Diesel Exhaust and Lung Cancer in the Trucking Industry: Exposure–Response Analyses and Risk Assessment

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Background *Diesel exhaust is considered a probable human carcinogen by the International Agency for Research on Cancer (IARC). The epidemiologic evidence rests on studies of lung cancer among truck drivers, bus drivers, shipyard workers, and railroad workers. The general public is exposed to diesel exhaust in ambient air. Two regulatory agencies are now considering regulating levels of diesel exhaust: the California EPA (ambient levels) and the Mine Safety Health Administration (MSHA) (occupational levels). To date, there have been few quantitative exposure–response analyses of diesel exhaust and lung cancer based on human data.*

Methods *We conducted exposure–response analyses among workers in the trucking industry, adjusted for smoking. Diesel exhaust exposure was estimated based on a 1990 industrial hygiene survey. Past exposures were estimated assuming that they were a function of 1) the number of heavy duty trucks on the road, 2) the particulate emissions (grams/mile) of diesel engines over time, and 3) leaks from trucks' exhaust systems for long-haul drivers.*

Results *Regardless of assumptions about past exposure, all analyses resulted in significant positive trends in lung cancer risk with increasing cumulative exposure. A male truck driver exposed to 5 $\mu g/m^3$ of elemental carbon (a typical exposure in 1990, approximately five times urban background levels) would have a lifetime excess risk of lung cancer of 1–2%, above a background risk of 5%.*

Conclusions *We found a lifetime excess risk ten times higher than the 1 per 1,000 excess risk allowed by OSHA in setting regulations. There are about 2.8 million truck drivers in the U.S. Our results depend on estimates about unknown past exposures, and should be viewed as exploratory. They conform reasonably well to recent estimates for diesel-exposed railroad workers done by the California EPA, although those results themselves have been disputed.* Am. J. Ind. Med. 34:220–228, 1998. © 1998 Wiley-Liss, Inc.

KEY WORDS: diesel exhaust; lung cancer; risk assessment

INTRODUCTION

Diesel exhaust is considered a probable human carcinogen by the International Agency for Research on Cancer [IARC, 1989], based on sufficient evidence in animals and limited evidence in humans. The human epidemiologic evidence rests largely on studies of lung cancer among truck

drivers, bus drivers, dock workers, and railroad workers exposed to diesel exhaust [for a recent review, see Health Effects Institute Diesel Working Group, 1995]. The general public is also exposed to diesel exhaust in ambient air, at levels lower than exposed workers. To date, there have been few quantitative risk analyses for diesel exhaust and lung cancer. Most of the epidemiologic studies have not collected quantitative data on exposure level or, if they did, have not used those data in an exposure–response analysis.

Levels of diesel exhaust in the air have not been easy to measure because diesel exhaust is a complex mixture. In the past, investigators have used a single component of diesel exhaust as a surrogate for exposure, such as NO_2, carbon monoxide, or respirable particulate. However, these surro-

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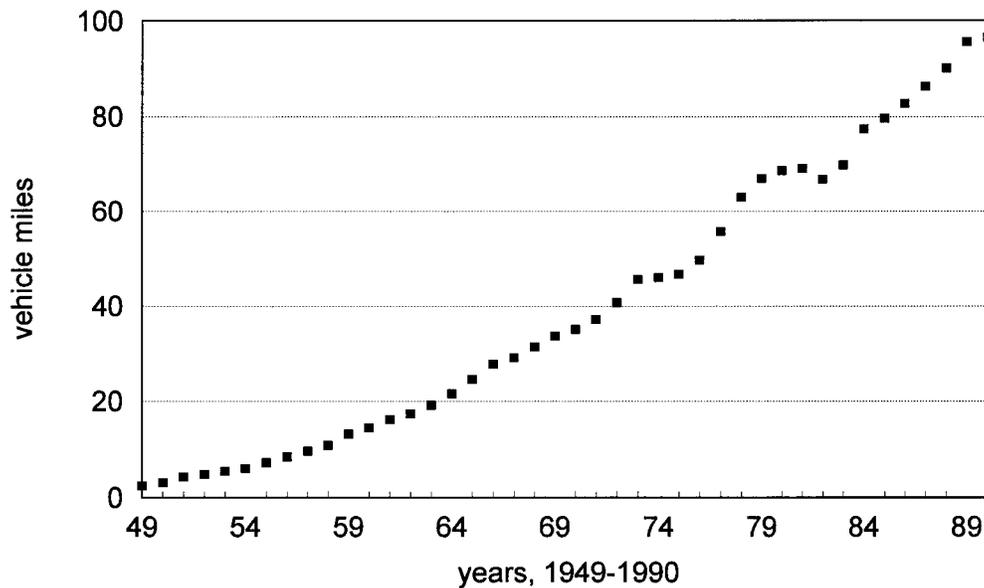
FIGURE 1. Vehicle miles traveled/10*9, U.S. heavy duty trucks, 1949–1990 (source: Federal Highway Administration).

gates are not specific for diesel. In recent years, a more specific surrogate for diesel exhaust, elemental carbon, has come into wider use [Zaebst et al., 1991].

