Rating Locomotive Crew Diesel Emission Exposure Profiles Using Statistics and Bayesian Decision Analysis

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For more than 20 years CSX Transportation (CSXT) has collected exposure measurements from locomotive engineers and conductors who are potentially exposed to diesel emissions. The database included measurements for elemental and total carbon, polycyclic aromatic hydrocarbons, aromatics, aldehydes, carbon monoxide, and nitrogen dioxide. This database was statistically analyzed and summarized, and the resulting statistics and exposure profiles were compared to relevant occupational exposure limits (OELs) using both parametric and non-parametric descriptive and compliance statistics. Exposure ratings, using the American Industrial Hygiene Association (AIHA) exposure categorization scheme, were determined using both the compliance statistics and Bayesian Decision Analysis (BDA).

The statistical analysis of the elemental carbon data (a marker for diesel particulate) strongly suggests that the majority of levels in the cabs of the lead locomotives (n = 156) were less than the California guideline of 0.020 mg/m³. The sample 95th percentile was roughly half the guideline; resulting in an AIHA exposure rating of category 2/3 (determined using BDA). The elemental carbon (EC) levels in the trailing locomotives tended to be greater than those in the lead locomotive; however, locomotive crews rarely ride in the trailing locomotive. Lead locomotive EC levels were similar to those reported by other investigators studying locomotive crew exposures and to levels measured in urban areas. Lastly, both the EC sample mean and 95% UCL were less than the Environmental Protection Agency (EPA) reference concentration of 0.005 mg/m³.

With the exception of nitrogen dioxide, the overwhelming majority of the measurements for total carbon, polycyclic aromatic hydrocarbons, aromatics, aldehydes, and combustion gases in the cabs of CSXT locomotives were either non-detects or considerably less than the working OELs for the years represented in the database. When compared to the previous American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) of 3 ppm the nitrogen dioxide exposure profile merits an exposure rating of AIHA exposure category 1. However, using the newly adopted TLV of 0.2 ppm the exposure profile receives an exposure rating of category 4. Further evaluation is recommended to determine the current status of nitrogen dioxide exposures.

[Supplementary materials are available for this article. Go to the publisher’s online edition of Journal of Occupational and Environmental Hygiene for the following free supplemental resource: additional text on OELs, methods, results, and additional figures and tables.]

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BACKGROUND

The dieselization of the American railroads began in the late 1940s. By 1959, 95% percent of the locomotives in service were diesel-powered.1 The operation of steam locomotives presented unique hazards that included thermal burns, ruptures of the pressure vessel, noise, and inhalation of smoke and soot from burning coal and oil as fuel, and often asbestos fibers from the boiler lagging. While the switch to diesel eliminated many of the acute and chronic hazards associated with steam locomotives, questions about the potential health hazards associated with diesel exhaust began to surface.

Diesel exhaust (DE) includes both gases and particulates produced from the combustion of fuel. According to Hesterberg et al.2 DE is “a highly complex mixture that varies widely depending upon engine type, fuel type, and operating conditions.” The majority of DE is made up of the gaseous phase, the majority of which is carbon dioxide, but also includes nitrogen oxides, sulfur dioxide, and aldehydes. The remainder of the mass fraction of DE, comprising less than 1% of the total, is made up of diesel particulate matter (DPM).

Early industrial hygiene studies conducted by the railroad focused primarily on carbon dioxide, carbon monoxide, and oxides of nitrogen. In the 1990s, railroads began measuring aerosols: e.g., elemental carbon (EC), organic carbon (OC), and total carbon (TC). A study or respirable particulate levels in the railroad industry published by Woskie et al.3 was one of the factors that prompted this change. Railroad industrial hygienists also began sampling for aldehydes and polycyclic aromatic hydrocarbons (PAHs) to address growing concerns about the potential carcinogenicity of some of these low-level constituents of DE.

As with other complex mixtures where no single substance can be identified as the agent of concern, a marker substance...
was needed for reliably and consistently measuring occupational exposures. Elemental carbon (EC) has become the marker of choice, given that it is proportional to DPM, relatively free of interferences (unlike organic carbon), and can be measured at low levels.\(^{(4,5)}\) Currently, in the United States there is no federal or authoritative (e.g., American Conference of Governmental Industrial Hygienists (ACGIH\(^{(1)}\)) occupational exposure limit (OEL) for EC.

In 1995, the ACGIH published a proposed threshold limit value (TLV\(^{1}\)) for diesel exhaust (to be measured as TC) of 0.15 mg/m\(^3\). After reviewing additional epidemiologic studies and available data on the toxicity of DPM, the ACGIH lowered the proposed TLV to 0.05 mg/m\(^3\) in 1999. The proposed TLV was lowered a third time in 2001 to 0.02 mg/m\(^3\), but now to be measured as EC. The revised value was not based on a reassessment of the health risk, but on the recognition that EC was a superior marker for exposure but constituted a smaller fraction of diesel particulate matter (DPM). For unknown reasons the proposed TLV was withdrawn in the 2003. However, based on an independent analysis of various studies of occupational exposures to EC and lung cancer, California\(^{(6)}\) also recommended that occupational exposures to EC be limited to 0.020 mg/m\(^3\).

