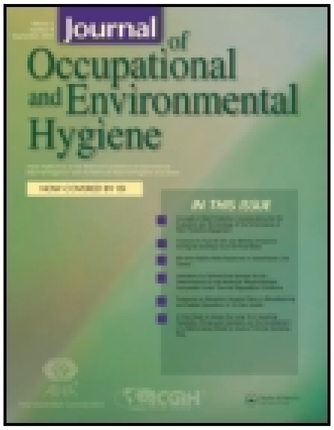

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Field Evaluation of Methods for Determining the Obstructed Section of Branches of Industrial Ventilation Systems

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Field Evaluation of Methods for Determining the Obstructed Section of Branches of Industrial Ventilation Systems

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This study proposes and evaluates the effectiveness of three methods in determining the location of obstructions and alterations in the branches of industrial ventilation systems. Three branch-screening methods (reference ratio, static pressure ratio, and power loss coefficient methods) were adapted to determine if obstructions lay in four distinct areas of a branch. The areas were the hood, middle, and end sections, with the middle and end sections combined to form the fourth area. These methods were evaluated for their ability to detect obstructions in each specific section and also for their ability to detect obstructions in sections after the branch was surveyed for obstructions using a screening method. The results of this study indicate that each method is very useful in determining the presence and location of an obstruction in every section of the branch except the hood section. Each method performed poorly when determining obstructions in the hood section. However, because of the ability of the methods to detect obstructions in the other three sections, the process of elimination can be used with confidence to determine obstructions in the hood.

Keywords location, monitoring, obstructions, pressure ratio, ventilation

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List of Abbreviations

E	denotes the measurement location for the end section
FPR	false positive rate
H	denotes the measurement location for the hood section
M	denotes the measurement location for the middle section
RefRatio	parameter computed for reference ratio method
Ref.	denotes the reference measurement location
ROC	receiver operator characteristic (curve)
SP	mean static pressure at a cross-section
SPR	parameter computed for static pressure ratio method
SP_{ref}	mean static pressure at the reference main or sub-main cross-section
TP	mean total pressure at a cross-section
VP	mean velocity pressure at a cross-section
X Value	parameter computed for power loss coefficient method

INTRODUCTION

As with most other systems, industrial ventilation systems must be maintained and monitored periodically to ensure that they are working properly and continue to be effective. Three methods—reference ratio, branch static pressure ratio, and power loss coefficient method—have been shown to be effective at screening a whole branch in a system for obstructions.[1,2] While beneficial, these methods would be even more useful if they were able to provide guidance in determining the location or the section of the branch where an obstruction lay. This would provide valuable information since it is often a very difficult and time-consuming process to gain access to the inside of some sections of a branch duct.

Therefore, these three screening methods were modified to allow the potential detection of an obstruction within sections of a branch duct (referred to as section methods). This study evaluates and compares three potential section methods.

Note that the section tests could be applied to each branch duct without any prior screening, or they could be employed with prior screening using the branch tests. For that reason they were evaluated both ways. The first test was to determine how effective each method was for each particular section without prior screening. The second test was to evaluate how well the section methods worked when used in conjunction with their respective screening methods.

BRANCH SCREENING AND SECTION METHODS

The x value method developed by Guffey[3] has already been demonstrated as an effective field tool at screening a whole branch for an obstruction in a working exhaust system.[1,2] Guffey proposed that an x value may be calculated for any section of a branch[3] such as the middle section. The

TABLE I. Method Parameters for Each Section

Section	X Method	Reference Ratio	Static Pressure Ratio
Hood section	$\frac{TP_H}{VP}$	$\frac{SP_H}{SP_{Ref.}}$	N/A
Middle section	$\frac{TP_M - TP_H}{VP}$	$\frac{SP_M - SP_H}{SP_{Ref.}}$	$\frac{SP_H}{SP_M}$
End section	$\frac{TP_E - TP_M}{VP}$	$\frac{SP_E - SP_M}{SP_{Ref.}}$	$\frac{SP_M}{SP_E}$
Hood to end section	$\frac{TP_E - TP_H}{VP}$	$\frac{SP_E - SP_H}{SP_{Ref.}}$	$\frac{SP_H}{SP_E}$
Branch screen	$\frac{-TP_E}{VP}$	$\frac{SP_H}{SP_{Ref.}}$	$\frac{SP_H}{SP_E}$