We conducted an exposure–response analysis for elemental carbon exposure and lung cancer using data from a study of workers in the trucking industry. Job-specific elemental carbon measurements in the trucking industry were made in 1990. Estimates of past levels of exposure from 1949–1990 in the current analysis were based on changes in diesel engine emissions over time and on the increased use of diesel engines over time. These estimates were assigned to study subjects based on their known work history. The resulting exposure–response estimates are clearly crude estimates, based on many assumptions. Nonetheless, they offer a starting point for a wider discussion of quantitative risk assessment for diesel exhaust.

METHODS

The original epidemiologic study was a case-control study of decedents in the Teamsters Union, with 994 cases and 1,085 controls. Details can be found in the original publication [Steenland et al., 1990]. Briefly, all cases and controls had died in 1982–1983, and were long-term Teamsters enrolled in the pension system. Subjects were divided into job categories based on the job held the longest. Most had held only one type of job. The job categories were short-haul driver, long-haul driver (over-the-road), mechanic, dockworker, other jobs with potential diesel exposure, and jobs outside the trucking industry without occupational diesel exposure. Smoking histories were obtained from next-of-kin. Odds ratios were calculated for work in an

exposed job category at any time and after 1959 (an estimated date when the majority of heavy duty trucks had diesel engines) compared to the work in nonexposed jobs (after adjustment for age, smoking, and potential asbestos exposure). Trends with duration of work in an exposed job were also calculated.

An extensive industrial hygiene survey of elemental carbon exposures in the trucking industry accompanied the epidemiologic study [Zaebst et al., 1991]. Sub-micrometer elemental carbon was measured in 242 samples covering the major job categories in the trucking industry, as well as ambient roadway and nonroadway levels. Mechanics had the highest levels in the trucking industry, while dockworkers (who drove propane-powered forklifts) had the lowest levels.

We assumed that ambient diesel exposure for all workers in the trucking industry (drivers on highways, dockworkers on loading docks, and mechanics in garages) increased in proportion to the use of diesel engines. We also assumed that the use of heavy duty (trailer combination) trucks is a good marker of diesel engine use, and we obtained data on vehicle miles traveled by heavy duty trucks from 1949–1990 from the Federal Highway Administration [FHWA, 1986–1991] for use in estimating past exposure in our data (Fig. 1).

Diesel exposure to workers in the trucking industry would also be expected to be proportional to emissions from diesel engines. It is known that diesel emissions in the U.S. have decreased since 1970 as engines became more fuel efficient and as regulations came into force requiring reduced emissions. However, few quantitative data are avail-
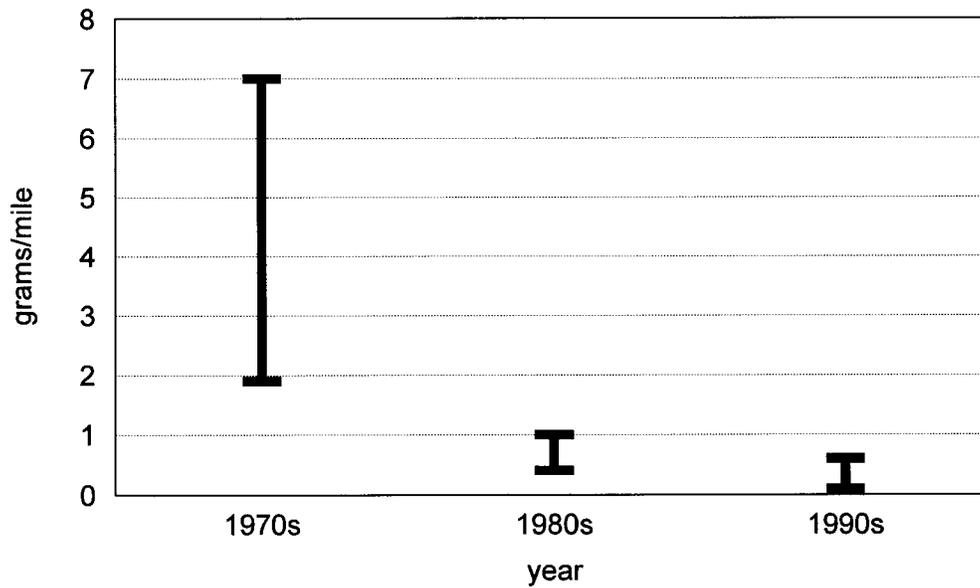
FIGURE 2. Estimated U.S. heavy duty engine particulate emissions (gm/mi) by decade (adapted from Sawyer and Johnson [1995]).

