

As shown in Table XIV, when data was associated with specific studies, General Linear Model Analysis (Datadesk of Princeton, NJ) found that the area under the curve was significantly related to vent system and to which troubleshooting method was employed. Scheffe Post Hoc Tests for Method (Table XV) showed no significant differences ($p>0.2$) between $SPrat_{br}$ and $X_{duct}$. Otherwise, all differences among methods were highly significant ($p<0.005$). If the lowest weighted obstructions were removed from the analysis, the differences between $SPrat_{br}$, $X_{duct}$, and $SPrat_{main}$ became insignificant ($p>0.10$). The same was true when any other combination of weights were removed from the analysis.

When the data was pooled so that there was a common prevalence among all systems (see Table XIV), all method differences were significant ($p<0.001$) except $X_{duct}$ and $SPrat_{main}$ ($P>0.50$). $SPrat_{br}$ was significantly better than $SPrat_{main}$ but marginally better than $X_{duct}$ ($p<0.04$). The same results prevailed when the lowest weighted obstructions were removed. When Weights 1 and 2 were removed then all comparisons were significant ($p<0.001$) except $SPrat_{br}$ and $X_{duct}$. The same was true when all weights below 4 were removed.

This analysis suggests that for these data $SPrat_{br}$, $X_{duct}$, and $SPrat_{main}$ all perform equally well and that all work much better than the direct pressure comparison methods.

Table XV: Thresholds for false positive rates of 10% and 20% and the resulting sensitivities for Branch Ducts in Field Studies

| | | | | | %Sensitivity for each weight diff. | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Method | %Thres hold | No. Cases | Prev -ance | %False Pos. | All | very light | light | mod -erat | heavys ubstan tial | gross, near plug |
| $SPH_{one}$ | 35 | 543 | 32 | 20 | 29 | 12 | 22 | 33 | 31 | 63 |
| | 46 | 543 | 32 | 10 | 19 | 5.9 | 7.3 | 25 | 23 | 63 |
| $SPH_{two}$ | 35 | 543 | 32 | 20 | 48 | 12 | 35 | 45 | 80 | 100 |
| | 46 | 543 | 32 | 10 | 35 | 6 | 16 | 32 | 69 | 100 |
| idIVM | 0 | 543 | 32 | 5 | 24 | 0 | 16 | 33 | 34 | 13 |
| $X_{duct}$ | 17 | 560 | 30 | 20 | 61 | 16 | 29 | 78 | 97 | 100 |
| | 25.5 | 560 | 30 | 10 | 51 | 11 | 14 | 63 | 94 | 100 |
| $SPrat_{br}$ | 8 | 543 | 32 | 20 | 65 | 18 | 38 | 85 | 89 | 100 |
| | 11.5 | 543 | 32 | 10 | 58 | 6 | 27 | 78 | 86 | 100 |
| $SPrat_{main}$ | 11 | 459 | 31 | 20 | 65 | 33 | 38 | 75 | 90 | 100 |
| | 21 | 459 | 31 | 10 | 44 | 6.7 | 12 | 48 | 84 | 100 |

## *Thresholds*

In practice, one must pick an optimal threshold for action for one's method of choice. It would then be useful to know what performance one could expect in terms of sensitivity for each weight of obstructions and in terms of the accompanying false positive rate.

As shown in Table XV, for thresholds for which false positive rates (FPR) were either 10% or 20%, no method was perfect for obstructions assigned a weight of less than 6. The lower the weighting, the less sensitivity achieved. However, some methods were clearly more sensitivity than others at the same false positive rate.

In particular, $SPH_{one}$ and idIVM performed very poorly even for the grossest weighting of obstructions. The $SPH_{one}$ and idIVM were grossly inferior in every category. Even with a zero threshold, idIVM achieved excellent selectivity (FPR=5%) but at the price of uselessly low sensitivities (24% overall). Even at FPR=20%, the overall sensitivity for $SPH_{one}$ was less than 65% even for the highest weighted obstructions.

The $X_{duct}$ method achieved the highest sensitivities for weights above 3. It was nearly perfect for the latter. The $SPrat_{br}$ and $SPrat_{main}$ methods were perfect for the profound obstructions, but were 7 to 10% lower than $X_{duct}$ for Weight 4. $SPrat_{br}$ was superior for Weight 3 with $X_{duct}$ second. The $SPrat_{main}$ was only slightly less sensitive for major obstructions if a 20% false positive rate was acceptable but considerably less effective if a 10% false positive rate was the goal. The $SPH_{two}$ method was perfect in detecting the most severe ranking of obstructions but otherwise was inferior to the pressure ratio methods.

