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Cancer Risk and Diesel Exhaust Exposure Among Railroad Workers

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Abstract Inhalation exposure to diesel exhaust in the railroad work environment causes significant and quantifiable cancer risks to many railroad workers. Diesel exhaust has been identified as a known human carcinogen by the International Agency for Research on Cancer ("IARC") and as a potential carcinogen by the United States Environmental Protection Agency ("USEPA"), the California Environmental Protection Agency's Office of Environmental Health Hazard Assessment ("OEHHA"), and the National Institute for Occupational Safety & Health ("NIOSH"). Peer-reviewed literature defines the ambient air concentrations of diesel exhaust for several railroad occupations as being above environmental background levels. This study uses diesel exhaust concentrations in the railroad work environment in conjunction with the USEPA's Integrated Risk Information System ("IRIS") risk assessment methodology to quantify the cancer risk posed to railroad workers due to occupational inhalation exposure to diesel exhaust. NIOSH Bulletin 68 (2017) states that there is "no known safe level" of exposure to carcinogens and recommends an evaluation of the USEPA's IRIS guidance to evaluate quantitative risk assessment of human exposure to occupational carcinogens. This is the first study to utilize USEPA methodology to calculate the excess lung cancer risk caused by railroad workers' cumulative exposure to diesel exhaust.

Keywords Diesel exhaust · Railroad workers · USEPA risk assessment · Carcinogen exposure · Cancer risk · NIOSH

1 Introduction

Occupational inhalation exposure to diesel exhaust in the railroad work environment causes a significant and quantifiable cancer risk to many railroad workers. Diesel exhaust is a complex mixture of hundreds of constituents in either a gas or particle form (USEPA, 2002). Diesel particulate matter ("DPM") is the particulate fraction of diesel exhaust and has historically been used as a surrogate measure of exposure for whole diesel exhaust (USEPA, 2002). DPM primarily consists of a solid elemental carbon ("EC") core, adsorbed organic compounds, and small amounts of sulfate, nitrate, metals, and other trace elements (USEPA, 2002). Many of the adsorbed organic compounds (organic carbon, or "OC") are individually known to have carcinogenic and mutagenic properties (USEPA, 2002). The OC are carbon- and hydrogen-containing molecules emitted largely as a result of unburned diesel fuel and, to a lesser extent, from

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engine lubrication oil (USEPA, 2002). Together, the mass of the solid EC cores and OC molecules constitute the mass of total carbon ("TC") of DPM (Liukonen et al., 2002).

DPM particle sizes range in diameter from < 2.5 to < 0.1 µm, which makes DPM highly respirable and capable of reaching the deep lung (USEPA, 2002). DPM contains ultrafine particles ("UFP") that penetrate further into the lungs and accumulate in lung tissue due to their size (Diaz et al., 2019). UFP, which are particles of less than 0.1 µm in diameter, account for 1 to 20% of the mass of DPM and 50 to 90% of the number of DPM particles (USEPA, 2002). Ultrafine DPM particles are capable of translocation into the vasculature and lymphatics allowing access to essentially all organs throughout the human body (Schraufnagel, 2020). DPM exposure is also associated with DNA strand breaks in peripheral blood mononuclear cells, and mutagenesis has been demonstrated (USEPA, 2002; Andersen et al., 2019). Many chemicals present in DPM exhibit mutagenic activity, namely polycyclic aromatic hydrocarbons ("PAHs") and nitro-PAHs which comprise the OC mass of DPM particles (USEPA, 2002).

Occupational exposure limits for whole diesel exhaust have been proposed by the ACGIH; however, no such limits have been established. OSHA enforces Permissible Exposure Limits ("PELs") for select constituents of diesel exhaust; however, OSHA has stated that its PELs are not protective of human health and, furthermore, are bound by non-health considerations such as feasibility (OSHA, 1989). OSHA considers NIOSH guidance to determine its PELs for carcinogenic and non-carcinogenic occupational contaminants (Howard, 2020). NIOSH has identified diesel exhaust as a potential carcinogen (NIOSH, 1988).

IARC identifies Diesel Exhaust as a known human carcinogen, while USEPA, OEHHA, and NIOSH consider diesel exhaust a potential carcinogen (IARC, 2012a; USEPA, 2003; OEHHA, 2001; NIOSH, 1988). In 2017, NIOSH published an updated Bulletin 68, which states that there is "no known safe level" of exposure to carcinogens (NIOSH, 2017a). Bulletin 68 recommends evaluation of the USEPA Integrated Risk Information System ("IRIS") guidance to quantify risk assessment of human exposure to chemical carcinogens (NIOSH, 2017a). However, the peer-reviewed literature has yet to quantify the excess lung cancer risks posed to railroad workers due to their occupational exposures to diesel exhaust using USEPA IRIS risk assessment methodology. The purpose of this study is to quantify the increase in lung cancer risk experienced by several railroad occupations due to occupational diesel exhaust exposure.