able to estimate past emission levels. What data do exist have been summarized by Sawyer and Johnson [1995], and we have used these data to create a best estimate of emissions changes over time, in terms of grams of emissions per mile traveled. As Sawyer and Johnson's emission data (for heavy duty trucks) were presented in units of gm/kilowatt-hour, we converted these units to grams/emissions per mile via

grams/kilowatt-hour * 0.746

$$= \text{grams/brake-horsepower-hour, and}$$

grams/brake-horsepower-hour * k = grams/mile,

where k = fuel density/(brake-specific fuel consumption

$$* \text{ fuel efficiency})$$

$$= \text{(lbs/gallon)/(lbs/brake-horsepower-hour)}$$

$$* \text{ (mile/gallon)}.$$

Estimates for the variables used to calculate "k" for heavy duty trucks were as follows (personal communications, Robert Sawyer and John Johnson): 1) fuel efficiency was assumed to be approximately 5 miles/gallon in the 1970s, 8 miles/gallon in the 1980s, and 10 miles/gallon in the 1990s; 2) fuel density was assumed to be 7 lbs/gallon, constant over time; and 3) brake specific fuel consumption was estimated to be 0.45 lbs/brake-horsepower-hour for the 1970s, 0.40 for the 1980s, and 0.35 in the 1990s. Sawyer and Johnson [1995] show a range of emission in terms of g/kW-hrs of 0.8–3.0 in the 1970s, 0.25–0.60 in the 1980s, and 0.10–0.39 in the 1990s, for new heavy duty truck engines. The above conversion results in emissions in terms of gm/mile of approximately 1.9–7.0 in the 1970s, 0.4–1.0 in the 1980s, and 0.1–0.6 in the 1990s (Fig. 2). Taking the

mid-points, we assumed the emissions decreased from approximately 4.5 gm/mile in the 1970s to 0.4 gm/mile in 1990s, decreasing linearly as new trucks were introduced into the fleet. For a sensitivity analysis, we also assumed more extreme scenarios for the 1970s, assuming emissions were either 7.0 or 1.9 gm/mile, again decreasing to linearly 0.4 in by the 1990s. These three scenarios are shown in Figure 3.

Estimates of past exposure to elemental carbon, as a marker of diesel exhaust, for subjects in the epidemiologic study were made by assuming that 1) average 1990 levels for a job category could be assigned to all subjects in that job category, and 2) levels prior to 1990 were directly proportional to vehicle miles traveled by heavy duty trucks and the estimated emission levels of diesel engines. We also tried adjusting vehicle miles traveled by total miles of interstate highways, but this adjustment had only minimal effect and was not used. These assumptions were made for all job categories, not just truck drivers (exposures for mechanics and dockworkers would also be expected to all be proportional to the number of diesel trucks and emissions levels).

We also assumed that long-haul drivers received some exposure from their own trucks (short-haul drivers drive lighter trucks which were not generally diesel trucks until the late 1970s and early 1980s; our study ended in 1983, so we did not add "own-truck" exposure for short-haul drivers). Ziskind et al. [1978] indicated that in the mid-1970s, exposure within heavy duty truck cabs under road conditions originated partly from the engine's own emissions, which leaked out of exhaust pipes. Engine exhaust entered the truck cab either through holes in the truck cab floor where the pedals were located or through the window. Ziskind et al. estimated that in-cab concentrations approximately doubled
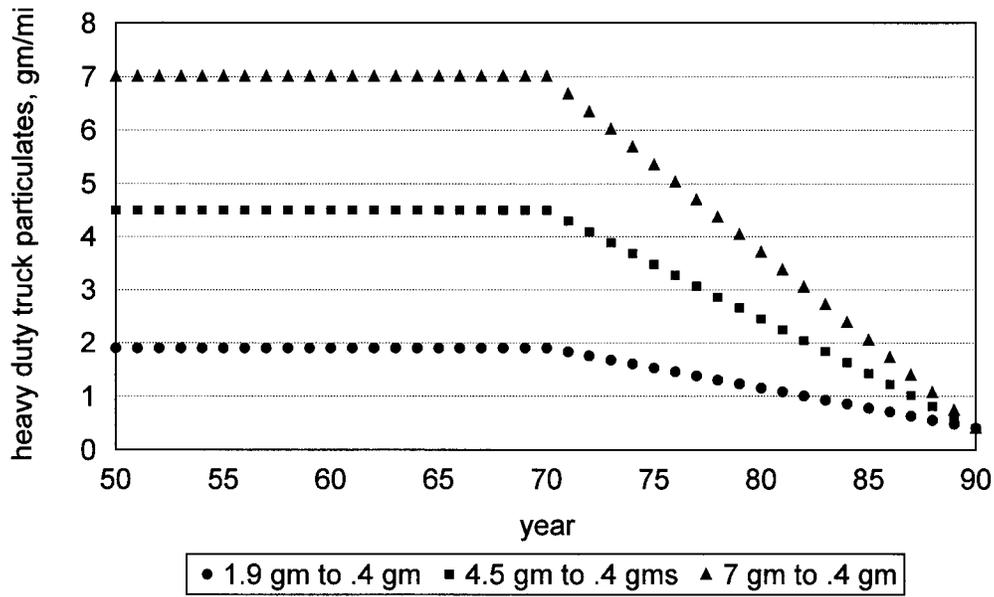
FIGURE 3. Three scenarios for emissions over time.

when leaks were present and that 40% of the 88 trucks tested had such leaks. Based on these data, we assumed that long-haul truckers' exposure was increased approximately 50% by exposures from their own trucks. By way of sensitivity analyses, we also conducted some analyses increasing long-haul drivers' exposures by 100%.