Even the highest scoring methods (i.e., $X_{duct}$, $SPrat_{br}$, and $SPrat_{main}$) produced sensitivities below 40% for weights below Weight 3.

## Discussion of all results

The efficacies of all methods were much higher for laboratory than for field conditions, probably because of the greater certainty of classification of obstructions and the ideal measurement conditions in the lab studies. However, the pressure ratio methods were substantially superior to the direct pressure comparison methods both in the field and in the lab. The traditional hood static pressure method ($SPH_{one}$) and the idealized version of the *Industrial Ventilation* commissioning method were greatly inferior to other methods in all tests and performed particularly poorly in the field tests. Given the number and diversity of the systems studied in the lab and in field, it is unlikely that wider testing would find that the traditional methods work well.

However, it is likely that the true efficacy of every method was moderately higher than found in the field study. It was certainly possible that some of the "false positives" produced by the methods should have been credited as true positives because the investigators simply failed to detect some obstructions using the borescope. Furthermore, some obstructions observed by the investigators could have been misclassified as "light" when they were truly "substantial" — or vice versa. As shown in Figure 6, the subjective weight classification scheme was perhaps too ambitious in attempting to distinguish between "clean" conditions and "very light" or "light" obstructions. In addition, the median $X_{duct}$ values of the lowest two classifications were below the 20% threshold associated with 5% shifts in airflow.

Assuming there were at least a moderate number of misclassifications, one would expect the troubleshooting methods to suffer deflated areas under the receiver operator characteristic curves ($A_{ROC}$). However, there is no reason to believe that the misclassifications would affect some troubleshooting methods more than others. The findings strongly support the robustness of the relative rankings of methods in two ways: 1) the same rankings were observed under the ideal conditions of laboratory studies, and 2) the same $A_{ROC}$ rankings were observed when the lowest weighted obstructions were removed.

The ability of the methods to detect obstructions varied with the level of false positives one was willing to accept. The P.I. chose 10% and 20% false positive rates as target levels of performance, but the sensitivity of the pressure ratio methods was superior at both higher and lower acceptable false positive rates.

It should be noted that the $SPH_{one}$ and idIVM methods produced inferior results despite numerous factors that would tend to maximize their performance. In addition to using an "idealized" version of the method of *Industrial Ventilation*, the study avoided two important test conditions that would nearly always defeat both methods, including :

1. leaks in ducts
2. alterations that *decreased* resistance to flow (easily demonstrated with the same data)

On the other hand, the $X_{duct}$ method is highly dependent on the accuracy of velocity pressure measurements, which in turn are dependent on measurement conditions and on the level of the velocities measured. Although some of the systems (e.g., Bandsaw) had very poor conditions, the $X_{duct}$ methods still performed well above $SPH_{one}$ and idIVM and as well as SPHref_br. However, the study systems were all designed for dusty processes and thus had relatively high velocities — which was appropriate for a troubleshooting study since they are far more prone to developing obstructions. For systems with duct velocities below 1,000 ft/min, one might expect the decreased accuracy of VP measurements to degrade the performance of the $X_{duct}$ method. However, the $SPrat_{br}$ and $SPrat_{main}$ methods do not employ velocities and thus should maintain their superiority over direct pressure comparison methods in low velocity systems.

Finally, the $SPH_{two}$ method had a performance somewhat lower than the pressure ratio methods and it could consistently mislead a practitioner if the fan speed is changed, but it has the advantage of convenience. It requires only SPH, which can usually be measured without recourse to ladders. For systems which are monitored frequently $SPH_{two}$ may be the method of choice. For systems that are rarely monitored, it also could be used as a screening test to determine if one needed to take the additional measurements required for the pressure ratio methods.

# CONCLUSIONS

For the study conditions (e.g., relatively high velocity dust systems) the pressure ratio methods were superior to the direct pressure comparison methods by wide margins. The efficacy of the $X_{duct}$ method could be expected to be lower for very low velocity systems (e.g., less than 1000 ft/min). All other methods should be affected equally by the lower static pressures typically found in low velocity systems.

Based on the results of this study, the $SPH_{one}$ method should be abandoned. If only $SP_H$ will be measured, the $SPH_{two}$ method is the better choice since it also requires only measurements of $SP_H$ and is superior to $SPH_{one}$ in values of $A_{ROC}$ and in sensitivities at reasonable false positive rates (e.g., 10% to 20%). The assumption that magnitudes of $SP_H$ can only decline if an obstruction occurs apparently was false even in a study where all obstructions occurred downstream of the $SP_H$ measurement location.

The commissioning method of *Industrial Ventilation* should not be used for troubleshooting installed systems if a previous round of measurements is available. Even when the effects of incorrect fan settings and loss coefficients were removed, it was greatly inferior to the $SPrat_{br}$ method, which requires exactly the same information.