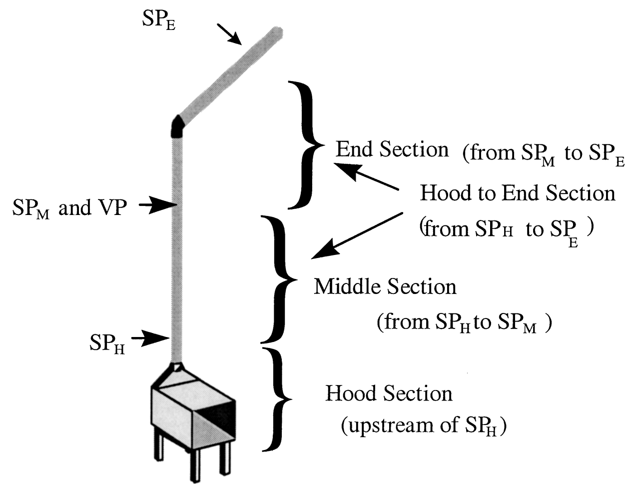

FIGURE 1. Branch sections and measurement locations

method parameter would then be the difference between the x value measured at the hood location (H) and the x value parameter measured at the middle location (M). The hood section and end section (E) x values are similarly computed. Table I gives the equation used to calculate each method's parameter for each section, including the branch screening parameter.

A similar approach was used to determine the section parameter for the reference ratio developed by Booth.[1] The reference ratio screening parameter is the ratio of the hood static pressure measurement to a reference static pressure measurement taken at a submain or main just upstream of the fan (Table I). Therefore, the reference ratio parameter used for a given section is the difference in static pressures that bounded the section divided by the reference static pressure.

The approach developed for the static pressure ratio method was slightly different. The method was modified for each section (Table I) by using the ratio of the static pressures that bound that section as the method parameter. The static pressure ratio method's screening parameter for a branch is simply the ratio of the H static pressure to the E static pressure. For example, the ratio of the H and M static pressure points is the method parameter for the middle section (the volume between the H and M measurement locations). A static pressure ratio for the hood section cannot be computed since the atmospheric pressure would then be part of the ratio (atmospheric pressure = 0). If the method is very successful in the other sections, the presence of obstructions in the hood may be determined by process of elimination.

EXPERIMENTAL

Branch Sections

The branch ducts were broken into the three main sections—the "Hood," "Middle," and "End" sections (see Figure 1). The hood section was bound by the atmosphere on one end and the hood measurement location (H) on the other. The middle section extends from H to the middle measurement location (M). Likewise, the end section is the area that lies between M and the end measurement location (E).

In many cases, the middle section consisted of only a short length of straight duct with little resistance to flow. Combining the middle section with the end section may help to reduce potential problems associated with straight ducts between H and M or between M and E. Therefore, in a separate analysis, the middle and end sections were combined ("Mid + End") to determine whether incorporating them into one section improved the ability of the method to detect the location of the obstruction.

Apparatus, Techniques, and Procedures

Ventilation Systems

Three ventilation systems from a community college woodshop were used in this study. They were designated as Cabinet Shop, Mezzanine East, and Mezzanine West. The systems were used to control wood dust from typical woodworking operations. The cabinet shop consisted of 11 branches with duct diameters between 4 and 8 in. Their duct velocities ranged between 400 and 6500 ft/min. The mezzanine west (7 branches) and the mezzanine east (5 branches) systems contained branches of 4, 5, and 6 in. The velocities for the mezzanine west branches ranged between 2000 and 6500 ft/min and the mezzanine east system velocities ranged from 2000 to 5200 ft/min.

