Statistical Modelling of the Determinants of Historical Exposure to Bitumen and Polycyclic Aromatic Hydrocarbons Among Paving Workers

IGOR BURSTYN†‡§, HANS KROMHOUT†*, TIMO KAUPPINEN‡, PIRJO HEIKKILA‡ and PAOLO BOFFETTA§

†Environmental and Occupational Health Group, Wageningen University, PO Box 238, 6700 AE Wageningen, The Netherlands; ‡Institute of Occupational Health, Topeliuksenkatu 41A, 00250, Helsinki, Finland; §Unit of Environmental Cancer Epidemiology, International Agency for Research on Cancer, 150 cours Albert-Thomas, 69372 Lyon Cedex 08, France

INTRODUCTION

The International Agency for Research on Cancer (IARC) is currently engaged in a cohort study of cancer risk among European asphalt workers. The objective of the exposure assessment in the study is to estimate exposures of road paving workers to bitumen and coal tar. An investigation of the potential cancer risk due to bitumen exposure is the primary goal of the study. However, coal tar exposure is an important confounder, since it is ‘causally associated with cancer in humans’ (IARC, 1985) and has been used in paving processes in the past (Partanen et al., 1994). Because polycyclic aromatic hydrocarbons (PAH) are a ‘major component’ of coal tar (IARC, 1985), we assumed a
priori that PAH exposure is an appropriate measure of exposure to coal tar.

Previously published inhalable dust, bitumen and PAH exposure data for the asphalt industry have been reviewed (Claydon et al., 1984; Brandt et al., 1985; Darby et al., 1986; Monarca et al., 1987; Ekstrom, 1991; Hansen, 1991; Brandt and Cordingley, 1992; CROW, 1992; Wong et al., 1992; Lien, 1993; Machado et al., 1993; Brandt and DeGroot, 1994; Levin et al., 1994; Greenspan et al., 1995; Hicks, 1995; Kitto et al., 1997). They revealed that in modern road paving workers are typically exposed to 0.1–2 mg m⁻³ of bitumen fume which includes 10–200 ng m⁻³ of benzo(a)pyrene. It was further concluded that these reports were of limited value in assessing historical exposure levels in the industry since they lack comprehensive evaluation of the determinants of exposure in road construction (Burstyn et al., 2000a). However, the published reports could be used to create the following crude grouping of road construction workers into groups with similar exposure (in order of decreasing exposure level to both bitumen and PAHs from left to right):

- mastic laying ≥ re-paving > surface dressing ≥
- hot mix paving > cold applications

Substantial non-differential misclassification of exposure can be expected to be present in such a grouping, and the degree of this misclassification would be impossible to estimate. Therefore, given that published reports appear to be insufficient for an accurate exposure assessment in the study, a database of individual exposure measurements in the asphalt industry of participating countries (AWE database) was assembled (Burstyn et al., 2000b). The analysis of the paving workers’ exposures collected in the database is presented in this report.

The specific goals of this investigation were: (a) to ascertain appropriate measures of exposure levels for use in the epidemiological study; (b) to identify factors influencing exposure intensity; and (c) to construct statistical models that can be used to infer averages of long-term exposure in the past for a group of road paving workers.

METHODS AND MATERIALS

Description of the AWE database

A detailed description of the Asphalt Worker Exposure (AWE) database is given in the companion paper (Burstyn et al., 2000b). However, key features of the database will also be summarized here. The exposure data collected into the database comprised measurements of exposure levels for a variety of agents among asphalt workers, plus supplementary information. The supplementary information was analogous to collected data from a company questionnaire on production characteristics in companies enrolled in the study. This ensures that AWE data can be linked directly to other data that will be used in the exposure assessment. All available exposure data were collected in eight participating countries (N = 2007). The major contributors (70% of samples) were four Scandinavian countries with 35% of samples originating from Norway. Germany contributed 20%. The remaining 10% of samples were approximately equally distributed among France and The Netherlands. A small portion of the data came from Israel. The majority of measurements were personal samples (92%) with the exception of samples collected from German asphalt plants, which were mostly stationary (273/283). Stationary samples were employed to determine vehicle exhaust emissions (CO and NO₂ monitors placed on the machines employed in road paving) as well as to measure bitumen fume/vapour emissions at different positions in asphalt plants and on road paving equipment.