By way of example how past exposures levels were estimated, consider the exposure level of a mechanic in 1975. In terms of μg/m³ of elemental carbon, we have:

1975 level = 1990 level

* (vehicle miles 1975/vehicle miles 1990)

* (emissions 1975/emissions 1990).

The 1990 arithmetic mean exposure level for mechanics in 1990 was 26.6 μg/m³ of elemental carbon [Zaebst et al., 1991], the vehicle miles traveled by heavy duty trucks in 1990 and 1975 were 96.5 and 46.7 million miles, respectively, while the estimated emission levels (assuming 4.5 gm/mile in 1970 decreasing gradually to 0.4 gm/mile in 1990, see Results) were 0.4 gm/mile in 1990 and 3.475 gm/mile in 1975. Therefore, the estimated exposure in terms of elemental carbon for a mechanic in 1975 was 111.8 μg/m³ = 26.6 μg/m³ * (46.7/96.5) * (3.475/0.4).

We also assumed a background exposure in ambient air of 1 μg/m³ per year, and added 1 μg/m³/year to everyone's cumulative exposure. This assumption had only minimal effects on exposure estimates, but seemed appropriate in light of the background residential level of 1 μg/m³ in the 1990 industrial hygiene survey [Zaebst et al., 1991].

Estimates of exposure were derived for study subjects from 1949–1990, although only estimates through 1983 were used in the analyses because that was the last year of

the epidemiologic study; 1949 was used as a start date because Federal Highway Administration data indicated that was the year when diesel fuel first began to be used in appreciable quantities, and when the use of heavy duty trucks also began to be appreciable. Once estimates of exposure for each year of work history were derived for each study subject, analyses were conducted by cumulative level of estimated elemental carbon exposure. Study subjects with jobs outside the trucking industry with potential diesel exposure, for whom no estimates could be made, were excluded from the analysis. Thus, the analysis was restricted to long-haul drivers (n = 1,237), short-haul drivers (n = 297), dockworkers (n = 164), mechanics (n = 88), and those outside the trucking industry (n = 120). Thirty workers in the trucking industry retired before 1949 and were therefore assumed to have had no diesel exposure and were added to the nonexposed group, increasing it to 150.

Three sets of exposure estimates were considered, each based on a different scenario for the decrease in engine emissions since 1970. Analyses were conducted with and without a 5-year lag, which discounted any exposures in the 5 years before death.

Analyses were conducted via logistic regression and were adjusted for age (five categories), race, smoking (never, former quitting before 1963, former quitting in 1963 or later, current with <1 pack a day, current with 1 or more packs per day), diet, and reported asbestos exposure. We considered a variety of models with cumulative exposure, including the basic log-linear model with cumulative exposure, a model adding a quadratic term for cumulative exposure and a model using a log transformation of cumulative exposure. Categorical analyses by quartile of cumula-

tive exposure (with the nonexposed as referent) and restricted cubic spline analyses (knots at 5th, 25th, 50th, 75th, and 95th percentile of cumulative exposure) were also conducted. Goodness-of-fit was tested for all logistic models using the test proposed by Lemeshow and Hosmer [1982]. An additional logistic model via Epicure [1993] was fit in which the cumulative dose term was considered to increase the odds in a linear fashion, while the covariates were again modeled log-linearly. In this model the odds of disease equals

$$\exp(\beta_0 + \beta_1 X_1 + \ldots . \beta_k X_k)(1 + \beta_{k+1} X_{k+1})$$

where X_1 through X_k are covariates while X_{k+1} is the variable for cumulative exposure. Finally, we used S-plus to fit a LOESS smoothing function within logistic regression [Mathsoft, 1994]. This smoothing function is also called a generalized additive model. The procedure is semiparametric and yields results similar to using spline curves.

Results of the regression analyses, in terms of lung cancer rate ratios for specific levels of exposure to elemental carbon, were then used to derive excess risk estimates for lung cancer after lifetime exposure to elemental carbon, according to the following formula, which adjusts for competing risks from other causes [Gail, 1975] :

$$\text{Excess risk} = \Sigma \, (rr_i - 1)^* \, q_l(i) \, \exp[- \Sigma \, (rr_j - 1)q_l(j)$$
$$+ \, q_a(j)].$$

In our use of this formula, excess risk refers to excess risk of lung cancer death by age 75, "q_l" is the lung cancer male mortality for the U.S. population, "q_a" is the all-cause mortality male rate for the U.S., "rr" is the rate ratio for the exposed vs. the nonexposed (a function of cumulative exposure), and "i" and "j" index age. We used age-specific male lung cancer mortality rates from the SEER data for 1987–1991 [SEER, 1994], and U.S. 1991 age-specific death rates for all causes.

