Experimental Determination of LOD for VOCs in Ambient Air Measured by Auto-GCs and Comparison with Reference Methods

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Abstract

Automatic Gas Chromatograph (auto-GCs) manufacturers perform an experimental method for a simple, rapid and low-cost Detection Limit evaluation for Volatile Organic Compounds in ambient air. The principle is the estimation of a minimum area of a peak. It is a relevant area value that discerns a real peak from the ground noise. This experimental LOD is equal to minimum area unit multiplied by a known ratio concentration/area unit defined after calibration. Three different international methods have been compared to this experimental method: the calibration curve method issued in Europe for Monitoring Certification Scheme (MCERTS) certification, the Method Detection Limit (MDL) issued during a Gas Chromatograph evaluation study organized by the U.S. Environmental Protection Agency (US EPA), and a third international method based on an approach by the use of background noise. The exploitation of the different results concludes that this experimental method gives values in the same order of magnitude as the other methods. This experimental approach is very concrete and beneficial for the axis of improvement of auto-GCs: less ground noise, more sample volume trapped, increase of the value area unit/mass injected.

Keywords:

Detection limit, Limit of Detection, Methods for determination of LOD, Volatile Organic Compounds, Gas Chromatography

1 INTRODUCTION

Volatile Organic Compounds (VOCs) are known to have many negative effects on the environment because they contribute significantly to the formation of tropospheric (ground-level) ozone (O3) resulting primarily from the reaction of VOCs with NOx (NO and NO2) in the presence of sunlight [1]. They can also have adverse effects on human health due to the well-known toxicity of several compounds, such as benzene (carcinogen) and toluene (central nervous system toxicant) [2]–[4]. In order to protect human and environmental health, accurate and precise quantification of VOCs in ambient air is critical to improve the understanding of the exposure to these compounds [2]–[4]. This requires that analyses should be performed via a validated standard method.

Method validation is one of the measures universally recognized as a necessary part of a comprehensive system of quality assurance in analytical chemistry. Laboratories must evaluate a series of method-performance characteristics to demonstrate that it is capable to provide data of a known and scientifically defensible quality and that it is acceptable for its intended purpose [5], [6]. These characteristics include precision, trueness, selectivity/specificity, linearity, operating range, recovery, limit of detection (LOD), limit of quantification (LOQ), sensitivity, ruggedness/robustness, and applicability [7].

LOD is a fundamental parameter in method validation. However, there has often been a lack of agreement to the terminology used to define it [5]. In general, the LOD is defined as "the lowest concentration of an analyte in a sample that can be detected, but not necessarily quantified, under the stated conditions of the test" [8].

Several approaches can be used to calculate LOD values. The most common methods for volatile organic compounds (VOCs) by experimental methodology using gas chromatography are: the visual evaluation (empirical) method, signal-to-noise, Method Detection Limit (MDL), and calibration curve methods [8]. In this study, these methods were compared to find the one that provides a detection limit determination that is appropriate for the analysis of interest with respect to sensitivity that is scientifically defensible. All the methods will be described in the next section.

For this purpose, three independent experiments are examined for each calculation approach. The first two were carried out for the analysis of a group of VOCs known as BTEX comprising the following aromatic hydrocarbons: benzene, toluene, ethylbenzene and m-, p- and o-xylene.

Field tests were carried out using auto-Thermal Desorption (TD)-Gas Chromatography (GC)-Flame Ionization Detector (FID) analyzers for the U.S. Environmental Protection Agency (US EPA) Gas Chromatograph Evaluation Study [9].

Furthermore, results on auto-TD-GC-Photoionization Detector (PID) analyzers will be discussed. These were evaluated by the National Physical Laboratory (NPL) to obtain the Monitoring Certification Scheme (MCERTS) certification [10] in compliance with the BS EN 14662-3: 2015, *Ambient air. Standard method for the measurement of benzene concentrations. Automated pumped sampling with in situ gas chromatography* norm.

Finally, an experimental study was performed on a GC coupled to a "wet-cell" Electrochemical Detector (ED) for the analysis of Sulfur-containing VOCs such as hydrogen sulfide (H_2S) and dimethyl sulfide (DMS).