## Recommendations for practitioners

If it is possible to measure only $SP_H$, use the $SPH_{two}$ method with the thresholds shown in Table XV. For the next level of effort, if many branches will be tested, use the $SPrat_{main}$ method, which requires values of $SP_H$ and the pressure in one downstream main. If a few highly suspect branches will be tested or if one is willing to go to the next level of effort, measure values of $SP_{end}$ for each branch to be tested and employ the $SPrat_{br}$ method. If one is willing to measure duct velocities, employ the $X_{duct}$ method.

Do not assume that an increase in magnitude of $SP_H$ rules out the presence of an alteration (i.e., do not use the $SPH_{one}$ method). Do not use the method of *Industrial Ventilation* (whether idealized or not) to troubleshoot installed systems if a previous round of measurements is available. In practice, it requires the same information as the $SPrat_{br}$ method, and its performance is greatly inferior to it.

## ACKNOWLEDGMENTS

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## REFERENCES

Alden J, Kane JM: Design of Industrial Ventilation Systems, 5th ed. New York, Industrial Press, 1982

Alnor Instrument Company: CompuFlow ElectroManometer Model 8530D-1, Manual #116-159-035 REV 2, Skokie, Illinois, April, 1990

American Conference of Governmental Industrial Hygienists Committee on Industrial Ventilation: Industrial Ventilation: A Manual of Recommended Practice, 23rd edition, Cincinnati, OH, ACGIH, 1997

American Society of Heating Refrigerating and Air-Conditioning Engineers: ASHRAE Handbook -- 1995 Fundamentals. Atlanta, GA, ASHRAE, 1995

Baturin VV: Fundamentals of Industrial Ventilation, 3d ed. Translated by O. M. Blunn. New York: Pergamon, 1972.

Beck JR, Shultz EK: The Use of Relative Operating Characteristic (ROC) Curves in Test Performance Evaluation. Arch. Pathol. Lab. Med. 110 Jan 1986: 13 - 20

Brandt AD: Dividends From Ventilation Dollars: Safety Engineering, pp 14-15, 36-38, August, 1950

Burgess WA, Ellenbecker M, Treitman R: Ventilation for Control of the Work Environment. New York: John Wiley, 1989

Burton D J: Industrial Ventilation: A Self Study Companion to the ACGIH Ventilation Manual, Salt Lake City, UT: Jeff Burton, 1982

Burton JD: Guidelines for Containment Testing in Exhaust Ventilation. Occupational Health and Safety, pp22, 26, June, 1995

Carrel TF: Validation of Power Loss Modeling in Predicting the Effects of Removing One or More Branches From a Five Branch Ventilation System, MS Thesis, University of Washington, 1993

Colvin SC: Experimental Validation of the Efficacy of Power Loss Coefficients in Detecting Ventilation System Modifications and in Predicting New Airflow Levels and Pressures, MS Thesis, Department of Environmental Health, University of Washington, 1993

Cutter TJ: Preparation Steps and Instruments for Testing Process Exhaust Systems, Plant Engineering, pp 97-132, September, 1976

Dwyer Instruments, Inc.: Pitot Tube Operating Instructions, Bulletin No. H-11, Michigan City, IN, 1989

Dwyer Instruments, Inc.: Series 1425 Hook Gage Operating Instructions, Bulletin No. D-56, Michigan City, IN

Geiger H: Test of the Accuracy of a Proposed Airflow Balancing Method in a Laboratory Ventilation System, MS Thesis, University of Washington, 1997

Guffey SE, Booth DW: Comparison of Pitot Traverses Taken at Varying Distance Downstream of Obstructions. Am. Ind. Hyg. Assoc. J. (submitted MS 823)

Guffey SE, Curran JC: Use of Power Balance to Model Pressures in Bilateral Junctions for Converging Flow Ventilation Systems. Am. Ind. Hyg. Assoc. J., 54(3):102–112, 1993

Guffey SE, Spann JG: Experimental investigation of power loss coefficients and static pressure ratios in an industrial exhaust ventilation system, Am. Ind. Hyg. Assoc. J. (submitted)

Guffey SE: A Computerized Data Acquisition and Reduction System for Velocity Traverses in a Ventilation Laboratory. ASHRAE Transactions, 98(1):98-106, 1992

Guffey SE: Airflow Distribution in Exhaust Ventilation Systems. Am. Ind. Hyg. Assoc. J., 52(3):93–106, 1991

Guffey SE: Airflow Redistribution in Exhaust Ventilation Systems Using Dampers and Static Pressure Ratios. Applied Occup. Environ. Hyg., 8(3):168–177, 1993

Guffey SE: Modeling Existing Ventilation Systems Using Measured Values. Am. Ind. Hyg. Assoc. J., 54(6):293–306, 1993

Guffey SE: Quantitative Troubleshooting of Industrial Exhaust Ventilation Systems. Applied Occup. Environ. Hyg., 9(4):267–280, 1994

Guffey SE: Simplifying Pitot Traverses. Applied Occup. Environ. Hyg., 5(2): 95-100, 1990

Guffey SE: HEAVENT: Software for the Design and Redesign of Industrial Exhaust Ventilation Systems for Contaminant Control. Seattle, WA, 1996.