The earliest collected samples originated from the late 1960s, while the majority of samples were collected in the late 1970s and between 1985 and 1997. The data set was sufficiently large to permit statistical modelling of the intensity of exposure to inhalable dust, organic matter in the dust (bitumen fume), organic matter content of gaseous emissions (bitumen vapour) and PAHs, since each agent was measured in 500–1000 samples. The majority of measurements were made among road paving workers (N = 1581), and only a few came from asphalt plants (351) and waterproofing or roofing operations (62). The overwhelming majority of measurements have not yet been described in peer-reviewed literature. Measurements were originally collected primarily to test compliance, and for industrial hygiene research. Half of the studies claimed to have used a representative sampling strategy.

In nine data sets included in the AWE database, up to six repeated measurements within individuals were identified. These studies were conducted between 1977 and 1996 in France, The Netherlands, Sweden and Norway. Exposures to dust, bitumen fume, vapour, and PAH in a variety of road paving and asphalt mixing operations were measured repeatedly for individual workers. This was typically achieved by monitoring exposures of a single crew over a number of consecutive days.

Correlation between exposure measures

Prior to statistical modelling, the correlation between different exposure measures has been explored in order to establish which exposure measure would be the best available proxy of agents
Table 1. Definition of company questionnaire-based variables used in statistical modelling

<table>
<thead>
<tr>
<th>Variable type</th>
<th>Definition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dummy</td>
<td>'1' if a positive answer was given to the following question, '0' otherwise</td>
<td>In AWE data, five indicators of coal tar use were correlated with primary cause of coal tar use being 'Application of coal tar solution'</td>
</tr>
<tr>
<td>Tar use</td>
<td>'Recycling tar containing asphalt' or 'Application of coal tar solution' or 'Application of coal tar pitch products' or 'Application of coal tar containing bitumen solution' or 'Application of coal tar emulsion'</td>
<td></td>
</tr>
<tr>
<td>Hot mix</td>
<td>'Paving hot mixes'</td>
<td></td>
</tr>
<tr>
<td>Surface dressing</td>
<td>'Surface dressing'</td>
<td></td>
</tr>
<tr>
<td>Oil gravel</td>
<td>'Oil gravel paving'</td>
<td></td>
</tr>
<tr>
<td>Emulsion</td>
<td>'Application of emulsion'</td>
<td></td>
</tr>
<tr>
<td>Other paving</td>
<td>'Other paving'</td>
<td></td>
</tr>
<tr>
<td>Mastic laying</td>
<td>'Mastic paving'</td>
<td></td>
</tr>
<tr>
<td>Recycling operation</td>
<td>Recycling operation; not part of company questionnaire</td>
<td></td>
</tr>
<tr>
<td>Recycle bitumen</td>
<td>'Recycling bitumen binders'</td>
<td></td>
</tr>
<tr>
<td>Recycling tar</td>
<td>'Recycling tar containing asphalt'</td>
<td></td>
</tr>
<tr>
<td>Modified bitumen</td>
<td>Polymer, scrap rubber, fly ash or other modified bitumen</td>
<td></td>
</tr>
<tr>
<td>Categorical</td>
<td>Country</td>
<td>Country where survey was performed</td>
</tr>
<tr>
<td>Continuous</td>
<td>Application temperature</td>
<td>Application temperature in °C</td>
</tr>
<tr>
<td>Year</td>
<td>Difference between 1997 and year of the start date of survey</td>
<td>Maximum duration of a survey was one year</td>
</tr>
</tbody>
</table>

*a*Considered to be a potential predictor that can be incorporated into the exposure assessment protocol.

*b*Missing values were not uniformly distributed among job titles, therefore they were substituted with job title-specific averages.