The peer-reviewed literature defines the ambient air concentrations of diesel exhaust in the railroad work environment as being above background levels for several railroad occupations (Pronk et al., 2009). This study uses ambient diesel exhaust levels in the railroad work environment in conjunction with USEPA risk assessment methodology to quantify the additional cancer risk posed to some railroad workers due to occupational diesel exhaust exposures.

2 Methods

In order to calculate the cancer risk from inhalation of diesel particulate matter ("DPM"), this health risk assessment ("HRA") relies upon methodology from USEPA's IRIS. This HRA uses a range of DPM annual air concentrations and occupational exposure durations to quantify occupational cancer risks caused by DPM exposure. It is important to note that for carcinogenic risk assessment, USEPA considers diesel exhaust and DPM to be synonymous, as DPM "is the most frequently determined measure of DE and the measure reported in toxicological studies of diesel engine exhaust" (USEPA, 2003).

The Exposure Concentration ("$E_{xp}C$") was first quantified for the exposed workers. The following equation was used to calculate the $E_{xp}C$ of DPM for the railroad workers (USEPA, 2009).

$$E_{xp}C = \frac{C_{air} \times EF \times ED \times ET \times (\frac{1\,day}{24\,hrs})}{AT}$$

$E_{xp}C$ = Exposure Concentration (µg/m^3).

C_{air} = Annual average concentration of DPM in air (µg/m^3).

EF = Exposure frequency (250-days/year).

ED = Exposure duration (years).

ET = Exposure time (8-h/day).

AT = Averaging time (365 days/year × 70 year lifetime).

This study calculated a range of $E_{xp}C$s based on the following information: The average annual air concentrations of DPM ("C_{air}") used are 1, 5, 10, 25, 50, and 100 µg per cubic meter (“µg/m^3”) over exposure durations (“ED”) of 1, 10, 20, 30, and 45 years. Exposure frequencies (EF) were 250 days, which is equivalent to working 5 days/week for 50 weeks/year (USEPA, 2020a). Exposure times (ETs) were 8 h/day (USEPA, 2020a). Averaging time (AT) was a period of 70 years (USEPA, 2020a). These demonstrative values calculated a range of E_{xp}Cs from 0.0326 to 9.76 µg/m^3 of DPM. The EF, ET, and AT values were based on USEPA recommendations for calculating occupational inhalation exposure (USEPA, 2020a). The C_{air} and ED values were selected by this study to relate to known concentrations present in the railroad work environment.

The following equation calculated the range of worker inhalation cancer risk ($Risk_{inh\text{-}work}$) values based on the E_{xp}C values of DPM articulated above and USEPA’s inhalation unit risk (IUR) value for DPM (USEPA, 2020b).

$$Risk_{inh-work} = E_{xp}C \times IUR$$

$Risk_{inh\text{-}work}$ = Worker inhalation cancer risk.
$E_{xp}C$ = Exposure concentration (µg/m^3).
IUR = Inhalation unit risk (m^3/µg).

The Inhalation Unit Risk (“IUR”) factor is determined by USEPA’s assessment of the carcinogenicity of DPM (USEPA, 2003). The IUR for DPM was first published by California’s OEHHA Scientific Review Panel in 1998 and was based on a meta-analysis of human studies and the detailed analysis of increased lung cancer risks among railroad workers (OEHHA, 2001; CalEPA, 1998).

Airborne EC measurements are widely accepted as a surrogate for measurements of DPM (Verma et al., 2003). NIOSH first published analytical method 5040 in 1996, which uses thermal-optical analysis to determine EC, OC, and TC concentrations (NIOSH, 2017b). This method is practical, inexpensive, and sensitive enough to measure environmental background samples of EC (Birch & Cary, 1996).

Available literature provides ambient average EC concentrations in the railroad work environment for several job categories and locations. This study evaluated and tabulated, when available, EC vales of the following categories: upper 95% confidence limit, maximum, arithmetic mean, and geometric mean. For studies that provided raw data sets of EC sample concentrations, upper 95% confidence limits were calculated using ProUCL, a statistical analysis software accepted by the USEPA. The EC concentrations evaluated from the peer-reviewed literature are tabulated below in Table 1.