Guffey SE: Hv_Meas: Data Acquisition Software for Industrial Ventilation System Measurements. Seattle, WA, 1997

Guffey, SE: Simplifying Pitot Traverses. Appl. Occup. Environ. Hyg. 5(2):95-100, 1990

Guffey SE, Fraser DA: A Power Balance Model for Converging and Diverging Flow Junctions. ASHRAE Transactions, 1988

Hoppe, SJ: Empirical Determination of the Error in the ACGIH Method of Predicting Airflow Distribution in Two Industrial Ventilation Systems, MS Thesis, University of Washington, 1995

McDermott HJ: Handbook for Ventilation for Contaminant Control, 2d ed. Boston, Butterworth, 1985

Metz CE: Basic Principles of ROC Analysis. Seminars in Nuclear Medicine 8, No. 4 283 - 98, 1978

National Safety Council, Data Sheet I-431-80, Instruments for Testing Exhaust Ventilation Systems. National Safety News, pp 71-78, April, 1980

Ower E, Pankhurst RC: The Measurement of Air Flow, 5th ed. New York, Pergamon, 1977

Pinsky A: Comparison of Efficacies of Current Methods for Troubleshooting Industrial Exhaust Ventilation Systems to a Proposed New Method, MS Thesis, Department of Environmental Health, University of Washington, 1996

Spann JG: Experimental Investigation of Power Loss Coefficients and Static Pressure Ratios in an Industrial Exhaust Ventilation System, MS Thesis, Department of Environmental Health, University of Washington, 1993

U.S. Department of Health, Education, and Welfare, Public Health Service Centers for Disease Control, NIOSH Research Project: A Recommended Approach to Recirculation of Exhaust Air, Cincinnati, Ohio, January 1978.

Wang L: Repeatability of Velocity Pressure Traverses and Static Pressure Measurements in Five Working Ventilation Systems, MS Thesis, Department of Environmental Health, University of Washington, 1997

# APPENDICES — MASTERS THESIS ABSTRACTS

1. Hoppe, JS. "Empirical Determination of the Error in the ACGIH Method of Predicting Airflow Distribution in Two Industrial Ventilation Systems," MS Thesis, University of Washington, 1995.
2. Moody, D. Comparison of the efficacies of Troubleshooting Methodologies for Ventilation Systems — A Field Study." MS thesis, Department of Environmental Health, University of Washington, 1996.
3. Pinsky, Ann. "Comparison of Efficacies of Current Methods for Troubleshooting Industrial Exhaust Ventilation Systems to a Proposed New Method." MS thesis, Department of Environmental Health, University of Washington, 1996.
4. Wang, L. "Repeatability of Velocity Pressure Traverses and Static Pressure Measurements in Five Working Ventilation Systems." MS thesis, Department of Environmental Health, University of Washington, 1997

## Hoppe Masters Thesis

"Empirical Determination of the Error in the ACGIH Method of Predicting Airflow Distribution in Two Industrial Ventilation Systems," MS Thesis, University of Washington, 1995.

Ventilation systems are important in reducing worker exposure to airborne contaminants. To do this job sufficiently, ventilation systems must deliver the correct airflow to each hood according to its requirements. Proper airflow distribution is achieved through proper design, installation and maintenance. Proper design requires an accurate predictive model of the system. The most commonly used model is that described by the American Conference of Governmental Industrial Hygienists (ACGIH) in Industrial Ventilation: A Manual of Recommended Practice. The efficacy of this predictive model, which is based on published loss coefficients, has not been documented in the field and published literature.

It is the purpose of this field study to compare the observed loss coefficients to those published by the ACGIH in the Industrial Ventilation manual. In this study, the error is determined by analyzing the differences between the observed sum of loss coefficients and the sum of published loss coefficients for each branch. Error in the loss coefficients is important because it results in a proportional error in airflow distribution.

The data analysis for this work focused on the coefficients for different components (e.g. hoods, elbows) in an effort to identify the sources of deviation from the predicted sum of coefficients. That analysis indicated substantial discrepancies between the predicted and observed sums of loss coefficients which may translate into unacceptable shifts in airflow distribution.