RESULTS

Table I gives the epidemiologic results and industrial hygiene results from the original 1990 studies. Epidemiologic results refer to main occupation after 1959. It can be seen that both long-haul and short-haul drivers had levels which were slightly above roadway levels and about 3–4 times background residential levels. Mechanics had the highest levels. Dockworkers had levels similar to residential ones. Odds ratios tend to parallel these levels. Both long-haul and short-haul drivers had positive monotonic trends of increasing odds ratios with increasing duration of employment after 1959 (not shown). Truck mechanics did not show a monotonic increasing trend with duration.

We used the data from Figures 1–3 to calculate estimated yearly exposure levels for each job category. Figure 4 gives an example of these estimates of elemental carbon levels for long-haul drivers from 1949–1983. Levels increase until the early 1970s with increased use of diesel trucks, then decrease due to decreasing emissions. The three

TABLE I. Prior Epidemiologic and Industrial Hygiene (IH) Results for Lung Cancer and Diesel Exhaust by Job Category in the Trucking Industry*

Job category (number IH samples, Zaebst et al. 1991)	1990 Exposure to elemental carbon ($\mu g/m^3$)		Odds ratio (95% CI) from Steenland et al. [1990]
	Geo. mean (s.d.)	Mean (s.e.)	
Dockworkers (n = 12)	1.3 (2.0)	1.6 (0.4)	0.93 (0.55–1.55)
Long-haul drivers (n = 72)	3.8 (2.3)	5.1 (0.4)	1.27 (0.83–1.93)
Short-haul drivers (n = 56)	4.0 (2.0)	5.4 (0.9)	1.31 (0.81–2.11)
Mechanics (n = 80)	12.1 (3.7)	26.6 (4.1)	1.69 (0.92–3.09)
Roadside (area samples)			
(n = 21)	2.5 (2.4)	3.4 (0.5)	n.a.
Off-roadway (area samples)			
(n = 23)	1.4 (0.2)	1.1 (2.0)	n.a.

*From Steenland et al. [1990] and Zaebst et al. [1991]. Referent for odds ratios are workers outside the trucking industry.

curves reflect the three alternative scenarios for the decline in emissions. We also considered a fourth scenario (not shown) in which emissions were considered constant at 4.5 gm/mile through 1975 (rather than 1970), and then decreased to 0.7 in 1990, to allow for a longer delay of introduction of new engines into the fleet. Results from this scenario were in the same range as our other results, and are not shown.

Across all exposed job categories (long-haul driver, short-haul driver, dockworker, mechanic) combined, cumulative exposure to elemental carbon (in terms of $\mu g/m^3$-years) had a median of 372.9 (range 0.45–2,439.9) among the 1,723 exposed subjects, under the emissions scenario of 4.5 gm/mile in 1970. When background levels were added (1 $\mu g/m^3$ per year), the median increased to 442.1 (range 57.4–2,497.9). Estimated exposures were correspondingly higher using the assumption of 7 gm/mile emissions in 1970, and correspondingly lower using the assumption of 1.9 gm/mile in 1970.

Use of the estimated cumulative exposure levels in logistic regression led to the data shown in Table II, which presents results for cumulative exposure (continuous), the log of cumulative exposure (continuous), a cubic spline of cumulative exposure, and a categorical analysis based on dividing the exposure into four groups (quartiles of cumulative exposure). The data in Table II are restricted for simplicity to the most likely emissions assumption (4.5 gm/mile in 1970). Results for more extreme assumptions (1.9 gm/mile in 1970 or 7 gm/mile in 1970) were essentially equivalent, except that the size of the exposure coefficients (effect of one unit of exposure) increased for 1.9 gm/mile (0.000807 for cumulative exposure) and decreased for 7 gm/mile (0.000227 for cumulative exposure). Lagged and unlagged results were similar, with similar model fit. For the categorical analysis (exposed divided into quartiles), the lagged data
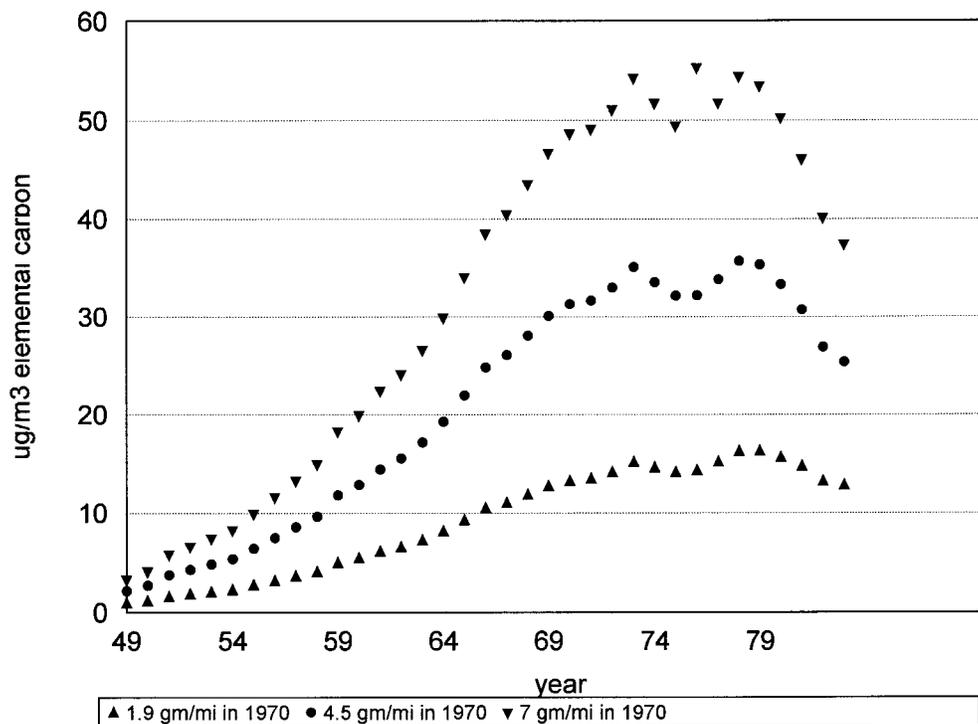
FIGURE 4. Estimated yearly exposure (μg/m3 elemental carbon) for long-haul truckers, by three emission scenarios.