More recently, the National Cancer Institute (NCI) and National Institute for Occupational Safety and Health (NIOSH) completed a study of DPM (measured as EC) and lung cancer.\(^{(7,8)}\) This was shortly followed by the International Agency for Research on Cancer (IARC) reclassifying “diesel engine exhaust” as a Group 1 carcinogen.\(^{(9)}\) Motivated by the NCI-NIOSH study and the IARC reclassification, the Australian Institute of Occupational Hygienists reviewed the findings of a wide range of authoritative organizations and recommended an “exposure standard” for DPM of 0.1 mg/m\(^3\) (measured as EC).\(^{(10)}\)

Recent industrial hygiene studies demonstrate that DE concentrations within the cabs of operating locomotives range from low to non-detectable. Liukonen, et al.\(^{(6)}\) found that EC exposures for train crews are “much lower than exposures for miners” and comparable to ambient levels found in urban areas. Seshagiri\(^{(11)}\) measured EC and gases (CO and NO\(_2\)) in locomotives on 48 runs under varying conditions and found that there were no “significant exposures to DE” and that the majority of the gas measurements were non-detects. Seshagiri also determined that EC was the best indicator of exposure to DPM because it “is made up primarily of OC and EC . . . the many nondiesel sources of organic carbon make a total carbon (TC) measurement prone to interferences.”

The exposure profiles for the operating crew of locomotives (e.g., engineer and conductor) demonstrate that exposure potentials to DPM are comparable to ambient levels (discussed in more detail later), reflecting the fact that for most runs the crew cab of the locomotive is in front of the exhaust stacks (see Figure 1). During forward movement, the locomotive exhaust plume will be moving up and in the opposite direction of the train.

Prior to the early 1990s, an off-duty crew often rode in the trailing locomotive; the process was called “deadheading.” Since that time off-duty crews are transported to a hotel, back to their home terminal, or to their next assignment using a contract van service. Deadheading may occur during inclement weather when it is safer that vehicle transportation. As a result, it was typical for the railroad industrial hygienists to collect area samples in the second or trailing locomotive. While there is a greater potential for DPM to enter a trailing locomotive if the windows are open, the data indicate that concentrations are not greatly elevated. This is due to the characteristics of the exhaust plume rising out of the exhaust stack at a high velocity then curving back along the train, resulting in a flow up and over the cabin of the trailing locomotive.

From the early 1990s a considerable amount of occupational exposure data for locomotive crews has been collected by CSX Transportation (CSXT). The purpose of this article is to present the data and compare the exposure profiles to current guidelines or limits for occupational exposure.

**METHODS**

**Data Acquisition and Validation**

After obtaining the data sets, the data were copied to a “working” Excel spreadsheet and then imported into a statistical analysis program (Version 13, Systat Software, Inc., San Jose, Calif.). The sampling methods used are listed in Table I. The data set fields used in the analysis were inspected for odd or inconsistent entries.

A pdf copy of the “CSX Transportation Air Sampling Record” for each sampling result was provided (carbon monoxide and nitrogen dioxide were not included). A selection of the records was extracted and the exposure data and information were compared to the entries in the database. A few discrepancies were found regarding the sampling method or sampling time. For example, there were four benzene results listed as detects when it was known that no detects for benzene had been measured by CSXT during the 1990 to 2011 interval. Upon checking the CSXT records, including the laboratory reports, it was found that these data had been entered incorrectly into the database.

**Data Standardization and Filtering**

In principle, the sampling time of a measurement should be consistent with the averaging time of the exposure limit. For this study, sampling time equaled the time required for the locomotive run, which nearly always was greater than 120 min. Measurements were deleted from the analysis if the sampling time was less than 120 min. This resulted in the deletion of only three EC non-detects where the sample times were 6, 26, and 46 min. None of the benzene cases was deleted.

Nitrogen dioxide was measured using both direct reading instruments and long-term passive dosimeters. The direct reading measurements and the passive dosimeter measurements that were either recorded as zero or were collected for less than
120 min were discarded. Several hundred carbon monoxide measurements were collected using a direct reading instrument and recorded as either non-detects or not greater than 5 ppm. Of the 68 measurements collected using long-term samplers, 45 were recorded as zero and three had sampling times less than 120 min. This left 22 measurements where the sampling time was 120 min or greater and the recorded concentration was greater than zero.

The sampling times corresponded to the length of the locomotive run, which tended to vary daily depending upon the assignment for each engineer and conductor crew. For comparison to the OELs, the concentrations were adjusted to a 480-min sampling period: \( C_{480} = \frac{c \cdot t}{480} \), where \( c \) = average concentration and \( t \) = sampling time. The time spent waiting for an assignment or after the run being transported via automobile to the next assignment was unsampled.

### Selection of OELs

Table II lists the various federal and authoritative OELs that were used as “working OELs” for this analysis. The working OEL was often the ACGIH TLV. The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) was used in those instances where the measurement sampling time was not consistent with that required for comparison to the ACGIH TLV. (The Supplemental Materials contains a table of additional OELs for each substance as well as additional text regarding the California guideline, the U.S. Environmental Protection Agency (EPA) “Reference Concentration,” and the Mine Safety and Health Administration (MSHA) limit for the total carbon in diesel emissions.) To generate figures that contain the results for several substances a “severity ratio” was calculated by dividing the measurement by the working OEL.

### Statistical Analysis

Each locomotive has an engineer and a conductor. They tend to be potentially exposed to similar substances (i.e., diesel emissions), at similar levels, and work at the same location and during identical periods. However, the conductor generally spends slightly less time in the cab due to the need to inspect the train prior to a run. The engineer and conductor will be considered here to be part of the same similar exposure group (SEG). Furthermore, this SEG will be considered to span all locomotive models.