Measurement Apparatus

All pressure measurements were made with either an Alnor CompuFlow ElectroManometer, Model 8530D-I[4] (Alnor Instrument Company, Skokie, Ill.) or a TSI DP-Calc, Model 8702 manometer[5] (TSI Inc., St. Paul, Minn.). Dwyer stainless steel Pitot tubes[6] (Dwyer Instruments Inc., Michigan City, Ind.) were used to take static pressure (SP) and velocity pressure (VP) measurements. They were inserted into the duct and held there by hand. The branch duct was divided into 10 annular areas using the log-linear method[7] to determine the velocity pressure traverse points. All pressure readings were downloaded directly into a ventilation measurement acquisition computer program.[8] A boroscope (Series 5, Olympus America, Melville, N.Y.) was used to inspect the ducts through

TABLE II. Weight Classification Scheme

Weight	Description	Percent Obstructed
0	Clean	0–1
1	Very light	1–5
2	Light	6–15
3	Moderate	16–40
4	Heavy	41–75
5	Gross	76–90
6	Nearly plugged	91–100

holes drilled to view spots where accumulation was likely to occur (hoods, elbows, junctions, bottom of vertical runs, and long, straight ducts) to determine the presence of obstructions.

Obstructions

Naturally occurring obstructions, investigator inserted blocks, and dampers were employed as "obstructions" in the systems' branches.[1,2] When a naturally occurring obstruction was not present and the configuration of the duct did not allow for placement of a standard block, a damper was used to obstruct the system.

A subjective weight classification scheme (see Table II) was developed for obstructions in the systems' branches based on the investigators' judgment of the visually apparent percentage the obstruction that blocked the duct.[1,2] All obstructions were assigned to a class prior to measurement of pressures and flows. Because the scheme is rooted in the judgment of the investigator, misclassifications of the degree of obstruction may have occurred. That is, in assigning "borderline" cases, it is likely that some obstructions assigned to a higher class should have been in the lower class and vice versa. In addition, since many different shapes and sizes of materials were used as obstructions, it is also very likely that weights assigned to the same classification had a range of true resistances.[1,2]

The purpose of assigning weights was to allow a more nuanced comparison of the effectiveness of the location techniques investigated in this study. By excluding lower weight classifications from some analyses, it was possible to determine relative effectiveness of competing methods with and without "penalizing" each method for failing to detect less substantial obstructions.

Procedures

Measurement positions were determined using the *Industrial Ventilation Manual*[9] recommendations as much as possible. However, it was frequently difficult to obtain such ideal measurement locations under field conditions. Under these conditions the best available position was chosen for each case.

Several rounds of data were collected each day of sampling. The condition of the system upon arrival was used for the initial measurements. There were no investigator alterations done to the system prior to the initial round of measurements on a given day. The rounds of measurements were taken starting with the most upstream branch and working toward the fan. Generally static pressures were measured at H first, then at M and E, and then finally the velocity pressures. This order was occasionally changed to save time and effort in moving the ladder to reach measurement locations.

After the initial round of measurements, the system was inspected for obstructions. A boroscope was used to examine the inside of ducts for obstructions in areas that were prone to settling. Each observed condition was assigned a classification code (Table II) based on the investigator's subjective visual assessment. Before subsequent rounds of measurements were taken that day, naturally occurring obstructions were removed from the duct and blocks or dampers were placed in one section of randomly selected branches. The investigator-inserted obstructions were previously assigned to the "weight" classifications in the same manner as the passively observed obstructions found in the ducts.

Exclusion of Data

Cases were rejected when obvious errors in measurements were found (e.g., velocity profile consistent with plugging of one port of the Pitot tube) or when there was an inadvertent failure to record the conditions inside the duct. Cases were also excluded if a measurement required to compute a parameter for any method was missing. Data were also omitted if the duct velocity was less than 900 ft/min in what was an otherwise high velocity system. If the static pressure ratio was 0.97 or greater then the case was also removed from the analysis. These exclusions represented cases with severe reductions in airflow, which should be obvious using any useful method.