---

considered. Correlation coefficients between inhalable dust, bitumen fume and bitumen vapour exposure levels were computed. A total of 27 different PAHs were determined in some samples in the AWE database. These PAHs were often determined in both fume and vapour, resulting in up to 54 different possible PAH levels for a sample. However, in some samples only benzo(a)pyrene levels were determined. Since we were primarily interested in modelling a proxy for exposure to all PAHs (such as benzo(a)pyrene), the sum of benzo(a)pyrene levels in fume and vapour was used as a measure of benzo(a)pyrene exposure when both were available for a sample. We investigated the correlation between benzo(a)pyrene levels and bitumen fume/vapour levels. In addressing the question of whether benzo(a)pyrene levels are representative of all other PAH levels, we have resorted to principal component analysis. Principal component analysis identified groups of variables that share a common feature. Only those groups of variables which contributed substantially to explaining multiple correlation in the data were examined in detail. Each variable comprising a principal component was judged by the absolute magnitude of its eigenvector (relative to other variables) in order to see how strongly it was associated with the factor common to all variables in a given principal component.

Building predictive models of exposure

We examined the frequency distributions of exposure levels in order to determine if transformations prior to statistical modelling were warranted. Skew in the distributions signalled that logarithmic transformation was needed to satisfy the assumptions of inferential statistical analysis.

Variables used to represent determinants of exposure were defined on the basis of the company questionnaires. All company questionnaire questions had analogues in the AWE database. Their definitions can be found in Table 1. In addition to these variables, other variables were constructed representing workers, sampling under conditions when highest exposures were anticipated, stationary samples, type of sampling head used, and sorbent type used to collect gas-phase emissions.

Multiple linear models for bitumen fume and bitumen vapour were constructed in the sequential procedure described below. At each step of the model building process, all variables that were not statistically significant (0.10 level) were removed from the models. Newly added variables were kept in the models if they were statistically significant, and if alterations in regression coefficients for other variables appeared to be interpretable. At step 1 all variables listed in Table 1, except for time- and country-related variables, were forced into each model. Patterns of correlation between variables in
Table 1 were explored by computing correlation coefficients, and if a correlation existed \((r > 0.70)\), only one of the correlates was used in further modelling. The choice of the correlate was driven by considerations of ease in interpretation, should it be included in the final form of the model. At step 2 a variable representing time trend was added to the models. At step 3 a country variable was added to the models. At step 4 variables representing sampling strategy (worst case versus representative) and sample positioning (area versus personal) were added to the models. At step 5 variables representing sampling methods were introduced into the models. At step 6 country-related variables were removed from the models in order to study their effect on model fit. Negligible change in model fit signalled that country-related variables could be removed without harming the predictive power of the models. The rationale for this was that country-related effects are difficult to interpret and it was considered that small losses in model fit could be compensated for by an increase in generalization of the model. Finally, at step 7 a random worker effect was introduced into the models (Proc Mixed in SAS 6.12, restricted maximum likelihood algorithm, compound symmetry covariance matrix). All effects included at step 6 were treated as fixed effects, and worker identity was introduced as a random variable. This consequently permitted the within- and between-worker components of exposure variability to be quantified. These values are needed for calculation of the maximum likelihood estimates of the average of long-term exposure for a group of individuals.

Models of PAH exposure were constructed by evaluating the statistical significance of significant predictors of total organic matter (that is, bitumen fume and vapour) plus the variable representing tar use. The rationale for this approach was based on the expectation that PAHs originate from both bitumen and coal tar.

The fit of the predictive models was evaluated graphically by plotting observed versus predicted exposure levels. Residuals were analysed by plotting predicted values against residual errors. Statistical analysis was performed using SAS 6.12 (SAS Institute Inc.), data management tasks were performed using Microsoft Access 2.0 (Microsoft Corp.) and graphs were prepared using SigmaPlot version 4.01 (SPSS Inc.).