To relate the EC values in the above table to the DPM values used in USEPA risk assessment equations, EC values must be converted to DPM values. This study converted EC values in the above table to DPM values using a range of EC to DPM ratios supported by the peer-reviewed literature. One issue of using EC as a surrogate for DPM is that the fraction of DPM mass that is EC varies significantly across different occupational environments (USEPA, 2002). As such, the ratio of EC to other constituents in DPM, including OC and trace metals, is not constant (Verma et al., 2003).

According to USEPA, EC contributes 50 to 85% of total DPM mass (USEPA, 2002). Several published studies and reports provide ratios of EC to DPM mass; however, these studies do not provide empirical data to substantiate their proposed ratios. Liukonen et al. (2002) state that EC comprises 60 to 70% of total DPM mass. Birch & Cary (1996) state that a fraction of EC mass to total DPM mass of 50% “appears reasonable.” The ACGIH concluded that the adsorbed OC constituents of DPM constitute 15 to 65% of the total particulate mass (Verma et al. 1999). In other words, EC may constitute between 45 and 85% of the total DPM mass, according to ACGIH. However, ACGIH also recommended that half of the TC mass in diesel exhaust be considered EC mass for evaluating exposure (Verma et al. 1999). Gray (1986) assumed that the chemical composition of railroad diesel oil emissions was similar to diesel autos, with an EC to TC mass ratio of 76.6%. Lastly, CalEPA (1998) determined that the EC mass of the average DPM particle will typically range from approximately 64 to 71%. In summary, the published literature does not provide a specific ratio of EC to DPM mass indicative of diesel exhaust emissions in the railroad work environment.

As such, it is most reasonable and comprehensive to use a range of EC to DPM mass fractions based on USEPA (2002) conclusions that EC mass constitutes 50 to 85% of total DPM mass. This range is inclusive of high estimates of EC to DPM mass fractions (i.e., 85%), which yields a conservative multiplier for conversion of EC to DPM. In addition, the range of 50 to 85% includes the EC to DPM mass fractions

Table 1 Peer-reviewed elemental carbon concentrations associated with railroad workers (μg/m^3)

Occupation/location	Sample size	95% Upper confidence limit[1]	Maximum	Arithmetic mean	Geometric mean
Driver (short-haul)[c]	8	-	69.0	-	18.3
Assistant driver (short-haul) [c]	4	-	71.8	-	18.3
Driver (shunter) [c]	6	-	30.8	-	12.3
Assistant driver (shunter) [c]	2	-	19.7	-	12.3
Turnaround personal[d]	43	-	18.8	-	-
Turnaround area[d]	72	-	27.8	-	-
Heavy repair personal[d]	19	-	6.0	-	-
Heavy repair area[d]	35	-	16.6	-	-
All outdoor mechanical personal and area[d]	8	-	5.0	-	-
Lead locomotives area[d]	23	-	11.3	-	-
Other locomotives area[d]	33	-	60.1	-	-
Caboose area[d]	6	-	9.3	-	-
Transportation personal[d]	7	-	4.9	-	-
Engineering trades personal and area[d]	6	-	7.8	-	-
Engineers/train driver (transportation) [d]	23	-	11.3	2.9	2.3
Conductors/trainmen (transportation) [d]	14	-	11.3	3.5	3.0
Machinists/mechanics (mechanical) [d]	28	-	18.8	4.6	3.2
Laborers/engine attendants (mechanical) [d]	15	-	10.8	4.3	2.8
Hostlers/laborers moving units (mechanical) [d]	5	-	5.0	3.5	3.3
Electricians (mechanical) [d]	3	-	17.6	7.2	4.4
Supervisors (mechanical) [d]	8	-	10.4	4.0	3.1
Leading locomotive (transportation) [d]	23	-	11.3	2.9	2.3
Trailing locomotive (transportation) [d]	24	-	60.1	7.9	3.6
Locomotive operating as lead and trail (transportation) [d]	9	-	4.7	2.5	2.3
Caboose[d]	6	-	9.3	3.6	2.6
Turnaround/fuel plant (mechanical) [d]	74	-	24.9	4.9	3.3
Heavy repair/backshop (mechanical) [d]	35	-	16.6	3.6	2.3
Track equipment (engineering) [d]	4	-	4.0	2.7	2.6
All locomotive cabs (lognmormal distribution)[e]	190	14	-	-	1.6
Lead locomotive cabs (lognmormal distribution) [e]	156	10	-	-	1.4
Trailing locomotive cabs (lognmormal distribution) [e]	22	42	-	-	5.6
All locomotive cabs (non-parametric distribution) [e]	190	15	37	3.7	-
Lead locomotive cabs (non-parametric distribution) [e]	156	14	32.4	2.8	-
Trailing locomotive cabs (non-parametric distribution) [e]	22	29	37	11.1	-
Trailing locomotive (winter)[f]	23	4	8.7	2.9	2.2
Trailing locomotive (summer)[f]	24	23	55.7	17.1	13.4
Locomotive cab (trailing and lead)[g]	49	13	45.0	-	3.7
Locomotive cab (trailing only)[g]	16	23	45.0	-	10.1
Railway repair and maintenance depot/railway station[h]	64	46	50.0	21.0	17.0