Use of Bootstrap Methods and ROC Curves

The data for each section of the branch were analyzed both for each duct system separately and with all three duct systems' data pooled. Analysis was done using receiver operator characteristic (ROC) curves and bootstrapping techniques.[1] ROC curves allow the comparison of techniques using both the sensitivity and specificity of each method over a large range of thresholds simultaneously.[10,11] A ROC curve was generated for each method and section for each grouping of weights that was investigated. The area under each ROC curve was then calculated for each analysis. The best method in detecting a given set of obstruction classes was judged to be the one that had the most area under the curve. A perfect method would have an area of unity.

Note that a single ROC curve is generated for each method, set of duct systems, and grouping of weight classes. Out of concern that a few cases could skew the results for a given analysis, bootstrapping techniques were employed to do statistical inference tests. Stated briefly, the 270 data points were randomly sampled from, with repeated replacement, to generate 10 sets of data that differed only in which data points were randomly selected. Areas under ROC curves were then computed for each of the random samples of the data pool. Such bootstrapped data is highly likely to fit a normal distribution, allowing it to be analyzed using standard tests of statistical inference, such as regression and analysis of variance.[12] Hence, the bootstrap technique provided estimates of the variability of the results without requiring any assumptions regarding the distribution of data.

Test One—Section Analysis

As stated earlier, each section method can be employed with or without prescreening to determine whether or not a given branch was partially obstructed. For Test One the methods were applied without such prescreening. Each section method was thus applied to every section of every branch duct. The threshold value for each test was varied by increments of 0.02 until reaching a 30% difference in value. At this point the increment was changed to 0.05.

Test Two—Combining Branch Screening Methods with Section Methods

As stated earlier, it is possible to prescreen branches to identify whether or not a given branch was partially obstructed using each of the competing methods. To employ a given branch detection method for this purpose, one must first determine a suitable threshold for that method. For this purpose we employed the threshold for each method found to produce a false positive rate of 20% in previous studies.[1,2] As found in additional analyses not further discussed here, use of a false positive rate of 10% would not have materially changed the relative effectiveness of the methods.

Thus, the branch was first screened using the recommended threshold value for a 20% false positive rate[1,2] for each screening method (Table III). When the branch was judged to have an obstruction by a given branch screening method, the corresponding section location method was used to identify the specific obstructed section within that branch. Hence, if the branch detection failed then the section method was judged to have failed also. The effectiveness of the various methods was determined for each section by using the respective ROC areas, as described earlier.

To account for a screening method's failure to indicate an obstruction within a branch, a screening factor was multiplied by the ROC areas of each section to penalize the combined methods that failed to indicate an existing obstruction. The screening factor for a section was the ratio of true positives in the section, indicated by the screening method, to the true number of obstructions in that section of the branches.

TABLE III. Recommended Thresholds for Screening the Whole Branch for Obstructions

Trouble Shooting Method	Recommended Threshold (%)
Branch static pressure ratio	8
X value	17
Reference ratio	10

Assume that there were 12 obstructions within the branches of a system. It is conceivable that within the data set the branch screening method may indicate that there were six obstructions in the various unknown sections of the branches (Table IV). The hood section method correctly identified two of the six as being in the hood section (the rest were from other sections). The combined hood method (screening plus hood section) appears to be 100% accurate since it detected all of the hood obstructions that made it past the screen. However, these results do not take into account the obstructions the screening method misdiagnosed. In this case a screening factor of 0.25 ($= 2/8$) would be multiplied by the resulting ROC area to account for missed obstructions.

RESULTS AND DISCUSSION

Test One—Section Analysis

Hood Section

The x value method did very well (area >0.90 overall) and consistently performed better than the reference ratio for every weight category of the hood section in Table IV. The reference ratio performed modestly well over all weight categories. Surprisingly, the results for heavy obstructions were slightly worse. However, these modest results were not unexpected because under the modification scheme, the screening parameter for the whole branch is the same parameter for the hood section (Table I). Therefore, the section method would tend to have a large number of false positives because the method would also be detecting obstructions in other sections of the branch. Despite the poor results, as with the static pressure ratio method, it may be possible to use process of elimination to determine the presence of an obstruction in the hood section after

$$\text{Screening factor} = \frac{\text{\# of obstructions correctly identified by the screen in a given section}}{\text{\# of obstructions actually in the branch}}$$