Table XVI: Frequency Breakdown of $F_{NotHood}$ Relative Error

| Group | Count | % |
|---|---|---|
| < -16% | 24 | 34.3 |
| Within ± 16% | 9 | 12.9 |
| > 16% | 37 | 52.9 |
| Total | 70 | |

| Group | Count | % |
|---|---|---|
| < -25% | 21 | 30 |
| Within ± 25% | 21 | 30 |
| > 25% | 28 | 40 |
| Total | 70 | |

| Group | Count | % |
|---|---|---|
| < -50% | 15 | 21.4 |
| Within ± 50% | 37 | 52.9 |
| > 50% | 18 | 25.7 |
| Total | 70 | |

Table XVII: Frequency Breakdown of Relative Error $F_{NotHood}$
(Branches with bad $SP_H$ location removed.)

| Group | Count | % |
|---|---|---|
| < -16% | 11 | 25.6 |
| Within ± 16% | 5 | 11.6 |
| > 16% | 27 | 62.8 |
| total | 43 | |

| Group | Count | % |
|---|---|---|
| < -25% | 8 | 18.6 |
| Within ± 25% | 17 | 39.5 |
| > 25% | 18 | 41.9 |
| total | 43 | |

| Group | Count | % |
|---|---|---|
| < -50% | 3 | 6.98 |
| Within ± 50% | 32 | 74.4 |
| > 50% | 8 | 18.6 |

## Moody Masters Thesis

Moody, D. Comparison of the efficacies of Troubleshooting Methodologies for Ventilation Systems — A Field Study." MS thesis, Department of Environmental Health, University of Washington, 1996.

For a ventilation system to control deleterious worker exposures most efficiently, the system ductwork must distribute the airflow in the correct proportions to all the branches serving the hoods. Even if good distribution is established when the system is first installed, the distribution may become increasingly unsatisfactory due to particle settling, alteration from the original design, wear, deformation of the ductwork, and other causes. This means that some hoods may receive excess airflow, while others receive a flow that is inadequate to properly protect workers using the hood. Visual inspection often fails to discover changes to ducts because of their opacity and poor accessibility. Thus, "troubleshooting" must rely on measurements of pressures and flows in the ducts to detect and locate alterations that can affect airflow distribution.

This field study compares the efficacy of six methods of troubleshooting ventilation system branches. Static pressures and airflows were measured on two different systems over a three month period. Repeat measurements were made on each system. The system was then inspected for obstructions or other alterations, cleaned out, and re measured. Sensitivity and specificity were then calculated for a full range of decision variable thresholds. Methods were compared using receiver operating characteristic curves.

The log transformed static pressure ratio and power loss coefficient (X-value) methods performed much better than the use of hood static pressures alone or the method described in *Industrial Ventilation Manual* (ACGIH, 1995). At a given sensitivity, both methods produce low numbers of costly searches for non-existent alterations. The log transformed static pressure ratio method does not require a time consuming velocity traverse, and thus may be the method of choice. The common hood static pressure method and the idealized IVM method both performed poorly.

The results of this study provide guidance to industrial hygienists and ventilation professionals as to what troubleshooting methodology is most effective. Equipped with troubleshooting methods that produce few false positives, practitioners may be encouraged to monitor systems more closely and intervene before hood performance has deteriorated to unsatisfactory levels.

## Pinsky Masters Thesis

"Comparison of Efficacies of Current Methods for Troubleshooting Industrial Exhaust Ventilation Systems to a Proposed New Method." MS thesis, Department of Environmental Health, University of Washington, 1996.

Industrial exhaust ventilation systems are designed to minimize worker exposure to airborne contaminants. For ventilation systems to operate effectively and to protect workers from harmful exposures, air drawn into the fan must be distributed among the hoods at predetermined (target) airflows. Over time systems age, incurring damage, obstructions, leaks and other alterations that skew the airflow distributions so that some hoods receive less than their target airflows. The ability to swiftly detect alterations ("troubleshooting") and restore systems to their previous working condition is therefore crucial for worker protection.

Two methods used to identify alterations that produce shifts in airflow distribution are long-standing, the Industrial Ventilation method (IVM) and the hood static pressure method. In use, it is assumed in both methods that a decrease in hood static pressure (SPH) indicates a new obstruction, but an increase in SPH does not. However, one could broaden the method and assume that an increase also can indicate a new obstruction, thus creating what is called here "One-Sided" and "Two-Side" Hood Static Pressure methods.