2 METHODS OF LOD DETERMINATION

There are several strategies for the determination of LOD, each one providing different definitions of these parameters that may lead to the obtention of different values. In this section, three widely used methods are discussed.

2.1 Calibration curve method

Linear calibration curves are obtained by plotting the analytical signal with respect to the different concentrations of several dilution points of the analyte. They are expressed as:

$$y = a + bx \quad (1)$$

where:
y = instrument response,
a= intercept,
x = analyte concentration, and
b = sensitivity, slope of the calibration curve.

The detection limit (L) can be calculated as:

$$L = \frac{t_{n-1;0.95} * S_{x0.5}}{b} \quad (2)$$

where:
$t_{n-1;0.95}$ = Student factor for a 95 % two-sided confidence level,
b = slope of the calibration curve, and
$S_{x0.5}$ = standard deviation of the response for one dilution point calculated as:

$$S_r(C) = \sqrt{\frac{\sum(C_{testi} - \overline{C_{test}})^2}{n-1}} \quad (3)$$

where:
$S_r(C)$ = repeatability standard deviation at the delivered concentration C,
C_{testi} = ith ?? individual measurement,
$\overline{C_{test}}$ = average of all the individual readings, and
n = number of individual readings.

It is used by the NPL, UK's National Measurement Institute, for the Environment Agency's Monitoring Certification Scheme (MCERTS) for Continuous Ambient air Monitoring (CAM) systems. The MCERTS

Scheme certifies that a manufacturer complies with the performance criteria of EN 14662-part 3 norm.

2.2 Method Detection Limit (MDL)

The US EPA uses another approach, based on the work by Glaser and others [11], that describes the Method Detection Limit (MDL) as the minimum concentration of a substance that can be measured and reported with 99-percent confidence that the analyte concentration is greater than zero [12].

The MDL is calculated as:

$$MDL_s = t_{(n-1,\, 1-\propto=0.99)} S_S \quad (4)$$

where:
MDL_s = method detection limit based on spiked samples,
$t_{(n-1,\, 1-\alpha = 0.99)}$ = Student's t-value appropriate for a one-sided 99th percentile t statistic and a standard deviation estimate with n-1 degrees of freedom (see Table 1A), and
S_s = sample standard deviation of the replicate spiked sample analyses.

2.3 Signal-to-noise method

In the case of chromatographic methods that exhibit constant background noise, the signal-to-noise method is commonly applied [13].

Shrivastava and Gupta [8] describe this approach as follows: "the peak-to-peak noise height (h) around the analyte retention time is commonly measured and, subsequently, the concentration of the analyte that would yield a signal equal to certain value of noise to signal ratio is estimated".

A signal-to-noise ratio (S/N) 3:1 is generally considered acceptable for estimating the detection limit.

In this work, the detection limit (L_D) based on the baseline noise was calculated using the following equation:

$$L_D = 3hR \quad (5)$$

where:
h= peak-to-peak noise height.
R = concentration of the substance/peak height response factor.

2.4 Visual evaluation method

Some instrument suppliers perform an empirical method based on visual evaluation for the determination of the limit of detection. Gradually reduced concentrations of analyte are analyzed and the minimum level at which the peaks can be reliably detected is established. To this end, the automatic integration of chromatograms obtained is carried out by chromatographic software. It takes into account the "minimum area" parameter: peaks with areas below this value are not identified.

Once the minimum area value is established, the detection limit can be defined as the concentration corresponding to the minimum area value by the following equation:

$$LOD = \frac{(Minimum\ area)(Concentration)}{Peak\ Area} \quad (6)$$

where concentration and peak area refer to the results obtained for a given substance in a single ambient air chromatogram.

This methodology provides for the identification of the smallest peak that can be distinguished from background noise in chromatograms obtained from the analysis of standard gases or permeation devices. This requires the careful review of chromatograms to ensure that background noise is not integrated by the software.