Reality		Method Detected			
No. of true obstructions in the branch	No. of true obstructions in the hood section	No. of true obstructions indicated by screen	No. of true obstructions indicated by screen actually in the hood	No. of obstructions indicated by hood method	Screening factor
12	8	6	2	2	0.25

TABLE IV. ROC Curve Areas for Each Section Method

Methods	ROC Area All Obstructions	ROC Area Light Obstructions	ROC Area Moderate Obstructions	ROC Area Heavy Obstructions
		Hood Section		
Reference ratio	0.712 (±0.045)	N/A	0.78 (0.047)	0.71 (0.056)
Static pressure ratio	N/A	N/A	N/A	N/A
X value	0.904 (±0.030)	N/A	0.85 (0.038)	0.96 (0.018)
		Middle Section		
Reference ratio	0.62 (±0.086)	0.45 (±0.064)	0.97 (±0.008)	N/A
Static pressure ratio	0.66 (±0.039)	0.45 (±0.088)	1.00 (±0.002)	N/A
X value	0.62 (±0.055)	0.39 (±0.065)	0.99 (±0.001)	N/A
		End Section		
Reference ratio	0.88 (±0.064)	0.861 (±0.044)	0.96 (±0.05)	0.99 (±0.002)
Static pressure ratio	0.93 (±0.023)	0.88 (±0.014)	1.00 (±0.003)	1.00 (±0.001)
X value	0.90 (±0.058)	0.85 (±0.048)	0.96 (±0.055)	1.00 (±0.001)
		Middle + End Section		
Reference ratio	0.86 (±0.040)	0.75 (±0.046)	0.94 (±0.003)	0.99 (±0.003)
Static pressure ratio	0.87 (±0.081)	0.72 (±0.096)	0.99 (±0.031)	1.00 (±0.001)
X value	0.85 (±0.023)	0.65 (±0.057)	0.99 (±0.001)	1.00 (±0.001)

eliminating the middle and end sections as potential locations for the obstruction.

Middle Section

For the category of all obstructions in the middle section, the ROC areas in Table IV appear to indicate that the methods performed poorly in this section. However, this is somewhat misleading due to the presence of light obstructions located in this section. None of the methods detected them well, which lowered the overall effectiveness of the methods. While light alterations provide a significant challenge to the method, they have little effect on the airflow[1,2] and, in the authors' experience, detection of them is not critical. Moderate obstructions can significantly affect the airflow through the branch and provide a more rigorous test than the easily discovered larger obstructions. Each of the methods did extremely well (ROC area > 0.97) in detecting moderate obstructions in this section. The static pressure ratio method was the only method to perform perfectly for the middle section (area = 1.00).

End Section

The ROC curves for the end section (Figure 2) and the resulting ROC area values (Table IV) indicate that all of the methods did very well even for light obstructions. The strong