Descriptive and compliance statistics were produced using both Systat (Version 13) and the IHDataAnalyst (Version 1.27, Exposure Assessment Solutions, Inc, Morgantown, WV). The majority of the figures were generated using Systat. The IHDataAnalyst was used to (a) evaluate the goodness-of-fit for the lognormal distribution model, looking for egregious departures, (b) calculate descriptive and compliance statistics

### TABLE I. CXST Sampling Methods

| Substance                                                                 | Method                      | Sampling Media          |
|--------------------------------------------------------------------------|-----------------------------|-------------------------|
| diesel particulate emissions (elemental carbon, organic carbon, total carbon) | NIOSH 5040                  | filter                  |
| aromatic hydrocarbons (benzene, toluene, ethyl benzene, xylene)          | NIOSH 1500 NIOSH 1501      | sorbent tube passive sampler |
| aldehydes (acetaldehyde, benzaldehyde, formaldehyde, glutaraldehyde)     | EPA TO-11 NIOSH 1501 NIOSH 2016 | sorbent tube passive sampler (manufactured by Draeger) |
| carbon monoxide                                                          | direct reading instrument colorimetric tube | sorbent tube |
| nitrogen dioxide                                                         | direct reading instrument NIOSH 6700 | passive sampler |
| polynuclear aromatic hydrocarbons (PAHs)                                 | NIOSH 5515 NIOSH 5506      | filter sorbent tube     |
TABLE II.  CXST Working Occupational Exposure Limits (OEL)

| Substance                  | OEL             | Source                     | Notes                                                                 |
|----------------------------|-----------------|----------------------------|----------------------------------------------------------------------|
| **Diesel Particulate Emissions** |                 |                            |                                                                      |
| elemental carbon (EC)      | 0.005 mg/m²     | EPA Reference Concentration\(^{(12)}\) | The RfC is a public exposure limit; upper limit for the average exposure occupational exposure limit; upper limit for full-shift exposures |
|                            | 0.02 mg/m³      | California guideline\(^{(6)}\) |                                                                      |
| total carbon (TC)          | 0.16 mg/m³      | MSHA PEL\(^{(13)}\)        |                                                                      |
| **Aromatics (BTEX)**       |                 |                            |                                                                      |
| benzene                    | 0.5 ppm         | ACGIH\(^{\circ}\) TLV\(^{(24)}\) |                                                                      |
| toluene                    | 20 ppm          | ACGIH TLV\(^{(24)}\)       |                                                                      |
| ethyl benzene              | 20 ppm          | ACGIH TLV\(^{(24)}\)       |                                                                      |
| xylene                     | 100 ppm         | ACGIH TLV\(^{(24)}\)       |                                                                      |
| **Aldehydes**              |                 |                            |                                                                      |
| acetaldehyde               | 200 ppm         | OSHA PEL\(^{(25)}\)        |                                                                      |
| benzoaldehyde              | 2 ppm           | AIHA WEEL\(^{(26)}\)       |                                                                      |
| formaldehyde               | 0.75 ppm, 2 ppm C | OSHA PEL\(^{(25)}\)       |                                                                      |
| glutaraldehyde             | 0.05 ppm C      | ACGIH TLV\(^{(24)}\)       |                                                                      |
| **Gases**                  |                 |                            |                                                                      |
| carbon monoxide            | 25 ppm          | ACGIH TLV\(^{(24)}\)       | In 2012 the ACGIH reduced the TLV from 3 ppm to 0.2 ppm.               |
| nitrogen dioxide           | 0.2 ppm         | ACGIH TLV\(^{(24)}\)       |                                                                      |

Note: Unless otherwise indicated with “C” for ceiling limit, all OELs are for an 8-hr full shift.

for censored data sets (i.e., a data set containing non-detects), (c) calculate non-parametric statistics, and (d) calculate BDA probabilities, which were used to assist in assigning the SEG exposure profile to the most appropriate exposure category.

**Descriptive Statistics**

In addition to the usual order statistics—sample size (n), minimum (min), maximum (max), and median—the following descriptive statistics are provided: sample mean and sample standard deviation (mean, SD) and the sample geometric mean (GM) and sample geometric standard deviation (GSD).

Most of the substance-specific data sets contained non-detects (i.e., the true concentration was less than the “minimum quantifiable concentration” (MQC) for the sampling and analytical method and laboratory combination). When non-detects were present, the percent censored was less than 80%, and the sample size was fairly large, the maximum likelihood estimation (MLE) method was used to calculate estimates of the lognormal distribution parameters.\(^{(15,16)}\) These estimates were then used to calculate the mean, exceedance fraction, and the 95th percentile of the substance exposure profile. The Kaplan-Meier method, as recommended by Helsel\(^{(17)}\) for censored data sets, was also used to estimate the mean EC level.

**Compliance Statistics**

The exceedance fraction and 95th percentile were calculated to assist in determining whether or not the exposure profile for each substance was generally in compliance with the working OEL (see Table II). The compliance statistics were estimated using non-parametric methods and using the lognormal distributional model. Because the statistics are estimates, and not the true values, the 95% lower and 95% upper confidence limits were calculated for each estimate. The statistics and confidence limits were calculated using standard methods.\(^{(14,18)}\)

If the data were censored, i.e., contained one or more non-detects, the sample size used to calculate each confidence limit was the total sample size minus the number of non-detects.\(^{(14)}\) There is no generally accepted method for calculating confidence intervals where the data set is censored. This ad hoc procedure results in somewhat wider confidence intervals, but compensates for the presence of non-detects in the data set.
Assigning an AIHA Exposure Rating

Exposure ratings of 0 to 4 are assigned using the rating scheme of the AIHA. For example, an exposure rating of Category 3 or less indicates that the majority of the occupational exposures—that is, at least 95%—were less than the OEL. An exposure rating of Category 2, 1, or 0 indicates that the majority of the exposures were less than 50%, 10%, or 1% of the OEL, respectively. An exposure rating of Category 4 indicates that occupational exposures frequently exceeded the OEL; that is, greater than 5% of the exposures exceeded the OEL. Exposure ratings are useful in that a succinct phrase—for example, “category two, high certainty”—can be used to convey a considerable amount of information: the most likely range for the true 95th percentile exposure, the statistical confidence in the assessment, and the degree of risk (relative to the chosen OEL) most likely experienced by members of the SEG.