3 MATERIALS AND METHODS

3.1 Auto-TD-GC-FID

An automatic gas chromatograph for C6 to C12 monitoring (airmoVOC C6-C12, Chromatotec) equipped with a Flame Ionization detector (FID) and on-line sample preparation was used.

The VOC US EPA PAMS standard gas mixture used contained 56 VOCs ranging from 20 to 60 ppb carbon (ppbC). A 10-port glass manifold (URG Corporation, Chapel Hill, NC) and dilution system (Environics® Series 2014 Computerized VOC Gas Dilution System and Environics® Series 7000 Zero Air Generator) were used to make dilutions with high-purity zero air [9].

For each analysis, 440 mL of sample were drawn into the system by an external pump with a flow rate of 44 mL.min^{-1} (sample is integrated over 10 min). The hydrocarbons were pre-concentrated at room temperature on a trap filled with graphitized carbon adsorbent (Carbopack™, Sigma-Aldrich). The pre-concentrated sample was thermally desorbed at 380 °C for 4 min and directly injected in a MXT capillary column (ID: 0.28 mm, length: 30 m, df: 1 µm) located inside the heated oven of the GC. A hydrogen cylinder (Air Liquide, alpha standard) was used as carrier gas.

For a concentration of 0.5 ppb of each compound of interest, 30 replicates were made.

3.2 Auto-TD-GC-PID

An automatic gas chromatograph (airTOXIC, Chromatotec) equipped with a Photoionization Detector (PID) was evaluated.

The low concentration multi-component VOC sample was generated from a 30-component EU Directive ozone precursor mixture. A specialized gas blending system consisting of one or more calibrated "Restrictor valves" (developed at NPL) was used to control the flow rate of the parent gas mixtures. Calibrated mass flow controllers were employed for diluting the parent mixtures with nitrogen BIP plus 99.99998% [10].

Sample introduction and chromatographic conditions are the same as that described above for an auto-TD-GC-FID. A nitrogen cylinder (Air Liquide, alpha standard) was used as carrier gas.

For a concentration of 0.15 ppb pf each compound of interest, 10 replicates were made.

3.3 Auto-GC-ED

An automatic gas chromatograph (TRS MEDOR, Chromatotec) equipped with an Electrochemical Detector (ED) was used.

The gas mixture was generated by H_2S and DMS cylinders of 500 ppb and diluted in zero air (AirmoPURE zero air generator, Chromatotec, France) by a dilution system equipped with two mass flow controllers and a dilution chamber (airmoCAL MFC, Chromatotec, France).

Zero air was also used as carrier gas. Samples were injected in two MXT capillary columns (ID: 0.53 mm, length: 4 m, df: 1.5 µm and ID: 0.53 mm, length: 30 m, df: 3 µm) by a 400 µL loop at a flow rate up to 4 $mL.min^{-1}$.

For a concentration of 2.47 ppb pf each compound of interest, 10 replicates were made.

4 COMPARISON OF DETERMINATION METHODS OF DETECTION LIMITS

This paper reports the results obtained in two independent measurement campaigns for the validation of two methods for the analysis of benzene, toluene, ethylbenzene and m-, p- and o-xylene by two different regulatory agencies. The first one was evaluated by the US EPA on several auto-GCs with FID detection. Meanwhile, in the second case, PID detection was studied to obtain the MCERTS certification.

The official results on MDL for auto-TD-GC-FID and detection limit by the calibration curve method for auto-TD-GC-PID were extracted from the documents from the US EPA Field Deployment Evaluation Report [9] and NPL test report [10] (reference: E09040018) respectively. They were compared with the values calculated by the other methods previously described, using the same data set.

Additionally, results obtained during an internal study carried out using an auto-GC-ED are presented. Sulfur specific detection is achieved by electrochemical detection for the analysis of H_2S and DMS.

4.1 Auto-TD-GC-FID

Based on the experimental results performed for the US EPA evaluation, detection limits were estimated for the different methods as summarized in Table 1.