[a] USEPA (1989) states to use the upper 95% confidence limit or reasonable maximum exposure. Seshagiri (2003), Hewett & Bullock (2014), and Groves & Cain (2000) provided upper 95% confidence limit. The Liukonen et al. (2002) upper 95% confidence limits were calculated using ProUCL

[b] The notation of "-" represents a non-reported or non-calculated data point

[c] Boffetta et al. (2002)

[d] Verma et al. (2003)

[e] Hewett & Bullock (2014). The arithmetic mean is published as the normal distribution statistic mean and the maximum is published as the order statistics maximum

[f] Seshagiri (2003)

[g] Liukonen et al. (2002)

[h] Groves & Cain (2000)

published by peer-reviewed literature (Liukonen et al., 2002; Birch & Cary, 1996; Verma et al. 1999; Gray, 1986; CalEPA, 1998).

To convert the EC concentrations tabulated in Table 1 to DPM concentrations, for use in USEPA IRIS equations, EC values must be scaled by appropriate multipliers to reflect the range of EC to DPM mass fractions of 50% and 85%. The equations used to develop the two multipliers that reflect the 50% and 85% EC to DPM mass fractions are presented below.

$$DPM = EC * Multiplier = EC * \frac{1\ DPM}{0.85\ EC} = EC * 1.18$$

$$DPM = EC * Multiplier = EC * \frac{1\ DPM}{0.50\ EC} = EC * 2$$

Using the 85% EC to DPM, mass fraction will convert EC concentrations using a multiplier of approximately 1.18, and using the 50% EC to DPM, mass fraction will convert EC concentrations using a multiplier of 2. That is, the 85% mass fraction will increase EC concentrations by approximately 118% and the 50% mass fraction will increase EC concentrations by 200%. All data generated or analyzed during this study are included in this published article.

3 Results

The results of converting EC concentrations from peer-reviewed literature to approximate DPM concentrations in the railroad work environment are presented in Tables 2 and 3 below. The methods described above, which utilize conversion multipliers of approximately 1.18 and 2, were used to convert the EC concentrations in Table 1 to the PM concentrations in Tables 2 and 3.

The result of using approximate DPM concentrations in conjunction with USEPA's risk assessment methodology clearly demonstrates that many individuals who work in the railroad industry incur a significant excess cancer risk due to diesel exhaust exposure, as presented in Table 4. Table 4 presents the incremental cancer risks for occupational exposure to DPM under various exposure scenarios. While most literature evaluated for this study presents arithmetic and geometric mean EC concentrations, USEPA guidance recommends using a reasonable maximum exposure or the 95% upper confidence limit as an exposure point estimate (USEPA, 1989). However, the authors of many of the papers used for this analysis did not provide the necessary data to conduct this calculation.

Table 4 presents a range of worker inhalation cancer risk values from a minimum of 1 per million to 4403 per million due to occupational inhalation exposure to DPM. Based on the above methodology, exposure to 1 μg/m^3 of DPM for 1 working year for 8 h per day results in an increased cancer risk of approximately 1 per million. Thus, any exposure to greater than 1 μg/m^3 of DPM for 1 working year for 8 h per day, or to 1 μg/m^3 of DPM for greater than 1 working year results in an increased cancer risk of greater than approximately 1 per million.

Figure 1 illustrates the cancer risk caused by occupational exposures to DPM. This graph was created using the ambient air DPM concentration, exposure duration, and worker inhalation cancer risk values from Table 4

As all five lines in the graph above pass through (0,0), this graph shows any non-zero exposure to DPM results in a non-zero cancer risk. Also, the red horizontal dashed line at value 1 on the *y*-axis represents an increased lifetime cancer risk of one in a million, which is the de minimis cancer risk used by USEPA (Graham, 1993). These trendlines of increased lifetime cancer risks are supported by the NIOSH Bulletin 68, which states that there is no known safe level of exposure to most carcinogens (NIOSH, 2017a).