A third method is proposed by Guffey. It incorporates a variant of the hood static method and introduces two more diagnostic tests: ratios of static pressures (variable called "SPratio") and equivalent loss coefficients ("X-values") which are kinetic power loss coefficients for any volume. Previous laboratory studies have demonstrated the superiority of X-values in locating obstructions that have been deliberately placed in systems. This is important because shifts in airflow are generally due to obstructions. However, to determine values of X requires a time-consuming velocity pressure traverse. Therefore, it would be convenient to use static pressures as screening tools to reduce the number of cases where X-values must be determined.

In this study of an eleven branch ventilation system, static pressures were measured downstream of the hood (SPH), at the end of the branch (SPend), and at a location between the hood and end of the branch (SPmid). Velocity pressures were measured by a Pitot traverse at a convenient location in each branch. Cases where the change in X exceeded a specified threshold were deemed "obstructed." A screening test was deemed "positive" if the change in its variable value(s) exceeded a given threshold. A "true positive" for a method occurred when the value of X for a branch changed by more than a given X-threshold and the value of the method variable changed by more than its threshold. Thresholds for X were tested at values ranging from 0.05 to 0.6 and thresholds for each screening test's variable were varied from 0.0 to 0.6. A family of receiver operating characteristic (ROC) curves were drawn at each threshold for X. Performance for each screening tool was judged in part by area under the ROC curve.

The results of this study were that in every case the areas under the ROC curves (indicating superior combinations of sensitivity and specificity) were higher for the SPratio Method and the "Two-Sided SPH" method and were very low for the IVM method and the "One-Sided SPH" method. One reason the IVM method and One-Sided SPH method performed poorly was because they ignored obstructions upstream of the SPH measurement location. There was little difference between Two-Sided SPH method and SPratio with high values of X. At moderate changes in X, (e.g., $\leq 30\%$) the SPratio method was clearly superior to all the other methods. Therefore, SPratio method is the best screening tool at finding moderate obstructions. For very substantial obstructions, the Two-Sided SPH method would be adequate.

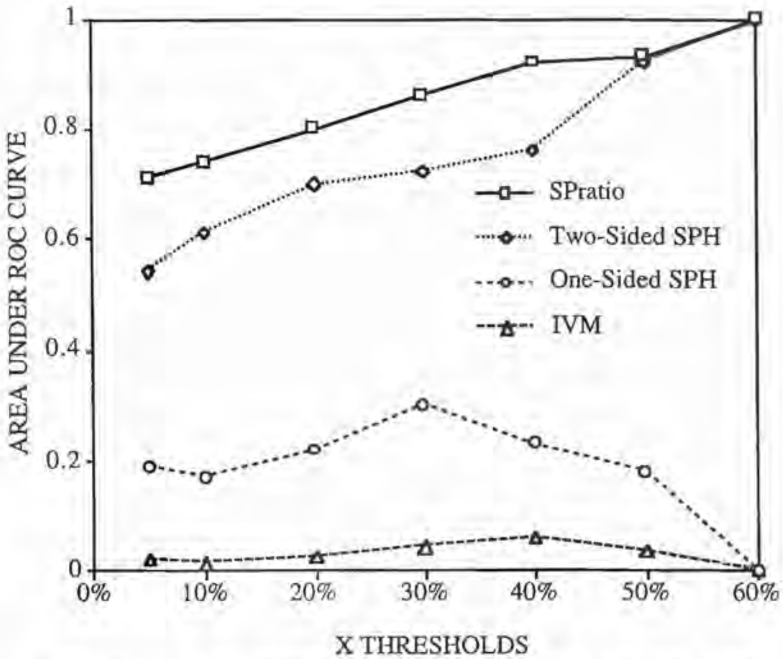


**Figure 7.** Area under ROC curves at selected thresholds of X

## Wang Masters Thesis

"Repeatability of Velocity Pressure Traverses and Static Pressure Measurements in Five Working Ventilation Systems." MS thesis, Department of Environmental Health, University of Washington, 1997

The goal of this study was to investigate the influence of some sources of measurement error on the repeatability of Pitot traverses, and to consider several shortcut methods that would simplify taking measurements without losing precision in the process. It consists of three parts or studies within the entire project itself. Several working ventilation systems were used without manipulation (e.g. flow straighteners, etc.) of any kind for the purpose of this study.

The first study investigating different Pitot tube nose shapes arose from the discovery of nonstandard probes, a majority of them, that were being used in the lab. The results of comparing two flat-nosed Pitot tubes, an ellipsoidally-shaped one, and a standard hemispherical probe showed that there was no statistically significant difference among the ellipsoidally- and hemispherically-shaped Pitot tubes and one of the flat-nosed ones, whereas the other flat-nosed one was different with each of the others. The unexpected difference was found to exist between the two similarly shaped Pitot tubes. The exact cause of this could not be determined. One cannot make any general statements due to limitations of the study (i.e. only 1 hemispherical, etc.). It can only be stated that for these particular Pitot tubes in this system and instance, differences were observed mainly between one flat-nosed Pitot tube and all the others. The important point of this study was that if differences existed between specific Pitot tubes, using the wrong one could contribute to the observed error in taking measurements. Because on visual inspection of the two flay-noses no physical differences could be seen to distinguish one from the other, a practitioner should send back any nonstandard Pitot tubes he receives to the manufacturer unless a larger study can demonstrate no problems.