While the sample 95th percentile (and its confidence interval) can be used to assign an exposure rating, the method of BDA was employed for most of the exposure rating assignments. BDA is a statistical method for estimating the likelihood that the true 95th percentile exposure falls within the range associated with each of the AIHA exposure rating categories and is capable of handling both detects and non-detects. For this analysis a flat, non-informative prior was used (see the “Methods” section in the Supplemental Materials and Hewett et al. for more information).

Goodness-of-fit Evaluation

The substance-specific data sets were evaluated using both subjective and objective goodness-of-fit procedures to determine if the lognormal distributional model was appropriate for describing the exposure profiles. Goodness-of-fit is not an issue whenever non-parametric statistics are calculated, as these statistics do not require a distributional model. Non-parametric statistics, also called large-sample statistics, may be more informative whenever the goodness-of-fit determination is equivocal and the sample size is fairly large. In this study, both parametric and non-parametric statistics are reported, with a general finding that they are consistent, and lead to identical or near identical conclusions.

RESULTS

A total of 190 EC measurements was collected from lead, trailing, and miscellaneous yard locomotives. Sample times for EC ranged between 121 and 669 min, with a median of 403 min. (There was no obvious trend in a plot of the sample times and concentrations. The Pearson and Spearman correlation coefficients were −0.12 and −0.15, respectively.) The EC measurements were collected starting in 1996 through 2007. Measurements for benzene, toluene, ethylbenzene, and xylene (BTEX) were collected starting in 1994 through 2007, although sampling did not occur every year. Aldehydes, PAHs, and gases (CO and NO₂) were collected on and off between 1990 and 2007, respectively. (see Table SII for additional details).

The data for all substances (except PAHs), normalized to the working OEL, are shown in Figures 2–5. The majority of the measurements for BTEX and aldehydes were non-detects. None of the detects exceeded the working OELs. Nearly 98% of the PAH measurements were non-detects, with a maximum detect of 0.024 mg/m³. All but one of the CO detects was less than 10% of the working OEL. For NO₂, 6.4% of the measurements exceeded the working OEL.

Traditional Statistical Analysis

Table III contains the usual descriptive and compliance statistics for all substances (except PAHs). Given the large percentages for non-detects, the calculation of the standard normal and lognormal descriptive statistics was not possible for many substances. For the remainder, the maximum likelihood method (MLE) was used to estimate the geometric mean (GM) and geometric standard deviation (GSD). These were then used to calculate the minimum variance unbiased estimator of the mean. Confidence intervals for the median and mean are provided to assess the uncertainty in the point estimates. (Descriptive statistics for PAHs are shown in Table SIII.)

The usual compliance statistics—exceedance fraction and 95th percentile—and confidence intervals are provided in Table IV. In general, there was good agreement between the non-parametric and parametric (i.e., lognormal distribution)
| Substance                  | OEL      | Locomotive Position | N    | % < MQC | Order Statistics                          | Normal Distribution Statistics | Lognormal Distribution Statistics |
|----------------------------|----------|---------------------|------|---------|------------------------------------------|-------------------------------|----------------------------------|
|                           |          |                     |      |         | Min    | Max    | Median | Mean   | SD     | GM     | GSD    |
| Diesel Carbon Emissions    |          |                     |      |         |        |        |        |        |        |        |        |
| elemental carbon           | 0.02 mg/m³ | All                | 190  | 53.7%   | 0.0003 | 0.0370 | 0.0029 | (0.0026, 0.0031) | (0.0028, 0.0053) | — | 0.0016 | 3.66 |
| Lead                      |          |                     | 156  | 57.7%   | 0.0003 | 0.0324 | 0.0027 | (0.0025, 0.0029) | (0.0021, 0.0040) | — | 0.0014 | 3.23 |
| Trailing                  |          |                     | 22   | 22.7%   | 0.0013 | 0.0370 | 0.0073 | (0.0033, 0.0096) | 0.0111 | — | 0.0056 | 3.40 |
| Other                      |          |                     | 12   | 58.3%   | 0.0019 | 0.0134 | 0.0030 | (0.0021, 0.0061) | (0.0015, 0.0558) | — | 0.0019 | 2.92 |
| Total carbon               | 0.16 mg/m³ | All                | 141  | 2.1%    | 0.0030 | 2.9705 | 0.0351 | — | — | 0.0340 | 2.14 |
| Aromatics (BTEX)           |          |                     |      |         |        |        |        |        |        |        |        |
| benzene                   | 0.5 ppm  | All                | 94   | 100%    | < 0.0005 | < 0.0581 | < 0.0027 | — | — | — | — |
| ethyl benzene             | 20 ppm   |                     | 11   | 72.7%   | 0.0149 | < 0.2594 | < 0.0392 | — | — | — | — |
| toluene                   | 20 ppm   |                     | 32   | 90.6%   | < 0.0004 | < 0.0370 | < 0.0015 | — | — | — | — |
| xylene                    | 100 ppm  |                     | 7    | 100%    | < 0.0740 | < 0.0925 | < 0.0780 | — | — | — | — |
| Aldehydes                 |          |                     |      |         |        |        |        |        |        |        |        |
| acetaldehyde              | 200 ppm  | All                | 137  | 31.4%   | < 0.0002 | 4.8798 | 0.0557 | — | — | D | D |
| benzaldehyde              | 2 ppm    |                     | 137  | 86.1%   | < 0.0001 | < 4.632 | < 0.0011 | — | — | — | — |
| formaldehyde              | 0.75 ppm |                     | 140  | 36.4%   | < 0.0013 | < 0.7444 | 0.0081 | 0.0096 | — | 0.0060 | 2.66 |
| glutaraldehyde            | 0.05 ppm | C                   | 137  | 94.2%   | < 0.0001 | < 1.4060 | < 0.0012 | — | — | — | — |
| Gases                     |          |                     |      |         |        |        |        |        |        |        |        |
| carbon monoxide           | 25 ppm   | All                | 22   | 4.5%    | 0.008  | 3.0E  | 0.12   | 0.63 | 1.99 | 0.13 | 6.55 |
| nitrogen dioxide          | 3 ppm    |                     | 234  | 32.9%   | < 0.0003 | 0.78 | 0.03   | 0.07 | 0.15 | 0.03 | 3.84 |