4 Discussion

One uncertainty of using EC as a surrogate for DPM is that the proportion of EC in DPM varies in different occupational environments. Factors that affect the ratio of EC to total DPM include diesel engine type, diesel engine operating conditions, and fuel formulations (USEPA, 2002). The EPA determined that TC constitutes 88% of the total mass of DPM (Madl & Paustenbach, 2002); however, the portion of TC that is EC varies in different environments.

Fuel and oil properties including specific energy content, ignition quality, and specific gravity affect hydrocarbon composition and the composition of exhaust emissions (USEPA, 2002). In addition, different types of engines can impact the ratio of EC

Table 2 Diesel particulate matter concentrations associated with railroad workers based on the EC to DPM multiplier of 1.18 (µg/m^3)

Occupation location	Sample size	95% Upper confidence limit[1]	Maximum	Arithmetic mean	Geometric mean
Driver (short-haul)[c]	8	-	81.2	-	21.5
Assistant driver (short-haul) [c]	4	-	84.5	-	21.5
Driver (shunter) [c]	6	-	36.2	-	14.5
Assistant driver (shunter) [c]	2	-	23.2	-	14.5
Turnaround personal[d]	43	-	22.1	-	-
Turnaround area[d]	72	-	32.7	-	-
Heavy repair personal[d]	19	-	7.1	-	-
Heavy repair area[d]	35	-	19.5	-	-
All outdoor mechanical personal and area[d]	8	-	5.9	-	-
Lead locomotives area[d]	23	-	13.3	-	-
Other locomotives area[d]	33	-	70.7	-	-
Caboose area[d]	6	-	10.9	-	-
Transportation personal[d]	7	-	5.8	-	-
Engineering trades personal and area[d]	6	-	9.2	-	-
Engineers/train driver (transportation)[d]	23	-	13.3	3.4	2.7
Conductors/trainmen (transportation) [d]	14	-	13.3	4.1	3.5
Machinists/mechanics (mechanical)[d]	28	-	22.1	5.4	3.8
Laborers/engine attendants (mechanical)[d]	15	-	12.7	5.1	3.3
Hostlers/Laborers moving units (mechanical)[d]	5	-	5.9	4.1	3.9
Electricians (mechanical)[d]	3	-	20.7	8.5	5.2
Supervisors (mechanical)[d]	8	-	12.2	4.7	3.6
Leading locomotive (transportation)[d]	23	-	13.3	3.4	2.7
Trailing locomotive (transportation)[d]	24	-	70.7	9.3	4.2
Locomotive operating as lead and trail (transportation)[d]	9	-	5.5	2.9	2.7
Caboose[d]	6	-	10.9	4.2	3.1
Turnaround/fuel plant (mechanical)[d]	74	-	29.3	5.8	3.9
Heavy repair/backshop (mechanical)[d]	35	-	19.5	4.2	2.7
Track equipment (engineering)[d]	4	-	4.7	3.2	3.1
All locomotive Cabs (lognmormal distribution)[e]	190	16.5	-	-	1.9
Lead locomotive Cabs (lognmormal distribution)[e]	156	11.8	-	-	1.6
Trailing locomotive Cabs (lognmormal distribution)[e]	22	49.4	-	-	6.6
All locomotive cabs (non-parametric distribution)[e]	190	17.6	43.5	4.4	-
Lead locomotive cabs (non-parametric distribution)[e]	156	16.5	38.1	3.3	-
Trailing locomotive cabs (non-parametric distribution)[e]	22	34.1	43.5	13.1	-
Trailing locomotive (winter)[f]	23	4.7	10.2	3.4	2.6
Trailing locomotive (summer)[f]	24	27.1	65.5	20.1	15.8
Locomotive cab (trailing and Lead)[g]	49	15.3	52.9	-	4.4
Locomotive cab (trailing Only)[g]	16	27.1	52.9	-	11.9
Railway repair and maintenance depot/railway station[h]	64	54.1	58.8	24.7	20.0

Table 2 (continued)

[a] EPA states to use the upper 95% confidence limit or reasonable maximum exposure (USEPA, 1989). Seshagiri (2003), Hewett & Bullock (2014), and Groves & Cain (2000) provided upper 95% confidence limit. The Liukonen et al. (2002) upper 95% confidence limits were calculated using ProUCL