RESULTS

Exposure levels and correlation between exposure measures

Arithmetic and geometric summary statistics for bitumen fume, bitumen vapour and benzo(a)pyrene exposure levels among paving workers

<table>
<thead>
<tr>
<th>Non-detectable values</th>
<th>N</th>
<th>GM</th>
<th>GSD</th>
<th>AM</th>
<th>Range</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen fume (mg m(^{-2}))</td>
<td>184</td>
<td>119</td>
<td>0.28</td>
<td>6.25</td>
<td>1.91</td>
<td>13.1</td>
</tr>
<tr>
<td>Bitumen vapour (mg m(^{-2}))</td>
<td>5</td>
<td>510</td>
<td>1.86</td>
<td>6.91</td>
<td>7.59</td>
<td>20.0</td>
</tr>
<tr>
<td>Benzo(a)pyrene (mg m(^{-2}))</td>
<td>321</td>
<td>487</td>
<td>8.58</td>
<td>6.82</td>
<td>95.8</td>
<td>476</td>
</tr>
</tbody>
</table>

\(N\): sample size; GM: geometric mean; GSD: geometric standard deviation; AM: arithmetic mean; SD: arithmetic standard deviation.

### Table 2. Bitumen fume, bitumen vapour and benzo(a)pyrene exposure levels among paving workers.

<table>
<thead>
<tr>
<th>Bitumen fume (mg m(^{-2}))</th>
<th>All paving operations(^a)</th>
<th>N</th>
<th>GM</th>
<th>GSD</th>
<th>AM</th>
<th>Range</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOD-8(^{\text{L}})</td>
<td>11</td>
<td>3.27</td>
<td>3.14</td>
<td>13.4</td>
<td></td>
<td>39.5</td>
<td></td>
</tr>
<tr>
<td>LOD-8000</td>
<td>35</td>
<td>1.34</td>
<td>1.72</td>
<td>13.4</td>
<td></td>
<td>39.5</td>
<td></td>
</tr>
<tr>
<td>LOD-8000</td>
<td>19(^b)</td>
<td>6.27</td>
<td>6.84</td>
<td>20.0</td>
<td></td>
<td>47.5</td>
<td></td>
</tr>
<tr>
<td>LOD-8000</td>
<td>119</td>
<td>1.34</td>
<td>1.72</td>
<td>13.4</td>
<td></td>
<td>39.5</td>
<td></td>
</tr>
<tr>
<td>LOD-8000</td>
<td>119</td>
<td>1.34</td>
<td>1.72</td>
<td>13.4</td>
<td></td>
<td>39.5</td>
<td></td>
</tr>
</tbody>
</table>

\(a\): LOD: method limit of detection.

Downloaded from https://academic.oup.com/annweh/article-abstract/44/1/43/175327 by guest on 19 January 2019
ene exposures are summarized in Table 2. It is apparent that the exposures cover a wide range of values and tend to be higher during mastic laying.

There was a high degree of correlation between fume and inhalable dust levels (Fig. 1). This allowed us to construct the following regression model:

\[
\text{bitumen fume} = 0.93 \times \text{inhalable dust},
\]

which accounted for 97% of variability in bitumen fume levels. The intercept of the above model was not different from zero, and was therefore excluded from the final form of the model. Thus, we have concluded that inhalable dust emitted in road paving consists primarily of organic particulate matter, which we refer to as ‘bitumen fume’. In all subsequent analyses, when an inhalable dust level was reported for a sample but the organic matter content of that dust was not determined, we assumed that bitumen fume constituted 93% of inhalable dust and used that value in statistical modelling.

No consistent correlation between bitumen fume and bitumen vapour levels appeared to exist. Its magnitude and statistical significance varied greatly between countries (Table 3). Thus, we concluded that we were justified in creating separate predictive models for bitumen fume and vapour.

Not all PAHs were determined in the 414 samples for which series of PAHs were quantified, so missing values were replaced with averages of reported levels for each PAH. Furthermore, for each PAH a sum of its levels in particle and vapour phase was used as an indicator of ‘total’ exposure. The first two principal components accounted for 50% of the multiple correlation between PAH levels in fume and vapour. The first principal component appeared to be dominant (it explained 38% of the multiple correlation). None of the PAHs contributed disproportionately to the first two principal components. In effect, when eigenvectors indicated that a set of PAHs was contributing to a principal component (> 0.20), all eigenvectors for the set of ‘significant’ PAHs were approximately equal (0.20–0.44). The set of PAHs comprising the first principal component consisted of 13 out of 27 measured PAHs. The first two principal components included 18 out of 27 monitored PAHs. Benzo(a)pyrene was an important contributor only to the second principal component and had a high degree of correlation with it \((r = 0.79, P < 0.0001, N = 414)\). Thus, we have concluded that total benzo(a)pyrene is a good proxy of one of the principal sources of PAH exposure. In subsequent statistical modelling we have considered both the first principal component and total benzo(a)pyrene as proxies of PAH exposure. The expression used to calculate the value of the first principal component is given below (all PAH levels were in ng m\(^{-3}\)):