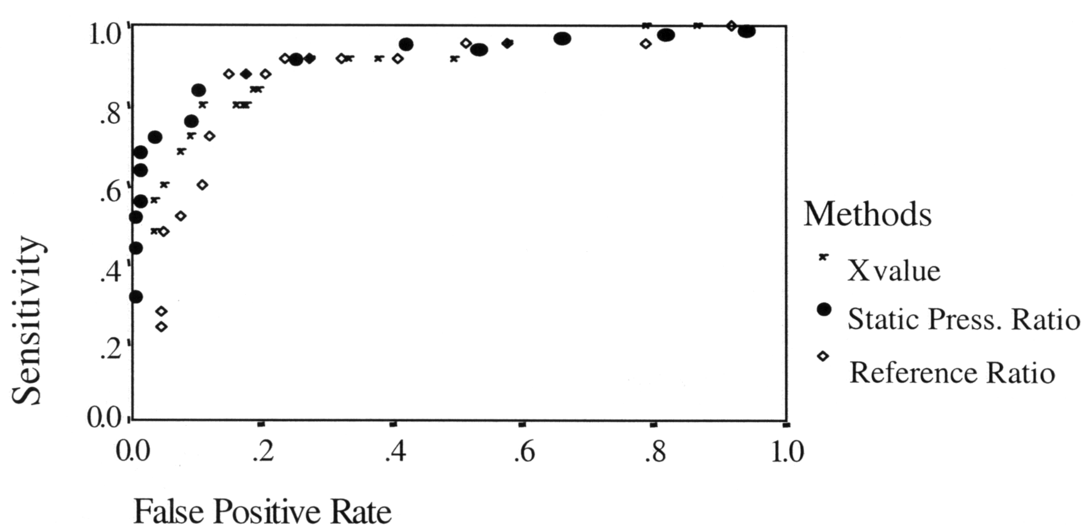

FIGURE 2. ROC curves for the end section

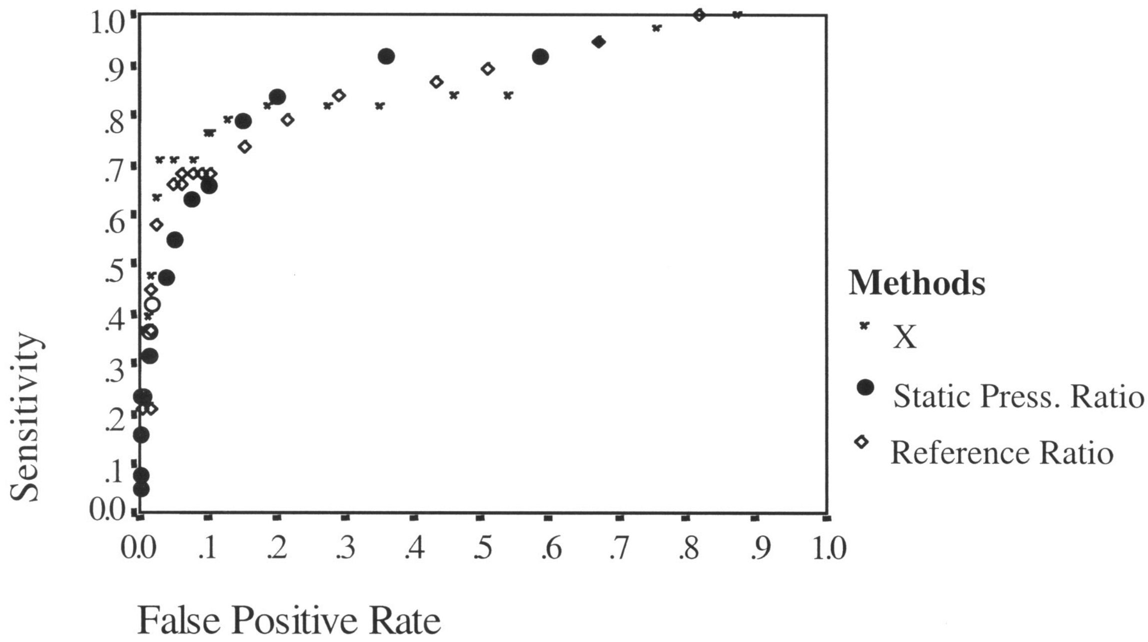

FIGURE 3. ROC curves for the middle + end section

individual results of the methods for the middle and end sections indicate that the process of elimination should do very well in determining obstructions in the hood. The ROC areas for all methods were very high (>0.95) for the moderate and heavy obstructions. These same methods also performed very well for the light obstructions (areas >0.84).

Middle + End Section

Figure 3 indicates that the areas for the x value, the static pressure ratio, and the reference ratio methods are nearly identical for this section. The ROC areas were extremely high (Table IV) for the moderate and heavy obstructions for all of the methods. Interestingly, the areas increased significantly as compared to the areas in the middle section (areas >0.85). The middle section contained a large number of branch ducts that were either straight or contained one slightly angled elbow. The increased performance of the methods would seem to indicate that they perform better when obstacles such as elbows are present to increase the resistance so that measured static pressures at the boundaries are not nearly equivalent.