fit slightly better than the unlagged data and resulted in a monotonically increasing exposure–response. Goodness-of-fit tests [Lemeshow and Hosmer, 1982] for all models showed no significant departure from an adequate fit.

Of the models shown in Table II, the model using the log of cumulative exposure had the best fit to the data. Figure 5 shows results for log cumulative exposure, cumulative exposure, and categorical results by quartile of cumulative exposure, for the lagged data under the assumption of 4.5 gm/mile emissions in 1970.

We also tried several other models. Use of a quadratic term did not improve fit and results are not presented. Results using a linear rather than log-linear model for exposure showed that the model fit (based on the deviance) was essentially equivalent to the usual log-linear modeling (e.g., model deviance 2,349.9 for the linear term vs. 2,349.5 for the log-linear model with log cumulative exposure, lagged). We also used a LOESS smoothing function with the log of cumulative exposure within the logistic regression model. This model did not fit the data significantly better than the simpler model using the log of cumulative exposure (lagged) (deviance of 2,345.7, yielding a chi-square value of 3.8 with 3.5 degrees of freedom, or a P-value of 0.36, when compared to the model using the log of cumulative exposure).

We assumed that historical exposure to all workers in the trucking industry were proportional to vehicle miles driven by heavy duty trucks and emissions levels. While this is a reasonable assumption because short-haul truckers, dockworkers, and mechanics can be assumed to have increased exposure to diesel exhaust with more diesel trucks

on the road, and decreased exposure as emissions fall, by way of sensitivity analysis we restricted the data to just heavy duty truck drivers (the largest job category) and nonexposed workers. Results (not shown) were similar to the results presented including all workers. Such similar results would be expected, as heavy duty drivers form by far the largest job category in the data.

Lifetime (through age 75) excess risk of lung cancer death for a male truck driver was calculated assuming the emissions scenario of 4.5 gm/mile in 1970, a 45-year exposure at 5 μg/m³ of elemental carbon beginning at age 20 and ending at age 65, and using the unlagged model for the log of cumulative exposure (lagged results are virtually the same). The estimated excess lung cancer risk is 1.6% (95% CI 0.4–3.1%). The corresponding excess risks assuming emissions were 7 gm/mile in 1970 or 1.9 gm/mile in 1970 are 1.4% (0.3–2.7%) and 2.3% (0.5–4.6%).

DISCUSSION

Analyses by cumulative exposure show significantly increasing trends of risk with increasing exposure. These trends are monotonic in categorical (quartile) analyses when cumulative dose is lagged 5 years. This increasing trend is partly due to the fact that a component of cumulative dose is simple duration of exposure, unweighted for intensity, and analyses by simple duration also exhibit a positive trend with duration. However, models using duration fit less well than the model with cumulative exposure (e.g., model chi square 230.1 vs. 235.4 for a model with log of cumulative

TABLE II. Logistic Regression Results for Lung Cancer in the Trucking Industry and Estimated Cumulative Exposure to Diesel Exhaust ($\mu g/m^3$ Elemental Carbon), Using Four Different Exposure Metrics*