\[
\begin{align*}
0.28 \times (\text{acenaphthene}) + 0.27 \times (\text{acenaphthylene}) \\
+ 0.27 \times (\text{anthanthrene}) + 0.26 \\
\times (\text{benzo(a)anthracene}) + 0.22 \times (\text{benzo(a)fluorene}) \\
+ 0.29 \times (\text{benzo(k)fluoranthene}) + 0.28 \\
\times (\text{fluoranthene}) + 0.30 \times (\text{fluorene}) + 0.30 \\
\times (\text{phenanthrene}) + 0.26 \times (\text{pyrene}) + 0.23 \\
\times (2\text{-methylphenanthrene}) + 0.29 \\
\times (1\text{-methylphenanthrene}) + 0.30 \times (\text{biphenyl})
\end{align*}
\]

Benzo(a)pyrene levels had a statistically significant correlation with bitumen fume \((r = 0.42, P < 0.0001, N = 419)\), but bitumen fume exposures explained only 18% \((0.42^2)\) of variability in benzo(a)pyrene levels. This moderate correlation was driven by the high correlation between benzo(a)pyrene and bitumen fume levels during mastic laying (mastic laying: \(r = 0.96, P < 0.0001, N = 12\); other paving: \(r = 0.32, P < 0.001, N = 407\)). In general, there was no correlation between benzo(a)pyrene and bitumen vapour exposures \((r = -0.01, P < 0.87, N = 364)\). However, the correlation between mastic vapour and benzo(a)pyrene was very strong \((r = 0.99, P < 0.0001, N = 10)\). Thus, it appeared that factors other than bitumen fume and vapour levels have an important bearing on benzo(a)pyrene exposure levels. The first principal component of PAHs was not correlated with either bitumen fume or vapour.

Thus, on the basis of the correlation patterns presented above, we selected bitumen fume \((N = 1193)\), bitumen vapour \((N = 510)\), total benzo(a)pyrene \((N = 487)\) and the weighted sum of PAH levels comprising the first principal \((N = 414)\) as dependent variables in subsequent statistical models.

\textbf{Statistical distribution of exposure levels and treatment of non-detectable values}

All four measures of exposure levels followed skewed distributions, which were normalized by logarithmic transformations (base \(e\)). Thus, natural logarithms of exposure levels were used in the subsequent statistical modelling in order to stabilize variance. Values below the limit of detection were set to be equal to that limit. This will result in an upward bias in the absolute levels of bitumen fume and vapour. Nevertheless, this should have negligible effect on the identification of determinants of exposure, since non-detectable values represented only a small proportion of bitumen fume \((184/1193)\) and vapour \((5/510)\) measurements. A large proportion \((321/487)\) of benzo(a)pyrene values appeared to be non-detectable, even if, in order to qualify as a non-detectable value, both fume and...
Fig. 1. Correlation of bitumen fume and inhalable dust exposure among asphalt workers (bitumen fume = 0.93 × inhalable dust; $R^2 = 0.97; N = 266$).

vapour PAH levels had to be reported as non-detectable. Non-detectable benzo(a)pyrene exposure levels were replaced by survey-specific limits of detection, which ranged from 1 to 50 ng m$^{-3}$. The use of the detection limit was justified because it was not possible to assess how the limit of detection was calculated in different surveys and we used the reported values as an indicator of the original investigator’s best estimate of the measured values.