In general, similar trends are observed for all compounds by calibration curve and MDL methods because the same standard deviation is used, which seems to be the most influential parameter. Benzene and m&p-xylene present the highest values. This is due to the proximity of the carbon tetrachloride (CCl_4) peak to the benzene peak (this one with only 4s lower retention time), which can affect the repeatability of the automatic integration of the benzene peak. On the other hand, the coelution of the m- and p- xylene isomers may double the standard deviation of the m&p-xylene peak, as it is directly proportional to the concentration.

Likewise, values obtained by signal-to-noise determination were comparable to the visual evaluation method, both using a graphic approach. These empirical methods showed lowest values of detection limits for all the analytes.

From these findings, it can be said that not all the methods used to estimate detection limits for the same study are equivalent, even if they are of the same order of magnitude for most of the compounds studied. However, the differences between the smallest and the largest values estimated by different methods could vary by a factor of five for benzene and m&p-xylene.

4.2 Auto-TD-GC-PID

Based on the experimental results performed for the MCERTS certification, detection limits were determined for the different methods as summarized in Table 2.

Values of detection limits obtained for GC analyzers with PID detection were generally very low, around 10 parts-per-trillion (ppt). They are significantly lower than the signal-to-noise method since this detector leads to much less noisy chromatograms compared to auto-TD-GC-FID.

Few differences were found with respect to the compound analyzed. However, the lower limit of detection value for benzene by the visual evaluation method could be explained by the higher linearity of response of this compound for an auto-TD-GC-PID system. Finally, as discussed previously, the detection limit by the first two statistical methods is negatively affected by the coelution of the m- and p- xylene isomers.

4.3 Auto-GC-ED

Results performed for the internal study on detection limits of Sulfur-containing VOCs are given in Table 3.

For a GC system with electrochemical detection, all the detection limit values obtained are similar, regardless of the method used for their estimation. This could be related to the fact that electrochemical detection leads to non-Gaussian peaks, as can be seen in Figure 1. In addition, the system with electrochemical detection gives very noisy chromatograms and therefore high minimum area values.

However, differences are observed depending on the substance analyzed. Detection limits are, in any case, lower for DMS than for H_2S. That is why DMS is the compound chosen to compare the detectors in the next section. This could be due to a better response of the detector for DMS than for H_2S. Response of the detector seems to be a determining parameter for the calculation of the limit of detection by graphical methods, since the difference between the two compounds analyzed is more significant for them (0.5 ppb) than for the statistical methods (0.3 ppb).

5 DISCUSSION

This section will focus on the comparison of the detection limits obtained depending on the system used.

Values presented in Table 1 and Table 2 for benzene will be taken into account to compare PID and FID detection, under the same sampling and chromatographic separation conditions. Benzene is the most representative element among those analyzed by auto-TD-GC-PID and auto-TD-GC-FID and the only one that presents a linear response for PID, essential requirement for evaluation. As already noted, values of detection limit are much better for an auto-TD-GC-PID than for an auto-TD-GC-FID, despite being obtained for the same injection volume. For example, this value was more than three times lower for benzene using an auto-TD-GC-PID than an auto-TD-GC-FID by the visual evaluation method. This could be due to two reasons:

- First, the FID leads to more background noise, so calculation by graphical methods is more difficult.

- Secondly, PID is more sensitive: Base Sensitivity (area unit compared to mass injected) is around 30000 for a PID and around 4500 for an FID. However, FID is more stable than PID, as its sensitivity drifts because of lamp ageing.

6 CONCLUSION

Detection limits have been calculated by four different methods for three different chromatographic systems. The comparison of the results shows that all methods give values in the same order of magnitude. However, most theoretical approaches for the calculation of limits of detection (calibration curve and MDL methods) depend mainly on the standard deviation, while for the graphical methods (signal-to-noise and visual evaluation methods) the predominant parameter is background noise.

When background noise is not important, detection limit values seem to be overestimated by the statistical methods, while it is equivalent to the graphical methods for higher values of this parameter. Visual evaluation method allows a rapid, low-cost estimation of the detection limit thanks to the ability of defining a minimum area value by a single chromatogram, without the need for linearization or repeatability tests. That is why visual evaluation method is favorable for field measurements, where fast and simple determinations are required, as well as for manufacturers, to perform routine Quality Control tests to ensure that analyzers are in conformity before shipping. Moreover, minimum area values are highly useful in instrumentation manufacturing as a reference for acceptable sensitivity and background noise.