The second study investigated whether reliable consistent measurements could be taken by hand instead of the need to use a mechanical traverse device to obtain accurate and precise readings. Again, due to limitations of the study, one cannot make sweeping generalizations from this study. A change in air flow with time inflated variances for both methods, few Pitot tubes and devices were tested, and inconsistencies especially in a greater variance in Branch 6 mechanically-held Pitot tube were observed. Further analysis is required.

The objective of the last study was to investigate and test several possible shortcut methods that would facilitate the standard method for and reduce the time and effort in determining the mean velocity in a duct.. A shortcut method that would not introduce additional error would greatly help the practitioner in the field. The results of this study showed that PF=0.9 allowed for large errors (>10%); a repeat measurement of centerline velocity pressure did not help; using a pipe factor determined by initial observation eliminated bias but reduced variance from only 6% to 5%. A single traverse allowed a few moderate errors (>5%) but substantial modest errors (>3%). Using a PF>1 as an indicator to do a second traverse produced few substantial or modest errors above those attributable to a double traverse. The decision one must make is how much precision and accuracy is one willing to sacrifice in exchange for reducing work and time, and also the level of error that would be significant.

Table XVIII. Wang summary of cases analyzed in each system.

| System | Count | Branch ID no. | Range of branch mean velocities |
|---|---|---|---|
| SCC-mezeast | 47 | between 1-10 | 1625-5018 fpm |
| SCC-mezwest | 61 | between 11-20 | 2124-6477 fpm |
| Blum-bandsaw | 56 | between 30-40 | 1637-2463 fpm |
| Boeing-modelshop | 7 | between 40-55 | 1756-3090 fpm |

Table XIX. Mean, median, and standard deviation of the percent error from estimating mean velocity from using pipe factor = 0.9.

| PF value | Mean (%) | Median (%) | St. Dev. | Range (%) |
|---|---|---|---|---|
| PFa = 0.9 | -4.29 | -4.04 | 6.53 | -24.9 - 9.56 |
| PFb = 0.9 | -4.72 | -4.61 | 6.21 | -23.8 - 9.37 |

Table XX. Mean, median, standard deviation, and range of the percent error in mean velocity in using a specific pipe factor computed from an earlier round.

| PF value | Mean (%) | Median (%) | St. Dev. | Range (%) |
|---|---|---|---|---|
| PFa = 0.95 | 0.38 | -0.33 | 5.56 | -18.11 - 16.38 |
| PFb = 0.95 | 0.81 | 0.64 | 4.53 | -14.31 - 11.21 |

Figure 8. Percent error resulting from looking at the perpendicular traverse b versus the standard two traverses to determine mean velocity

# LIST OF PRESENT AND POSSIBLE FUTURE PUBLICATIONS

This study will be productive in terms of peer-reviewed journal articles and in Masters theses. We had hoped to have submissions in before now, but they were delayed due to two problems: 1) lack of access sufficient to validate obstructions during the first 15 months of the study, and 2) our continuing to collect data until just three months ago. In addition, the P.I. has been reluctant to publish preliminary results from such a complex study.

Once this Final Report has been submitted, the final results will be submitted to a peer-reviewed research journal in two manuscripts, one covering laboratory-based studies and the other covering the field studies. Opportunistic findings will be submitted in at least two other submissions. The tentative titles and topics for the manuscripts are listed below:

1. Guffey, S.E. A comparison of the efficacies of troubleshooting methods in detecting alterations to two ventilation systems under laboratory conditions.
2. Booth, D.W. and S.E. Guffey. A comparison of the efficacies of troubleshooting methods in detecting alterations to five working industrial exhaust ventilation systems under field conditions.
3. Guffey, S.E. Use of simple measurement techniques and data acquisition software to speed exhaust ventilation measurements and interpretations.
4. Guffey, S.E. Observed versus expected loss coefficients in four apparently unobstructed working industrial exhaust ventilation systems.
5. Guffey, S.E. Comparison of mean ventilation duct velocities determined from dual Pitot traverses to those determined by various shortcut methods.

The publications to date have all been Masters theses. Each was helpful in documenting different aspects of this study. In addition, a PhD dissertation on the overall study is expected by June 1998.