**Predictive models of exposure**

Statistical models of exposure to PAHs comprising the first principal component accounted for less than 9% of total variability and revealed no association between production factors and this measure of PAH exposure. On the other hand, statistical models of exposure to bitumen fume, bitumen vapour and benzo(a)pyrene exposure explained 36–43% of total variability and revealed strong associations with various production factors. They are summarized in Table 4. In the table, the reference category (defined by the intercept) depends on what variables were important in that model, but in all cases hot mix paving is included in the reference category. The models have the same general form:

$$\log_e(\text{exposure}) = \sum_i \beta_i \times (\text{determinant of exposure } i) + \text{intercept + worker effect}$$

It is apparent that mastic laying was associated with elevated exposures to all three agents. Recycling operations produced elevated bitumen fume exposures, while below-average bitumen fume exposures resulted from oil gravel paving. Surface dressing, oil gravel paving and elevated application temperatures increased bitumen vapour exposures. There were no differences in the exposures to bitumen fume and bitumen vapour between countries, when adjusted for the effects of other determinants of exposure. The effect of application temperature on bitumen fume exposure in non-mastic applications, adjusted for other predictors of exposure, was the same as in univariate analysis (Fig. 2), but it failed to improve model fit and was thus excluded from the final form of the bitumen fume model. Bitumen vapour and benzo(a)pyrene exposures have declined from the 1970s to the 1990s (11 to 14% per year) more rapidly than bitumen fume exposures (6% per year). These time trends are illustrated in Fig. 3. Since coal tar use is a time-dependent variable, interaction between time trend and tar use was examined in a benzo(a)pyrene model, but it was found to be not statistically significant ($P = 0.29$).

The benzo(a)pyrene model shared most determinants of exposure with the bitumen fume and
Table 4. Statistical models of loge (mg m$^{-3}$ bitumen fume), loge (mg m$^{-3}$ bitumen vapour) and loge (ng m$^{-3}$ benzo(a)pyrene)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Bitumen fume</th>
<th>Bitumen vapour</th>
<th>Benzo(a)pyrene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mastic laying</td>
<td>0.88</td>
<td>1.71</td>
<td>1.67</td>
</tr>
<tr>
<td>Mastic laying × worst case (indoors)</td>
<td>0.22</td>
<td>0.29</td>
<td>0.37</td>
</tr>
<tr>
<td>Recycling</td>
<td>0.89</td>
<td>1.70</td>
<td>1.51</td>
</tr>
<tr>
<td>Recycling × worst case</td>
<td>0.25</td>
<td>NS</td>
<td>0.28</td>
</tr>
<tr>
<td>Surface dressing</td>
<td>1.88</td>
<td>0.48</td>
<td>0.38</td>
</tr>
<tr>
<td>Oil gravel</td>
<td>-1.51</td>
<td>0.47</td>
<td>-0.65</td>
</tr>
<tr>
<td>Tar use</td>
<td>NS</td>
<td>NS</td>
<td>0.38</td>
</tr>
<tr>
<td>Years before 1997</td>
<td>-1.51</td>
<td>0.135</td>
<td>0.107</td>
</tr>
<tr>
<td>Application temperature in non-mastic paving(°C)</td>
<td>NS</td>
<td>0.009</td>
<td>0.107</td>
</tr>
<tr>
<td>Area sample (yes/no)</td>
<td>NS</td>
<td>2.66</td>
<td>0.107</td>
</tr>
<tr>
<td>Sorbent type</td>
<td>NA</td>
<td>-2.74</td>
<td>NS</td>
</tr>
<tr>
<td>Sampling head</td>
<td>NA</td>
<td>-0.95</td>
<td>0.37</td>
</tr>
<tr>
<td>37 mm closed face</td>
<td>-1.32</td>
<td>0.15</td>
<td>NA</td>
</tr>
<tr>
<td>GGP</td>
<td>1.20</td>
<td>0.16</td>
<td>NA</td>
</tr>
<tr>
<td>Intercept</td>
<td>-2.09</td>
<td>-1.19</td>
<td>0.91</td>
</tr>
<tr>
<td>Percentage variance explained by fixed effects</td>
<td>41</td>
<td>36</td>
<td>43</td>
</tr>
<tr>
<td>Number of observations</td>
<td>1193</td>
<td>510</td>
<td>487</td>
</tr>
<tr>
<td>$\text{bw}S^2 (\text{wR}_{0.95})^b$</td>
<td>0.99 (49)</td>
<td>1.16 (68)</td>
<td>0.43 (13)</td>
</tr>
<tr>
<td>$\text{ww}S^2 (\text{wR}_{0.95})^b$</td>
<td>1.08 (59)</td>
<td>1.26 (81)</td>
<td>1.71 (168)</td>
</tr>
</tbody>
</table>