A All of the data sets were censored. The sample GM and GSD were estimate using the Maximum Likelihood Estimation (MLE) method. The sample mean was estimated using the Minimum Variance Unbiased Estimator (MVUE), which is calculated from the sample GM, sample GSD, and sample size.\(^{(17)}\)

B Includes, where appropriate, a parametric 90% confidence interval: 95%LCL and 95%UCL. The confidence interval was calculated using a sample size equal to the number of detects, rather than the full sample size. This results in a conservative confidence interval; i.e., a confidence interval that is probably greater than then 90% nominal width.

C “Other” locomotives included yard locomotives.

D The acetaldehyde data were highly variable (spanning nearly five orders of magnitude), making the calculation of exposure profile statistics problematic.

E The maximum non-detect for CO was 24.5 ppm.
### TABLE IV. Compliance Statistics by Substance for All Locomotive Positions

| Substance                | OEL                | Locomotive Position | N | % > OEL | 95th Percentile | % > OEL | 95th Percentile |
|--------------------------|--------------------|---------------------|---|---------|-----------------|---------|-----------------|
|                          |                    |                     |   |         |                 |         |                 |
| Diesel Carbon Emissions  |                    |                     |   |         |                 |         |                 |
| elemental carbon         | 0.02 mg/m³         | All                 | 190| 4.7% (2.5, 8.1) D | 0.0152 (0.0130, 0.0262) | 2.7% (1.3, 5.1) | 0.0137 (0.0100, 0.0203) |
|                          |                    | Lead                | 156| 3.2% (1.3, 6.6)  | 0.0144 (0.0062, 0.0212) | 1.2% (0.4, 3.0) | 0.0097 (0.0070, 0.0147) |
|                          |                    | Trailing            | 22 | 18.2% (6.5, 36.9)| 0.0291 (0.0204, -)E | 14.8% (6.3, 29.7)| 0.0416 (0.0225, 0.1164) |
|                          |                    | Other               | 12 | 0.0% (0.0, 22.0) | -                 | 1.4% (<0.1, 24.3) | 0.111 (0.0046, 0.1726) |
| total carbon             | 0.16 mg/m³         | All                 | 141| 1.4% (0.3, 4.4)  | 0.1114 (0.0670, 0.1455) | 2.1% (1.1, 3.7) | 0.1188 (0.1021, 0.1422) |
| Aromatics (BTEX)         |                    |                     |   |         |                 |         |                 |
| benzene                  | 0.5 ppm            | All                 | 94 | 0.0% (0.0, 3.1)  | <0.054 (<0.053, <0.056) | -       | -               |
| ethyl benzene            | 20 ppm             | All                 | 11 | 0.0% (0.0, 23.8) | -                 | -       | -               |
| toluene                  | 20 ppm             | All                 | 32 | 0.0% (0.0, 8.9)  | <0.037 (<0.0367, -) | -       | -               |
| xylene                   | 100 ppm            | All                 | 7  | 0.0% (0.0, 34.8) | -                 | -       | -               |
| Aldehydes                |                    |                     |   |         |                 |         |                 |
| acetaldehyde             | 200 ppm            | All                 | 137| 0.0% (0.0, 2.2)  | 0.4022 (0.2699, 0.5791) | -       | -               |
| benzaldehyde             | 2 ppm              | All                 | 137| 0.7% (0.0, 3.4)C | <0.1179 (<0.0179, <0.1511) | -       | -               |
| formaldehyde             | 0.75 ppm           | All                 | 140| 0.0% (0.0, 2.1)  | 0.0857 (0.0610, 0.1433) | <0.01% (<0.1, <0.1) | 0.0298 (0.0235, 0.0400) |
| glutaraldehyde           | 0.05 ppmC          | All                 | 126| -       | <0.3153 (<0.0454, <0.3836) | -       | -               |
| Gases                    |                    |                     |   |         |                 |         |                 |
| carbon monoxide          | 25 ppm             | All                 | 22 | 0.0% (0.0, 12.7)| 3.0 (1.5, -) | 0.2% (<0.1, 2.3) | 2.9 (1.2, 10.8) |
| nitrogen dioxide         | 0.2 ppm            | All                 | 234| 6.4% (4.0, 9.7) | 0.22 (0.18, 0.29) | 6.9% (5.1, 9.2) | 0.25 (0.20, 0.31) |

A includes, where appropriate, a non-parametric 90% confidence interval: 95%LCL and 95%UCL. The non-parametric 95th percentile cannot be calculated if the sample size is less than 19. The non-parametric 95%UCL cannot be calculated if the sample size is less than 59.

B includes, where appropriate, a parametric 90% confidence interval: 95%LCL and 95%UCL. The confidence interval was calculated using a sample size equal to the number of detects, rather than the full sample size. This results in a conservative confidence interval; i.e., a confidence interval that is probably greater than the 90% nominal width.

C One non-detect exceeded the OEL.

D Greater than 94% of the data were non-detects. Several non-detects exceeded the OEL. Calculation of an exceedance fraction using only non-detects is misleading.

estimates. For BTEX, aldehydes, and the gases, all of the non-parametric and parametric 95th percentiles were considerably less than the working OELs. For NO₂, the parametric 95th percentile was 0.25 ppm, which exceeded the working OEL (i.e., the new ACGIH TLV) of 0.2 ppm, but was considerably less than the previous ACGIH TLV of 3 ppm.