Individual Systems

The results for each section of the individual systems were consistent with the pooled data results for the other sections. General linear model analysis showed that each section's area under the curve was significantly related to the troubleshooting method ($p < 0.05$).

Test Two—Branch Screening Methods Combined with Section Methods

Table V presents the screening factors and the weighted ROC areas developed from the analysis. The weighted ROC areas in this table are simply the results of multiplying the ROC areas for the various obstruction classifications by the

TABLE V. Screening and Location Weighted ROC Areas

Method	Weight Factor	Weighted ROC Areas Moderate	Weighted ROC Areas Heavy
	Hood Section		
Reference ratio	0.77	0.14	0.55
X value	0.62	0.56	0.60
	Middle Section		
Static pressure ratio	1.0	1.0	N/A
Reference ratio	1.0	0.92	N/A
X value	1.0	0.96	N/A
	End Section		
Static pressure ratio	1.0	0.99	0.99
Reference ratio	1.0	0.91	0.94
X value	1.0	0.85	0.97
	Middle and End Section		
Static pressure ratio	1.0	0.92	0.98
Reference ratio	1.0	0.89	0.96
X value	1.0	0.95	0.96

screening method's screening factors for each section. In this analysis, only obstructions of weight classified as moderate or higher were considered.

Combined Method Analysis

When the screening method was used in conjunction with the section methods, the overall success rate in the hood section was sharply reduced for all methods. The reference ratio method did not perform well (Table V), which was expected since the hood section method did not do well when used exclusively in the earlier analysis. However, the x value method, in which the hood section method did do well, does not do well here. This is because many of the obstructions in the hood resulted in branch parameter changes below the screening method's threshold value and were screened out of the analysis. The x value screening method was only able to detect 62% of the obstructions that were actually in the hood section. The combined method was heavily penalized because of its failure to detect a high percentage of the obstructions.

All of the methods did very well for the rest of the sections and were nearly equivalent in performance. Each of the screening methods successfully detected all of the obstructions in the three sections, so that their screening factor was united. Each combined method showed an overall ROC area of 0.85 or higher. The combined static pressure ratio method performed exceptionally well with areas of 0.99 or higher, except in the case of the moderate obstructions in the middle + end section, when its ROC area was 0.92.

Sensitivities and Thresholds for Section Methods at the 20% False Positive Rate

Table VI gives the threshold values and sensitivities that correspond to the 20% false positive rate for each section of the combined screening and section methods. The x value method was the only method that had good sensitivities at the 20% false positive rate for both moderate and heavy obstructions (75 and 100%, respectively) in the hood section. The reference ratio, at a 20% false positive rate, had a poor sensitivity for heavy obstructions of only 75%. The static pressure ratio was not applied to this section.

The static pressure ratio and the x value methods had excellent sensitivities to moderate obstructions (100%) in the middle section. The reference ratio sensitivity was not quite as good but was respectable at 80%.

In the end section the combined method analysis for the static pressure ratio, reference ratio, and the x value methods had excellent sensitivities to heavy obstructions (100%). Their sensitivities for the moderate obstructions were somewhat varied. The static pressure ratio method was consistent with a sensitivity of 100% at a 7% threshold. The reference ratio was also very good with 95% sensitivity at a threshold of 38%, while the x value method had some difficulty in this section with a sensitivity of 75% for moderate obstructions.

The reference ratio, static pressure ratio, and x value methods had very good sensitivities for both moderate and heavy obstructions. Each had sensitivities of 100% at the 20% false positive rate for heavy obstructions. The results for moderate obstructions were very good for each method (88, 90, and 94%, respectively).