[b] The notation of "-" represents a non-reported or non-calculated data point

[c] Boffetta et al. (2002)

[d] Verma et al. (2003)

[e] Hewett & Bullock (2014). The arithmetic mean is published as the normal distribution statistic mean and the maximum is published as the order statistics maximum

[f] Seshagiri (2003)

[g] Liukonen et al. (2002)

[h] Groves & Cain (2000)

to TC in DPM. Engine component wear and from different compounds in the fuel and lubricant also affect DPM mass and composition (USEPA, 2002). Higher amounts of carbonaceous particles form due to high loads or high fuel–air ratios (USEPA, 2002). Increasing the fuel injection rate in diesel engines by increasing the fuel injection pressure can decrease the duration of diffusion combustion and promote EC oxidation during the expansion stroke, which can reduce formation of EC agglomerates and reduce the particulate carbon fraction at high load (USEPA, 2002). As a result, high fuel injection pressures have been used to obtain compliance with PM standards that came into effect in the late 1980s (USEPA, 2002). In an analysis of data demonstrating the EC fraction of total fine PM, USEPA found that the EC content of DPM varied widely in the 1980s, ranging from approximately 20 to 90% (USEPA, 2002). In more recent years, USEPA observed a smaller range in the EC fraction from approximately 50 to 90% (USEPA, 2002). According to USEPA, this data suggests that newer model engines typically emit DPM with higher amounts of EC than older engines (USEPA, 2002). Madl & Paustenbach found significant and quantifiable cancer risks to railroad workers due to occupational inhalation exposure to DPM based on the ambient EC levels published in the peer-reviewed literature and USEPA's risk assessment methods. Similar cancer risks among railroad workers due to occupational inhalation exposure to DPM have been published, including Vermeulen et al. (2014). This study is conservative compared to Vermeulen et al. (2014) because the units of comparison from this study is additional risk of cancer, while Vermeulen et al. (2014) published units of lung cancer deaths. Vermeulen et al. (2014) published that 10 years of occupational exposure to 1 μg/m^3 of elemental carbon results in approximately a 400 per million increase in risk of lung cancer deaths. The USEPA risk assessment methods used in this study calculate that 10 years of exposure to 1 μg/m^3 of DPM (conservative estimate that EC mass equals DPM mass) causes an additional lung cancer risk of 10 in a million. In other words, this study calculated a lung cancer risk rate value that is approximately 40 times lower than the lung cancer death rate values published by Vermeulen et al. (2014) for a similar level of DPM exposure.

IARC has determined that exposure to diesel exhaust causes lung cancer and identified a positive association between diesel exhaust exposure and bladder cancer (IARC, 2012a). However, in 2002, USEPA identified an increased risk from malignancies of the lymphatic tissue among human populations potentially exposed to higher levels of diesel exhaust than typically seen in the environment (USEPA, 2002). A few authors have reported other malignancies related to elevated diesel exhaust exposure, including testicular cancer (Garland et al., 1985), gastrointestinal cancer (Balarajan & McDowall, 1988; Guberan et al., 1992), multiple myeloma (Boffetta et al., 2002; Hansen, 1993), prostate cancer (Aronson et al., 1996), and kidney cancer (Brüning et al., 2003). Diesel exhaust contains detectable quantities of Benzo[a]pyrene (i.e., BaP) which has been associated with squamous cell neoplasia in the larynx, trachea, nasal cavity, esophagus, and forestomach tumor types in both

Table 3 Diesel particulate matter concentrations associated with railroad workers based the EC to DPM multiplier of 2 (μg/m^3)