The EC data for the lead locomotive are displayed in Figure 6. Nearly 58% of the measurements were non-detects. Four measurements exceeded the working OEL, while the
majority were less than the EPA Reference Concentration.(12) The lead locomotive data failed a formal goodness-of-fit test (for the lognormal distributional model), which is not surprising considering the large percentage of non-detects and the departures from lognormality in both tails (see Figure 7). Subjectively, however, the lognormal fit does not look unreasonable.

Both the non-parametric and parametric sample 95th percentile (and their 95%UCLs) for EC in the lead locomotives (see Table IV) were less than or nearly equal to the working OEL, which strongly suggests that the true 95th percentile was less than the working OEL. In addition, both the mean and its 95%UCL were less than the EPA Reference Concentration of 0.005 mg/m³, suggesting that the true mean was less than the EPA limit for general environmental exposures. (The non-parametric Kaplan-Meier mean for left censored data, which
### TABLE V. AIHA Exposure Ratings by Substance, Determined Using Bayesian Decision Analysis (BDA) (All BDA Decision Probabilities Were Calculated Using a Flat, Non-Informative Prior.)

| Substance            | OEL                  | Locomotive Position | N     | Exposure Rating | Certainty Level | 0     | 1     | 2     | 3     | 4     | Notes                                                                 |
|----------------------|----------------------|---------------------|-------|-----------------|-----------------|-------|-------|-------|-------|-------|------------------------------------------------------------------------|
| **Diesel Carbon Emissions** |                      |                     |       |                 |                 |       |       |       |       |       |                                                                         |
| elemental carbon     | 0.02 mg/m³           | All                 | 190   | 3               | high            | 0.000 | 0.000 | 0.009 | 0.965 | 0.026 |                                                                         |
| Lead                 |                      |                     | 156   | 2 or 3          | high            | 0.000 | 0.000 | 0.516 | 0.484 | 0.000 |                                                                         |
| Trailing             |                      |                     | 22    | 4               | high            | 0.000 | 0.000 | 0.000 | 0.007 | 0.993 |                                                                         |
| Other                |                      |                     | 12    | 3               | low             | 0.000 | 0.000 | 0.274 | 0.435 | 0.291 |                                                                         |
| total carbon         | 0.16 mg/m³           | All                 | 141   | 3               | high            | 0.000 | 0.000 | 0.000 | 0.994 | 0.006 |                                                                         |
| **Aromatics (BTEX)** |                      |                     |       |                 |                 |       |       |       |       |       |                                                                         |
| benzene              | 0.5 ppm              | All                 | 94    | 0               | high            | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |                                                                         |
| ethyl benzene        | 20 ppm               | All                 | 11    | 0               | high            | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |                                                                         |
| toluene              | 20 ppm               | All                 | 32    | 0               | high            | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |                                                                         |
| xylene               | 100 ppm              | All                 | 7     | 0               | high            | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |                                                                         |
| **Aldehydes**        |                      |                     |       |                 |                 |       |       |       |       |       |                                                                         |
| acetaldehyde         | 200 ppm              | All                 | 137   | 0               | high            | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |                                                                         |
| benzaldehyde         | 2 ppm                | All                 | 137   | 0               | high            | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |                                                                         |
| formaldehyde         | 0.75 ppm             | All                 | 140   | 1               | high            | 0.000 | 1.000 | 0.000 | 0.000 | 0.000 |                                                                         |
| glutaraldehyde       | 0.05 ppm             | All                 | 126   | 0 or 1          | high            | 0.302 | 0.698 | 0.001 | 0.000 | 0.000 |                                                                         |
| **Gases**            |                      |                     |       |                 |                 |       |       |       |       |       |                                                                         |
| carbon monoxide      | 25 ppm               | All                 | 22    | 2               | medium          | 0.000 | 0.337 | 0.644 | 0.018 | 0.001 |                                                                         |
| nitrogen dioxide     | 0.2 ppm              | All                 | 234   | 4               | high            | 0.000 | 0.000 | 0.000 | 0.045 | 0.955 |                                                                         |

Note: The default parameter space was used unless otherwise indicated.

4 Exposure categories 0, 1, 2, and 3 refer to exposure profiles that have 95th percentiles that are less than 1%, 10%, 50%, and 100% of the exposure limit, respectively. A category 4 exposure profile has a 95th percentile that exceeds the exposure limit.

1. The sample GSD (calculated using MLE) approached or exceeded the default value of 4 for the maximum GSD. The maximum GSD for parameter space was increased to 8.
2. The sample GSD (calculated using MLE) was 10.5. However, all the detects were low relative to the OEL. The maximum GSD for parameter space was increased to 20.
3. The sample GSD (calculated using MLE) was an unrealistic 52.2. The maximum GSD for parameter space was increased to 50.
4. The sample GSD (calculated using MLE) was 6.55. However, all the detects were low relative to the OEL. The maximum GSD for parameter space was increased to 12.
5. The sample GSD (calculated using MLE) was 3.84. The maximum GSD for parameter space was increased to 8.