Assumed emissions in 1970 (gm/mile); lag/no lag; exposure metric	Coefficient for exposure term (std. error) or odds ratio (95% CI) for categorical model	2X change in log likelihood due to addition of exposure term(s) (d.f.)	P-value for exposure term(s)
4.5 gm; no lag;			
cumulative exposure	0.000352 (0.000155)	5.139 (1)	0.023
log cum exposure	0.1797 (0.0696)	6.706 (1)	0.010
cubic spline	n.a.	13.370 (4)**	0.010
quartiles cum exp*			
0–174	1.20 (0.79–1.81)	9.568 (4)	0.048
174–268	1.16 (0.77–1.75)		
268–360	1.39 (0.91–2.11)		
360+	1.72 (1.11–2.64)		
4.5 gm; 5-year lag;			
cumulative exposure	0.000389 (0.000176)	4.982	0.026
log cum exposure	0.1803 (0.0709)	6.510 (1)	0.011
cubic spline	n.a.	10.127 (4)***	0.038
quartiles cum exp*			
0–169	1.08 (0.72–1.63)	10.698	0.032
169–257	1.10 (0.74–1.65)		
257–331	1.36 (0.90–2.04)		
331+	1.64 (1.09–2.49)		

*Referent group composed of those with 0 cumulative exposure above background (n = 150); units of cumulative exposure are $\mu g/m^3$-years of elemental carbon.
**Spline vs. log cumulative exposure, chi square 6.664, 3 d.f., $P = .08$.
***Spline vs. log cumulative exposure, chi square 3.617, 3 d.f., $P = .31$.

exposure, assuming 4.5 gm/mile emissions in 1970), indicating that adding intensity added information to the model (the Spearman correlation coefficient between duration and cumulative exposure is 0.42).

Our results are dependent on very broad assumptions and are limited by a variety of factors. First, our exposure estimates are based on assignment of mean job-specific levels from a sample of measurements in 1990 to all workers in the same job categories, with extrapolations to earlier time periods. We do not have actual exposure measurements on our study subjects. While this is not uncommon in epidemiology, it must be recognized as an important limitation. Our extrapolations over time are based on assuming that exposures for all job categories in the trucking industry were proportional to the vehicle miles traveled by heavy duty trucks and to the level of emissions of particulates from heavy duty engines. It is not known if these assumptions are accurate, although they appear reasonable.

There are no good data on actual highway levels of elemental carbon or of particulate over time, which would enable us to evaluate our assumptions. The U.S. EPA [Flachsbart, 1995] has estimated levels of volatile organic compounds emitted on highways in 1960, 1970, 1980, and

1990. These levels, which might be expected to correlate with elemental carbon, peaked in 1970, paralleling our own assumptions. In one of the few datasets with estimated elemental carbon data over time, Cass and Gray [1995] estimated that levels decreased from the late 1950s through 1982 in Los Angeles. However, these data are difficult to generalize to our estimates because the sampling stations were off-highway, and only approximately 50% of estimated elemental carbon levels were thought to be due to highway diesel emissions.

Another important limitation is that we do not know to what degree drivers may have received exposure from their own truck engines, although we do know that in the past some proportion of exposure to long-haul drivers did come from their own trucks due to leaky exhaust systems. We assumed an increase of 50% above background occupational exposure due to exposure of a long-haul driver to their own exhaust, although we have few data on which to base this assumption. On the other hand, our results do not vary appreciably if this assumption is changed. When we assumed a 100% increase for long-haul drivers instead of 50%, results changed only slightly (the coefficient for cumulative exposure, assuming 4.5 gm/mile emissions in 1970, decreased from 0.000352 to 0.000339).
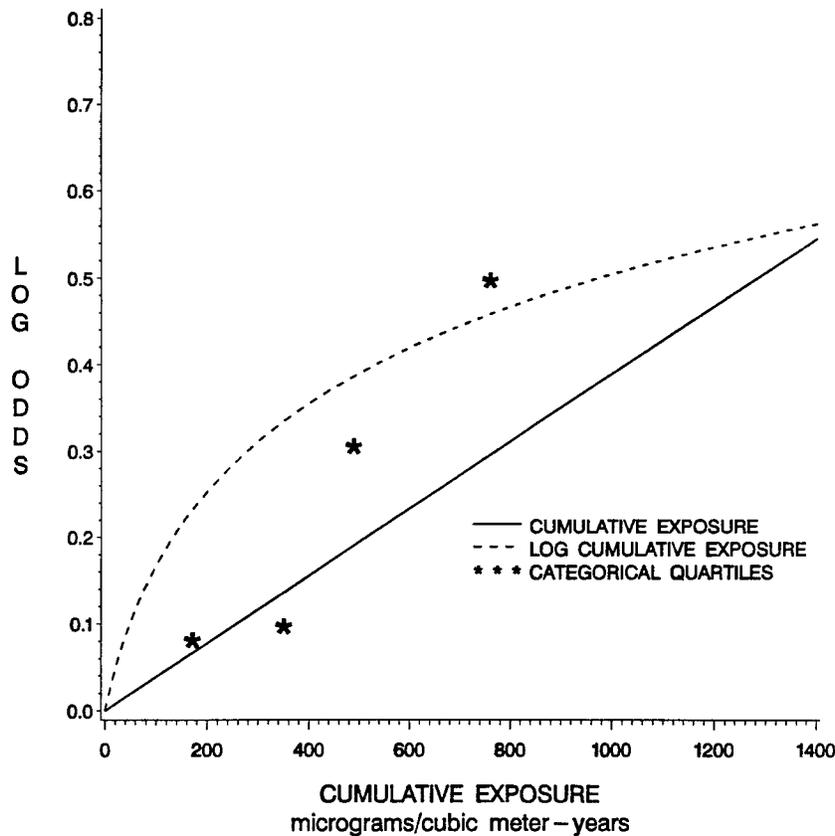
FIGURE 5. Log odds vs. cumulative exposure; lagged 5 years. Assumes 4.5 gram/mile emissions in 1970.