Occupation/location	Sample size	*95%* Upper confidence limit[1]	Maximum	Arithmetic mean	Geometric *mean*
Driver (short-haul)[c]	8	-	138	-	36.6
Assistant driver (short-haul) [c]	4	-	144	-	36.6
Driver (shunter) [c]	6	-	61.6	-	24.6
Assistant driver (shunter) [c]	2	-	39.4	-	24.6
Turnaround personal[d]	43	-	37.6	-	-
Turnaround area[d]	72	-	55.6	-	-
Heavy repair personal[d]	19	-	12	-	-
Heavy repair area[d]	35	-	33.2	-	-
All outdoor mechanical personal and area[d]	8	-	10	-	-
Lead locomotives area[d]	23	-	22.6	-	-
Other locomotives area[d]	33	-	120	-	-
Caboose area[d]	6	-	18.6	-	-
Transportation personal[d]	7	-	9.8	-	-
Engineering trades personal and area[d]	6	-	15.6	-	-
Engineers/train driver (transportation)[d]	23	-	22.6	5.8	4.6
Conductors/trainmen (transportation) [d]	14	-	22.6	7	6
Machinists/mechanics (mechanical)[d]	28	-	37.6	9.2	6.4
Laborers/engine attendants (mechanical)[d]	15	-	21.6	8.6	5.6
Hostlers/laborers moving units (mechanical)[d]	5	-	10	7	6.6
Electricians (mechanical)[d]	3	-	35.2	14.4	8.8
Supervisors (mechanical)[d]	8	-	20.8	8	6.2
Leading locomotive (transportation)[d]	23	-	22.6	5.8	4.6
Trailing locomotive (transportation)[d]	24	-	120	15.8	7.2
Locomotive operating as lead and trail (transportation)[d]	9	-	9.4	5	4.6
Caboose[d]	6	-	18.6	7.2	5.2
Turnaround/fuel plant (mechanical)[d]	74	-	49.8	9.8	6.6
Heavy repair/backshop (mechanical)[d]	35	-	33.2	7.2	4.6
Track equipment (engineering)[d]	4	-	8	5.4	5.2
All locomotive cabs (lognmormal distribution)[e]	190	28	-	-	3.2
Lead locomotive cabs (lognmormal distribution)[e]	156	20	-	-	2.8
Trailing locomotive cabs (lognmormal distribution)[e]	22	84	-	-	11.2
All locomotive cabs (non-parametric distribution)[e]	190	30	74	7.4	-
Lead locomotive cabs (non-parametric distribution)[e]	156	28	64.8	5.6	-
Trailing locomotive cabs (non-parametric distribution)[e]	22	58	74	22.2	-
Trailing locomotive (winter)[f]	23	8	17.4	5.8	4.4
Trailing locomotive (summer)[f]	24	46	111	34.2	26.8
Locomotive cab (trailing and lead)[g]	49	26	90	-	7.4
Locomotive cab (trailing only)[g]	16	46	90	-	20.2
Railway repair and maintenance depot/railway station[h]	64	92	100	42	34

[a] EPA states to use the upper 95% confidence limit or reasonable maximum exposure (USEPA, 1989). Seshagiri (2003), Hewett & Bullock (2014), and Groves & Cain (2000) provided upper 95% confidence limit. The Liukonen et al. (2002) upper 95 percent confidence limits were calculated using ProUCL

[b] The notation of "-" represents a non-reported or non-calculated data point

[c] Boffetta et al. (2002)

[d] Verma et al. (2003)

[e] Hewett & Bullock (2014). The arithmetic mean is published as the normal distribution statistic mean and the maximum is published as the order statistics maximum

[f] Seshagiri (2003)

[g] Liukonen et al. (2002)

[h] Groves & Cain (2000)

Table 4 Incremental cancer risk incurred due to occupational exposure to diesel particulate matter

Ambient air DPM concentration	Exposure frequency	Exposure duration	Exposure time	Averaging time	Exposure concentration	Inhalation unit risk	Worker inhalation cancer risk
[μg/m^3]	[days/year]	[years]	[hours/day]	[days]	[μg/m^3]	[m^3/μg]	[per million]
1-year exposure							
1	250	1	8	25,550	0.003	0.0003	1
5	250	1	8	25,550	0.016	0.0003	5
10	250	1	8	25,550	0.033	0.0003	10
25	250	1	8	25,550	0.082	0.0003	24
50	250	1	8	25,550	0.163	0.0003	49
100	250	1	8	25,550	0.326	0.0003	98
10-year exposure							
1	250	10	8	25,550	0.033	0.0003	10
5	250	10	8	25,550	0.163	0.0003	49
10	250	10	8	25,550	0.326	0.0003	98
25	250	10	8	25,550	0.815	0.0003	245
50	250	10	8	25,550	1.631	0.0003	489
100	250	10	8	25,550	3.262	0.0003	978
20-year exposure							
1	250	20	8	25,550	0.065	0.0003	20
5	250	20	8	25,550	0.326	0.0003	98
10	250	20	8	25,550	0.652	0.0003	196
25	250	20	8	25,550	1.631	0.0003	489
50	250	20	8	25,550	3.262	0.0003	978
100	250	20	8	25,550	6.523	0.0003	1957
30-year exposure							
1	250	30	8	25,550	0.098	0.0003	29
5	250	30	8	25,550	0.489	0.0003	147
10	250	30	8	25,550	0.978	0.0003	294
25	250	30	8	25,550	2.446	0.0003	734
50	250	30	8	25,550	4.892	0.0003	1468
100	250	30	8	25,550	9.785	0.0003	2935
45-year exposure							
1	250	45	8	25,550	0.147	0.0003	44
5	250	45	8	25,550	0.734	0.0003	220
10	250	45	8	25,550	1.468	0.0003	440
25	250	45	8	25,550	3.669	0.0003	1101
50	250	45	8	25,550	7.339	0.0003	2202
100	250	45	8	25,550	14.677	0.0003	4403