Analysis Using BDA

Table V contains exposure ratings and certainty levels for all substances (except the PAHs). The exposure ratings provide an alternative means for assessing compliance with an OEL. This table allows one to quickly evaluate the exposure ratings and uncertainties in these ratings. BDA was used to determine the probability that data for each substance came from exposure profiles that could be given AIHA exposure ratings of category 0 through 4. The decision probabilities in Table V also reflect the parameter space (i.e., the range of geometric means and geometric standard deviations considered in the BDA analysis) used for each substance, which in several cases had to be expanded beyond the default parameter space recommended for BDA (see Hewett et al. for additional details on the use of BDA). (Expanding parameter space tends to shift the decision probabilities into the higher exposure categories.)
For EC in the lead locomotive the exposure rating could be either category 2 or 3 (which reflects the fact that the sample 95th percentile is roughly half of the working OEL, therefore nearly equal to the dividing line between category 2 and 3). For BTEX and the aldehydes, BDA strongly suggests that an exposure rating of 0 or 1 is appropriate. CO merited a category 2 rating while NO$_2$ received a category 4 rating using the new ACGIH TLV of 0.2 ppm. The exposure rating implies the range that most likely contains the true 95th percentile.

One has to look at the sample statistics to determine the best estimate of the true 95th percentile, which for NO$_2$ is 0.22 ppm using non-parametric methods, and 0.25 ppm using the lognormal distribution assumption (Table IV). (The exposure rating for NO$_2$ would be category 1 when using the former ACGIH TLV.)

**Determinants of Exposure**

**Effect of Locomotive Position and Window Status**

For most of the cases there was additional contextual information on the locomotive position (e.g., lead versus trailing) and the status of the locomotive windows during the run (open versus closed). The median level for the lead locomotives appears to be considerably less than that for the trailing locomotives (considering both detects and non-detects): 0.0027 mg/m$^3$ (n = 156) versus 0.0073 mg/m$^3$ (n = 22), respectively (see Table III). A two-sided t-test comparison of the log-transformed data indicated that the geometric means were significantly different ($p = 0.001$) (see Figures S1–S3). (This analysis was repeated for TC levels in the lead and trailing locomotives. The levels in the trailing locomotive tended to be slightly greater than the levels in the lead locomotive, but the difference in the geometric means was not significant (p = 0.229 and p = 0.336 assuming separate and pooled variances, respectively.)

It was not expected that window status (open vs. closed) would greatly affect the EC levels for the lead locomotive. A t-test comparison of the log-transformed data indicates that the geometric means were not significantly different ($p = 0.318$ and p = 0.334 assuming separate and pooled variances, respectively). In contrast, a t-test comparison of the TC levels showed that the TC levels were significantly greater ($p < 0.05$) when the windows in the lead locomotive were open.

It is logical to expect that window status might have a profound effect on the EC and TC levels in the trailing locomotive. However, a t-test comparison of the log-transformed EC values, by window status, was not significant ($p = 0.504$ and $p = 0.499$ assuming separate and pooled variances, respectively), indicating that the geometric mean EC levels when the windows were open versus closed were not significantly different. This analysis was repeated for TC levels in the trailing locomotive. The TC levels were not significantly greater when the windows in the trailing locomotive were open ($p = 0.964$ assuming either separate or pooled variances).

Analysis of variance (ANOVA) was used to evaluate the combined effects of locomotive position (lead vs. trailing) and window status (open vs. closed) on the EC levels (results not shown). The position has a significant effect ($p < 0.0001$), but neither window status nor the interaction term was close to being statistically significant (see the Supplemental Materials). To fully evaluate the effect of window status on the trailing locomotive additional data will be necessary.

**Effect of Tunnels**

EC levels for the lead locomotive were plotted versus the number of tunnels encountered per run (see Figure S4). There was no indication of an effect due to the number of tunnels encountered during the run.

(see the Supplemental Materials for additional text as well as an evaluation of the effect of locomotive manufacturer, class, and model on EC levels.)

**DISCUSSION**

**Data Interpretation Issues**

The data set is a result of a targeted sampling strategy where the objective was to obtain data from a cross-section of runs (e.g., yard, local, and through-freight service). Consequently, the data set is one of convenience and not the product of a stratified, randomized sampling plan. The data covered a broad span of time and were collected from nearly every model of locomotive owned by CSXT, with windows both open and closed, from both lead and trailing locomotives, from runs that included tunnels, and from a variety of geographic locations (15 of the 23 states in which CSXT has track) and run conditions. There is no reason to suspect that the data are not reasonably representative of exposure levels for the CSXT fleet of locomotives. As discussed below, the range and mean levels of EC were comparable to levels reported by other investigators, further supporting a conclusion that the data are representative.

In this analysis, locomotive engineers and conductors, regardless of the locomotive assigned during the run, have been treated as if they all belong to a single SEG. The effect of manufacturer and locomotive size (four axles versus six) on the EC levels was examined (see Tables SIV–SVI, Supplemental...
Materials). In general, EC levels did vary with manufacturer and locomotive size and there may be true locomotive model-to-model differences, reflecting the particular configuration and design of each model, but overall the differences appear to be of little consequence, as the overwhelming majority of the measurements were less than the working OELs. Further evaluation of differences related to model, class, and manufacturer would require additional measurements.

Robustness of the Data Set

The data for all substances were adjusted to a standard 8-hr shift for purposes of comparison to the 8-hr TWA working OELs. One might ask, would the results and conclusions change if the analyses were repeated for the unadjusted concentrations? The statistical analysis for all locomotive positions, lead locomotives, and the trailing locomotives was repeated using the “unadjusted,” original values for EC. The statistics tended to be slightly greater than those reported here. For example, for the lead locomotive the mean, exceedance fraction, and 95th percentile for the unadjusted EC levels were 0.0033 mg/m³, 1.4%, and 0.0109 mg/m³, compared to the values of 0.0028 mg/m³, 1.2%, and 0.0097 mg/m³ reported in Table IV.

Comparison to Other Railroad Studies

The CO and NO₂ results are consistent with findings in the literature. In a study of exposures to diesel exhaust in the Canadian railroad system, Seshagiri(11) reported that the majority of the samples—90% for NO₂ and 75% for CO—were less than the limits of detection (0.1 ppm for NO₂ and 0.2 ppm for CO). Seshagiri also reported maximum values of 0.3 ppm for NO₂ and 4.5 ppm for CO, which are consistent with the values reported here (see Table III). The mean EC level for the locomotive crews is consistent with those reported by other investigators (see Table SIX).