Our results regarding risk per unit of diesel exposure are also dependent on which emissions scenario is chosen. Unfortunately, data on past engine emissions are quite sparse, and there is a wide range of plausible emissions in the past. We considered three different scenarios for emissions, using our best estimate as well as the lowest and highest estimate of emissions levels in 1970. The exposure coefficient remained within a relatively narrow range (from 0.0002 to 0.0008), as did estimates of lifetime excess risk for a truck driver exposed for 45 years to 5 μg/m^3 of elemental carbon (excess risk 1.4–2.3%). We also considered another scenario, where changes in emissions began in 1975 instead of 1970, to allow for a further delay in introducing new engines into the fleet. Results from this analysis were similar to the analyses presented.

Because of the limitations outlined above, our results should be viewed as exploratory. Our estimated lifetime risks of lung cancer due to relatively low levels of exposure (5 μg/m^3 elemental carbon) are quite high. The Occupational Safety and Health Administration (OSHA) ordinarily sets standards so that workers are exposed to levels of carcinogens resulting in a lifetime excess risk of less than 1 in 1,000 [Infante, 1995], but the excess risks calculated here are on the order of 1 to 2 per 100.

These high excess risks per unit dose are a function of the fact that we found excess lung cancer risks for workers in

occupations with relatively low exposures, often only slightly above urban background. Exposure to workers in the trucking industry in 1990 averaged 2–27 μg/m^3 of elemental carbon, with background residential levels of 1 μg/m^3. By comparison, railway workers averaged 42–155 μg/m^3 of respirable particulate (adjusted for nicotine) in the 1980s [Woskie et al., 1988a], which represents approximately 17–62 μg/m^3 elemental carbon, assuming that elemental carbon is about 40% of the adjusted respirable particulate [Zaebst et al., 1991; Birch and Cary, 1996]. Diesel-exposed miners, another occupationally exposed group, are likely to have considerably higher exposures due to working in confined spaces, with elemental carbon typically ranging from 150–500 μg/m^3. To date, there are no epidemiologic data on lung cancer risk among diesel-exposed miners, but a joint NIOSH-NCI project is underway. For railroad workers, Garshick et al. [1987, 1988] have shown excess risk of lung cancer among railway workers, which increased with increasing duration of exposure.

The Garshick data have recently been subjected to a quantitative risk assessment by the California EPA [1998]. These authors based their quantitative exposure estimates, as we do, on a survey of recent workers in different job categories [Woskie et al., 1988a]. They then apply these estimates by job category to past workers, estimating how exposures may have changed over time [Woskie et al.,

1988b]. Using log-linear models, the California EPA investigators [Appendix D, California EPA, 1998] found an increase in log of the rate ratio per unit of cumulative exposure to nicotine-adjusted respirable particulate (i.e., the exposure coefficient) of approximately 0.00012 assuming exposure increased from 1949–1959, then decreased to end-of-study in the early 1980s (''roof'' pattern). Multiplying this coefficient by 2.5 to obtain the equivalent coefficient for elemental carbon, results in a coefficient of 0.00030. This coefficient corresponds well with our coefficient of 0.00035 for cumulative exposure, and therefore provides some support for findings. However, it should be noted that the California EPA results using the Garshick data have been disputed by analyses of the same data set by Crump et al. [1997]. These authors ran a large number of models with different exposure metrics. Overall, they found no significant positive exposure–response trend, and many models had negative exposure–response trends. They did find a positive exposure–response trend in the model most closely resembling one of the California EPA models, but it fell short of statistical significance.

In summary, our data suggest a positive and significant increase in lung cancer risk with increasing estimated cumulative exposure to diesel exhaust among workers in the trucking industry. They indicated that a male truck driver exposed to 5 $\mu g/m^3$ of elemental carbon (typical for a truck driver) over a 45-year working lifetime has an increase in lifetime lung cancer risk of 1–2%, above a background risk of 5%. There are currently approximately 2.8 million truck drivers in the U.S. [Bureau of the Census, 1992]. Quantitative analyses such as ours are relevant because at least two agencies in the U.S. are currently considering regulation of diesel exhaust (California EPA for ambient levels, and the Mine Safety Health Administration (MSHA) for occupational levels). Our results should be regarded with appropriate caution because our exposure estimates are based on broad assumptions rather than actual measurements.

ACKNOWLEDGMENTS

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