TABLE VI. Method Thresholds at 20% False Positive Rate for Each Section

Method	Threshold	Moderate Class	Heavy Class
Hood Section			
Static pressure ratio	N/A	N/A	N/A
X value	43	75	100
Reference ratio	30	0	75
Middle Section			
Static pressure ratio	14	100	N/A
X value	40	100	N/A
Reference ratio	76	80	N/A
End Section			
Static pressure ratio	7	100	100
X value	60	75	100
Reference ratio	38	95	100
Middle to End Section			
Static pressure ratio	19	90	100
X value	43	94	100
Reference ratio	25	88	100

CONCLUSION

For this dataset, the static pressure ratio section methods worked very well, both as a screening tool correctly identifying 100% of the obstructions, and as a branch section method. The only drawback was that the method could not be directly applied to the hood section. This is apparently of little or no consequence because it performs well (ROC area typically $\geq$0.99) in the other sections. Using the process of elimination should allow the practitioner to determine if an obstruction is located in the hood section with a measure of confidence without needing to open the duct to investigate.

The combined x value methods (screening and section) did not do well in the hood section because the screening method had difficulty detecting the obstructions located here. In the other sections, its screening methods correctly identified 100% of the obstructions in these sections of the branch, resulting in a perfect screening factor. Hence, obstructions could also be correctly identified in the hood section by process of elimination. Each of these x value section methods did very well at identifying the obstructions in their sections so that the overall ROC areas for the moderate and heavy weight classifications were typically greater than 0.95.

The reference ratio screening method and its hood section method combined to form a poor method. However, as with the static pressure ratio and the x value, the combined screening and section methods did very well in each of the other sections of the branch, with overall ROC areas typically greater than 0.90. Applying the process of elimination to discover obstructions in the hood section should work very well.

The reference ratio, static pressure ratio, and x value methods are useful tools for screening branches for obstructions and then determining which section of the branch the obstruction is located in. Each of these methods performed very well in this study. The static pressure ratio method is perhaps the most consistent, but any of these three methods should work well.

If the screening method indicated an obstruction and the analysis of the middle and end sections indicate them to be clear of obstructions, one could conclude that the obstruction is in the hood section. Further corroboration of section results may be obtained using the static pressure ratio section methods since each section method requires the same additional measurement.

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REFERENCES

1. **Booth, D.W.:** An Evaluation of Industrial Ventilation Troubleshooting Methodologies. Ph.D diss., Department of Civil Engineering, University of Washington, Seattle, 1998.
2. **Booth, D.W., and S.E. Guffey:** An evaluation of industrial ventilation branch screening methods for obstructions in working exhaust systems. *Am. Ind. Hyg. Assoc. J. 62*:401–410 (2001).
3. **Guffey, S.E.:** Quantitative troubleshooting of industrial exhaust ventilation systems. *Appl. Occup. Environ. Hyg. 9*:267–280 (1994).
4. **Alnor Instrument Company:** *CompuFlow ElectroManometer Model 8530D-I Owner's Manual* (#116-159-035 Rev. 2). Skokie, Ill.: Alnor Instrument Company, 1987.
5. **TSI Inc.:** *DP-Calc Digital Manometers Model 8702 Owners Manual*. St. Paul, Minn.: TSI Inc., 1996.
6. **Dwyer Instruments, Inc.:** *Pitot Tube Operating Instructions* (Bulletin No. H-11.) Michigan City, Ind.: Dwyer Instruments, Inc., 1989.
7. **Ower, E., and R.C. Pankhurst:** *The Measurement of AirFlow,* 5th ed. New York: Pergamon, 1977.
8. **Guffey, S.E.:** *Heavent Owner's Manual*. Seattle: Steven E. Guffey, 1996.
9. **American Conference of Governmental Industrial Hygienists (ACGIH®):** *Industrial Ventilation: A Manual of Recommended Practice,* 22nd ed. Lansing, Mich.: ACGIH, 1994.
10. **Beck, J.R., and E.K. Shultz:** The use of relative operating characteristic (ROC) curves in test performance evaluation. *Arch. Pathol. Lab. Med. 110*:13–20 (1986).
11. **Metz, C.E.:** Basic principles of ROC analysis. *Semin. Nucl. Med. 8*:283–298 (1978).
12. **Efron, B., and R. Tibshirani:** *An Introduction to the Bootstrap*. New York: Chapman and Hall, 1993.