Comparison to Background EC Levels and Levels in Other Industries

In Figure 8 the average EC levels determined for various settings—background, trucking, and mining—are displayed alongside the average value for the CSXT lead locomotives (and for other locomotives). The average EC levels and references are listed in Table SVII. The sample dates are provided because EC levels tend to change over time in response to regulations and economic considerations.

Figure 8 is rather busy, but leads to a number of observations. The mean for lead locomotives is consistent with those reported for other railroads; residential, urban, and highway exposures; and for local and long haul truck drivers. The mean for lead locomotives is also comparable to levels reported for the surface work areas of the underground mines used in the NCI-NIOSH diesel exhaust lung cancer study.(20) (The NCI-NIOSH investigators intended to use the surface workers as the reference group.) In contrast, the mean levels for the...
underground work areas of the mines in the NCI-NIOSH study were considerably greater than the background, railroad lead locomotive, and trucking averages.

Both Zaebst et al.\(^{(21)}\) and Garshick et al.\(^{(22)}\) noted that EC exposures for truckers are similar to background highway and urban levels. Garshick et al. concluded from a source apportionment study that the EC exposures in truckers are primarily influenced by background levels and secondarily by the vehicles driven. The data from this report suggest that a similar observation can be made about EC exposures in the cabs of locomotives when the crew sits in the lead locomotive in the shorthood forward configuration.

Based on the comparisons earlier to the California guideline and the EPA reference dose, one could conclude that the overall risk is low for lung cancer and other effects due to exposure to diesel emissions. Recently, however, a team of NCI and NIOSH researchers published the final two papers in a series describing a study of lung cancer and diesel exhaust in highly exposed underground miners and the less exposed surface employees.\(^{(7,8)}\) IARC,\(^{(9)}\) after reviewing these papers, announced that there is now sufficient evidence to conclude that “diesel exhaust is a cause of lung cancer” and reclassified diesel exhaust as a Group 1 carcinogen.

The Attfield et al.\(^{(7)}\) paper described the cohort study, while the Silverman et al.\(^{(8)}\) paper described a companion nested case-control study in which smoking as a confounding risk factor could be addressed. The odds ratios for the average EC quartiles (taken from Table 3 of Silverman et al.) can be used as an additional “tool” for gaining insight into the level of risk associated with the mean EC exposures for locomotive crews, as well as the mean EC levels for other industries and exposure scenarios, when compared to the NCI-NIOSH study results.

The horizontal lines in Figure 8 break the y-axis into the quartiles specified in Table 3 of Silverman et al., which summarizes findings for all subjects, both underground and surface workers. The mean EC levels for background, lead locomotives, truck drivers, and the surface work areas for the mines studied by NCI-NIOSH all are consistent with odds ratios of 1.00 or 1.03. In contrast, the means for the underground work areas in the NCI-NIOSH study were considerably greater, primarily falling within the two upper quartiles and are consistent with the higher odds ratios. This comparison again suggests that the background EC levels, levels in the cab of lead locomotives, and levels in truck cabs should be associated with low and similar risk potentials. This observation is consistent with the 2006 findings of Garshick et al.\(^{(23)}\) who reported a smoking-adjusted relative risk for lung cancer of 1.22 for workers with any experience working as an engineer or conductor.

**COMMENTS**

The exposure rating for EC was split between categories 2 or 3 (Table V). Given the substantial background levels of EC (relative to the working OEL) (see Figure 8), it is doubtful that an EC data set can lead to exposure rating of category 0 or 1. In other words, an exposure rating of category 2 is probably the best that one can expect in the presence of background levels of EC.

When compared to the previous ACGIH TLV of 3 ppm the nitrogen dioxide exposure profile merits an exposure rating of AIHA exposure category 1. Using the recently adopted ACGIH TLV of 0.2 ppm the exposure profile receives an exposure rating of exposure category 4. Further evaluation is recommended to determine the current status of nitrogen dioxide exposures.

**CONCLUSION**

The statistical analysis of the EC data strongly suggests that at least 95% of the levels encountered by CSXT locomotive crews in the lead locomotives were less than the California guideline of 0.02 mg/m\(^3\) for the years represented by the database. Relative to this guideline, the EC exposure profile merits an exposure rating of AIHA exposure category 2 or 3 (determined using BDA). The EC levels in the trailing locomotives tended to be greater than those in the lead locomotive; however train crews rarely ride in the trailing locomotive.

The mean of the EC exposure profile (and its 95% UCL) for the lead locomotive were less than the EPA reference concentration of 0.005 mg/m\(^3\), suggesting that it is highly likely that the true mean exposure was less than the EPA reference concentration for the years represented by the database. Comparison of the lead locomotive EC levels to those measured in urban areas reveals that the urban levels and CSXT lead locomotive levels are similar in terms of median, mean, and 95th percentile exposures.

With the exception of nitrogen dioxide, the overwhelming majority of the measurements for total carbon, PAHs, aromatics, aldehydes, and combustion gases in the cabs of CSXT locomotives were either non-detects or considerably less than the working OELs for the years represented by the database. Given the recent change in the ACGIH TLV for nitrogen dioxide, further evaluation is recommended to determine the current status of nitrogen dioxide exposures within locomotive cabs.

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**DECLARATION OF INTEREST**

Paul Hewett is the principal of Exposure Assessment Solutions, Inc., and was requested by CSXT to do a statistical analysis of the occupational exposure data for
locomotive crews. Billy Bullock is the director of industrial hygiene for CSX Transportation.

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