1. Hoppe, Schlichtman Jeanne, "Empirical Determination of the Error in the ACGIH Method of Predicting Airflow Distribution in Two Industrial Ventilation Systems," MS Thesis, University of Washington, 1995.
2. Moody, D. Comparison of the efficacies of Troubleshooting Methodologies for Ventilation Systems — A Field Study." MS thesis, Department of Environmental Health, University of Washington, 1996.
3. Pinsky, Ann. "Comparison of Efficacies of Current Methods for Troubleshooting Industrial Exhaust Ventilation Systems to a Proposed New Method." MS thesis, Department of Environmental Health, University of Washington, 1996.
4. Wang, L. "Repeatability of Velocity Pressure Traverses and Static Pressure Measurements in Five Working Ventilation Systems." MS thesis, Department of Environmental Health, University of Washington, 1997

The abstract for each thesis is listed in the Appendix. Usefulness of each thesis research for the overall study is described below:

1. Hoppe, J. A. Empirical Determination of the Error in the ACGIH Method of Predicting Airflow Distribution in Two Industrial Ventilation Systems (June 1995).

Comment: The Hoppe study showed remarkably poor results for Industrial Ventilation methods of pressure calculations. The sum of loss coefficients predicted from adding loss coefficients deviated markedly from observed values. Nearly 60% of predicted values deviated by more than 25% from observed values, and one-quarter deviated by more than 50%. These results prompted the P.I. to idealize the method of Industrial Ventilation so that it would not suffer from errors in published loss coefficients. The P.I. was reluctant to report what would be controversial findings based on results from only two ventilation systems. Once the main results of the study have been submitted for publication, the P.I. will include findings from 2 other systems and submit the results for peer-reviewed publication.

2. Pinsky, A. Comparison of Efficacies of Current Methods for Troubleshooting Industrial Exhaust Ventilation Systems to a Proposed New Method (1996).

   Comment: Although this part-time student did not defend until 1996, this thesis was based on data collected before the purchase and use of a borescope. Lacking a valid means for determining truth and falsity, the student compared predictions from other methods to those of the $X_{duct}$ method. This established that the methods often disagreed on the presence or absence of an alteration, which was important for the study but not suitable for peer-reviewed publication.

3. Moody, D. Comparison of the efficacies of Troubleshooting Methodologies for Ventilation Systems — A Field Study (1996)

   Comment: Moody analyzed preliminary data for two field systems and compared the efficacy of the different troubleshooting methods. Obstructions were verified with a borescope. The P.I. and Moody were reluctant to publish his much smaller study when so much more data would be available for the final results. His findings were similar to the final results for the same systems.

4. Wang, L. Repeatability of Velocity Pressure Traverses and Static Pressure Measurements in Five Working Ventilation Systems (1996).

   Comment: This work sought to establish the repeatability of mean velocities from Pitot traverses. Wang found that traverses repeated randomly on the same day in the same system varied by roughly 4 percent. An unknown portion of the change could be attributable to real changes in fan output during the day. This finding suggests that the much larger changes in airflow observed in apparently "obstruction-free" systems over a period of months could be due to gradual changes too subtle or hidden to notice by visual observation.

   Another finding of this study was guidelines for determining whether or not a second perpendicular traverse is needed. If the ratio of the mean velocity to the centerline velocity (i.e., the pipe factor) exceeded unity, the second traverse frequently deviated from the first by more than 7%. If it did not, the deviation was seldom greater than 3%. Thus, one need not take the second traverse unless the pipe factor of first exceed unity. This finding is important because no troubleshooting method can mean much unless one knows the actual airflows in the system at some point. Ms Wang's findings provide a useful guide in minimizing effort in taking such measurements. These findings will be augmented with additional data and analyzes and submitted for publication once the main results of this study have been submitted.

*Additional modes of dissemination of findings*

There is a substantial opportunity for the results of this study to affect routine professional practice much more quickly than could be expected from peer-reviewed journal articles alone. The P.I. is a member of the ACGIH Ventilation Committee and has been charged with revising the *Testing and Measurement* chapter of Industrial Ventilation for use in the next edition of that manual. The P.I. has been encouraged by the Committee to include a lengthy section adding the P.I.'s proposed troubleshooting methods to the chapter and providing general guidance on using all available troubleshooting methods. The P.I. will do so with caution until manuscripts from this study have been approved for publication. If such publication approval is forthcoming and the Committee continues to support inclusion of new methods, the results of this study will see widespread dissemination and will likely have a substantial impact on professional practice.

# 2. FINANCIAL STATUS REPORT

Will be done separately by the University of Washington Grants and Contracts office

# 3. EQUIPMENT INVENTORY

Will be done separately by the University of Washington Grants and Contracts office

# 4. FINAL INVENTION STATEMENT

There were no inventions developed from this research.

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