gastrointestinal and respiratory sites (USEPA, 2017; USEPA, 2002; Tancell et al., 1995). IARC determined that BaP contributes to the genotoxic and carcinogenic effects of occupational exposure to complex polycyclic aromatic hydrocarbon mixtures that contain BaP (IARC, 2012b). USEPA has also identified BaP to be carcinogenic to humans (USEPA, 2017).

Locomotive diesel exhaust also contains detectable quantities of benzene, according to a study of diesel exhaust in a locomotive repair facility (Madl

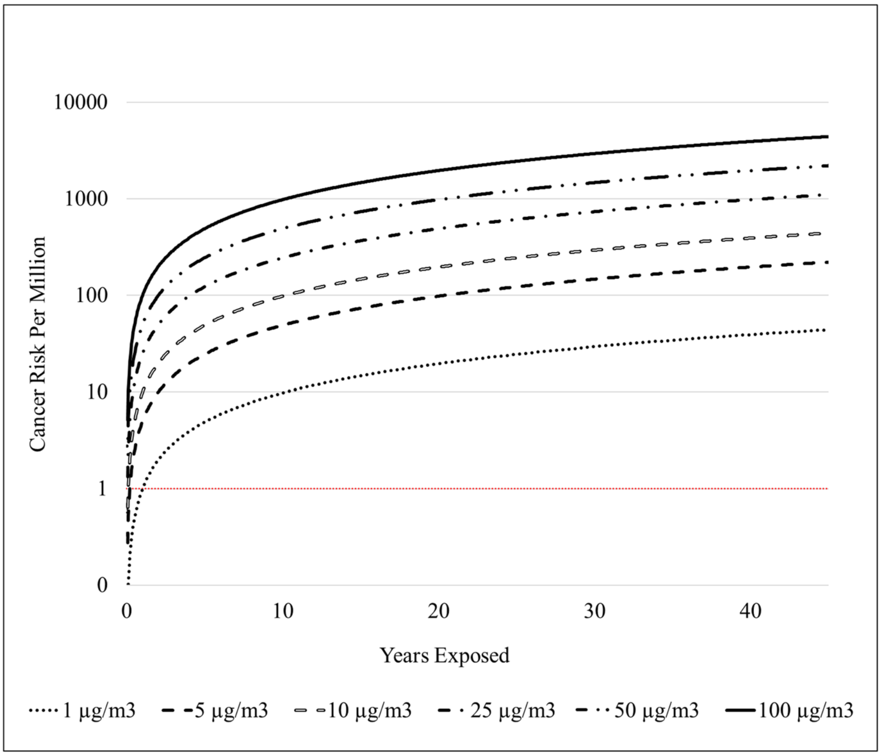

Fig. 1 Occupational inhalation cancer risk for 1 to 45 years of diesel exhaust exposure (log transformed linear regression)

& Paustenbach, 2002). Madl & Paustenbach (2002) detected benzene at approximately 47.9 µg/m^3 inside the locomotive repair facility due to airborne diesel exhaust emissions. OSHA believes that occupational exposure to benzene at low levels poses a carcinogenic risk to workers, and that any exposure must be attended by risk (OSHA, 1978). Benzene exposure has been shown to increase the risk of a range of hematopoietic malignancies including multiple myeloma, lung cancer, leukemias and lymphoma (Rinsky et al., 2002; NIH, 2007; Stenehjem et al., 2021).

5 Conclusion

Occupational exposure to diesel exhaust in the railroad work environment causes a significant and quantifiable increase in cancer risk to many railroad workers due to the inhalation of diesel exhaust. This analysis clearly demonstrates that many railroad workers are subjected to an excessive cancer risk due to their occupational exposure to diesel exhaust using peer-reviewed literature data of elemental carbon and diesel particulate matter in conjunction with USEPA's risk assessment methodology.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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