Limit of detection is an expression of the sensitivity of the whole system. It depends not only on the detector, but on the prior gas chromatography separation conditions, sampling and sample introduction factors. Therefore, the experimental conditions and the procedure for estimating the LOD should be clearly specified for comparisons between laboratories or between analyzers from different manufacturers.

Appendixes

Table 1A. Student's t-distribution values

Number of replicates	*Degrees of freedom (n-1)*	*One-sided* $t_{(n-1,\ 0.99)}$	*Two-sided* $t_{(n-1,\ 0.95)}$
5	4	3.365	2.571
6	5	3.143	2.447
7	6	2.998	2.365
8	7	2.896	2.306
9	8	2.821	2.262
10	9	2.764	2.228
30	29	2.457	2.042
50	49	2.403	2.009
100	99	2.364	1.984

Table 2A. Data for calculation of detection limits for an auto-TD-GC-FID in Table 1.

Parameter	*Benzene*	*Toluene*	*Ethylbenzene*	*m&p-Xylene*	*o-Xylene*
Standard deviation for 0.5 ppb (30 replicates)	0.037	0.012	0.016	0.041	0.020
b (slope of the calibration curve)	1.07	1.07	1.19	1.14	1.1
Peak height	209	247	334	485	532
Measured concentration (ppb)	0.260	0.233	0.189	0.318	0.335
Measured area (a.u.)	1341.8	1872	1208	2027	2139

Table 3A. Data for calculation of detection limits for an auto-TD-GC-PID in Table 2.

Parameter	*Benzene*	*Toluene*	*Ethylbenzene*	*m&p-Xylene*	*o-Xylene*
Standard deviation for 0.15 ppb (10 replicates)	0.01	0.01	0.01	0.03	0.01
b (slope of the calibration curve)	1.0056	0.9762	0.9829	0.9777	0.9926
Peak height	499	1385	227	825	264
Measured concentration (ppb)	0.127	0.517	0.105	0.386	0.134
Measured area (a.u.)	2012	5004	742	3124	846

Table 4A. Data for calculation of detection limits for an auto-GC-ED in Table 3.

Parameter	H_2S	*DMS*
Standard deviation for 2.47 ppb (10 replicates)	0.31	0.18
b (slope of the calibration curve)	0.9993	0.9996
Peak height	218	347
Measured concentration (ppb)	2.460	1.710
Measured area (a.u.)	2075	3473

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List of table captions

Tables

Table 1. Detection limits (ppb) for an auto-TD-GC-FID.

Method	*Benzene*	*Toluene*	*Ethylbenzene*	*m&p-Xylene*	*o-Xylene*
Calibration curve	0.070	0.023	0.028	0.073	0.038
MDL (USEPA state result)	0.090	0.030	0.040	0.100	0.050

Signal-to-noise (*h*=7)	0.026	0.020	0.012	0.014	0.013
Visual evaluation (minimum area=100)	0.019	0.012	0.016	0.016	0.016

Table 2. Detection limits (ppb) for an auto-TD-GC-PID.

Method	*Benzene*	*Toluene*	*Ethylbenzene*	*m&p-Xylene*	*o-Xylene*
Calibration curve (NPL MCERTS state result)	0.007	0.006	0.005	0.016	0.005
MDL	0.009	0.007	0.006	0.019	0.006
Signal-to-noise (*h*=3)	0.002	0.003	0.004	0.004	0.005
Visual evaluation (minimum area=100)	0.006	0.010	0.014	0.012	0.016

Table 3. Detection limits (ppb) for an auto-GC-ED.

Method	H_2S	*DMS*
Calibration curve	0.88	0.51
MDL	0.71	0.41
Signal-to-noise (*h*=30)	1.02	0.49
Visual evaluation (minimum area=800)	0.95	0.39

List of figure captions

Figure 1. Example of non-Gaussian peaks by an auto-GC-ED.

Figures

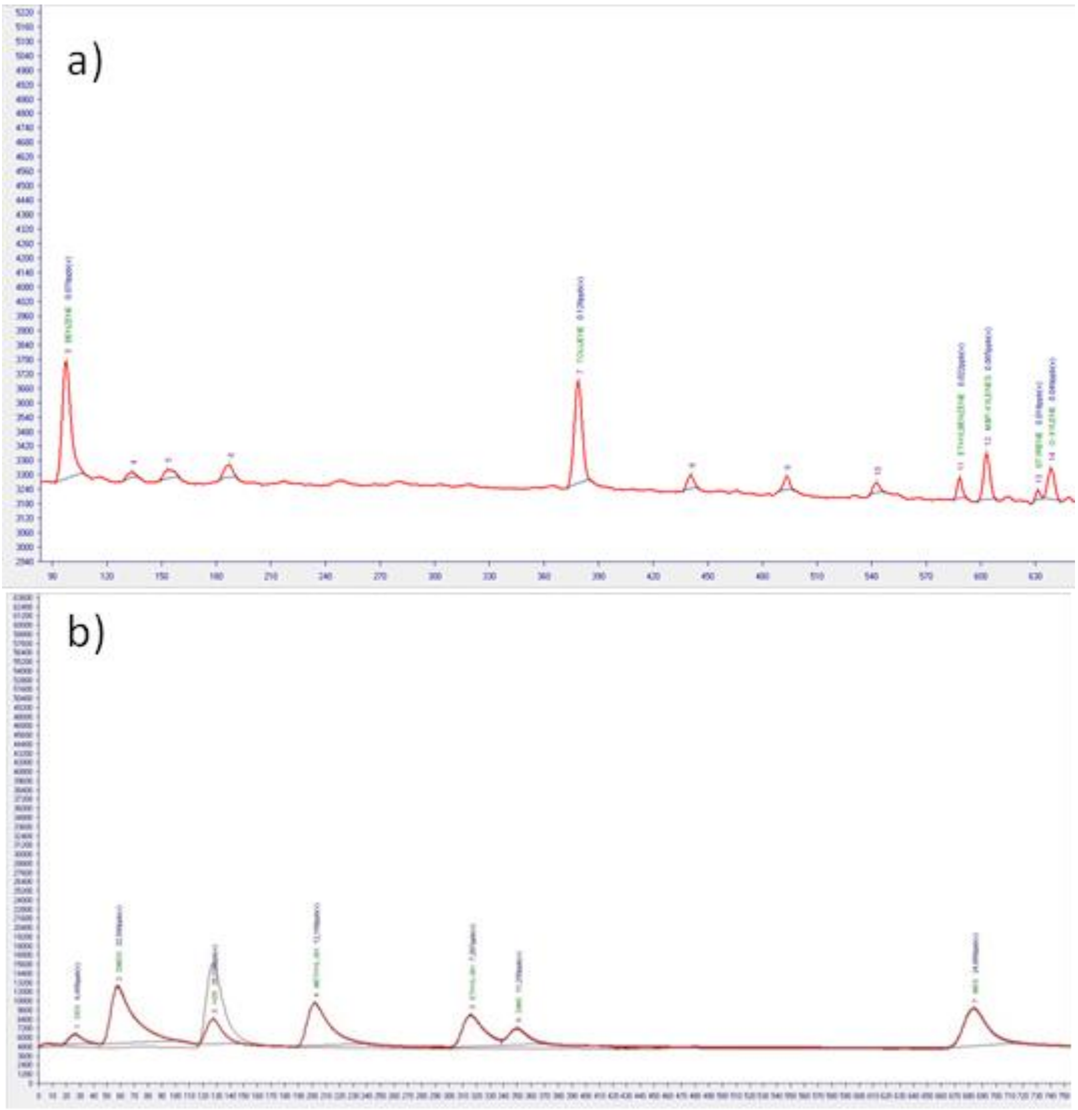

Figure 1. Example of Gaussian peaks by an auto-TD-GC-PID (a) and non-Gaussian peaks by an auto-GC-ED (b).