\[ \beta^a: \text{regression coefficient}; \text{SE}: \text{standard error of regression coefficient}. \]
\[ ^b\text{Symbol ‘ × ’ denotes a multiplicative interaction of variables.} \]
\[ ^c\text{Not possible to estimate.} \]
\[ ^d\text{Variable is not statistically significant and therefore is not included in the model or did not improve model fit upon inclusion in the model.} \]
\[ ^e\text{Reference category is XAD2 sorbent.} \]
\[ ^f\text{Not applicable.} \]
\[ ^g\text{Reference category includes: 37 mm open face cassette, 25 mm closed face cassette (Millipore) and PAS6.} \]
\[ ^h\text{b}\text{bw}S^2: \text{variance of the distribution of logarithmic means of an individual’s exposures (between-worker); }\text{ww}S^2: \text{variance of the distribution of logarithmic means of exposure from day to day for an individual (within-worker); }\text{wR}_{0.95}: \text{ratio of 97.5th to 2.5th percentile of the between-worker distribution of exposures; }\text{wR}_{0.95}: \text{ratio of 97.5th to 2.5th percentile of the distribution of exposures within a worker.} \]

When tar use is ‘yes’, the value used is 1; when tar use is ‘no’ the value used is 0. In the model, tar use per se accounted for 20% of variability in benzo(a)pyrene exposure.

The results presented in Table 5 indicate that predictors of exposure identified in our models are predominantly associated with between-worker variance components. It would appear that fixed effects explain a greater proportion of between-worker variance in the benzo(a)pyrene model (\((2.00 - 0.43)/2.00 = 79\%\)) than they do in the bitumen fume model (\((2.27 - 0.99)/2.27 = 56\%\)) and bitumen vapour models (\((2.51 - 1.16)/2.51 = 54\%\)).

**DISCUSSION**

**Comparison with the literature and interpretation of the observed pattern of determinants of exposure**

Organic matter content of inhalable dust emitted during paving. Our finding of a high degree of correlation between inhalable dust and its organic matter content implies that little information is gained about bitumen fume exposure by analysing organic matter content of samples compared to gravimetric analysis. Organic matter content of asphalt dust has been reported to vary considerably, especially under low inhalable dust exposure conditions (Monarca *et al.*).
Fig. 2. Influence of application temperature on bitumen fume ($N = 855$) and bitumen vapour ($N = 411$) exposures in non-mastic applications.

Fig. 3. Predicted time trends in bitumen fume, bitumen vapour and polycyclic aromatic hydrocarbon exposures, adjusted for production characteristics and sampling methods.
Table 5. Influence of fixed effects and random effects on variance components in models of bitumen fume, bitumen vapour and benzo(a)pyrene exposure among paving workers

<table>
<thead>
<tr>
<th>Model</th>
<th>Worker and fixed effects</th>
<th>Worker</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>logₑ (mg m⁻³ bitumen fume)</td>
<td>logₑ (mg m⁻³ bitumen vapour)</td>
<td>logₑ (ng m⁻³ benzo(a)pyrene)</td>
</tr>
<tr>
<td></td>
<td>bwS_y</td>
<td>wwS_y</td>
<td>bwS_y</td>
</tr>
<tr>
<td>Worker and fixed effects</td>
<td>0.99</td>
<td>1.08</td>
<td>1.16</td>
</tr>
<tr>
<td>Worker</td>
<td>2.27</td>
<td>1.18</td>
<td>2.51</td>
</tr>
<tr>
<td>N</td>
<td>1193</td>
<td>510</td>
<td>346</td>
</tr>
<tr>
<td>k</td>
<td>904</td>
<td>487</td>
<td></td>
</tr>
</tbody>
</table>

Notes:

1. All models include intercept.
2. Estimate of logarithmic between-worker variance.
3. Estimate of logarithmic within-worker variance.
4. Number of exposure measurements.
5. Number of workers.

Sources of PAHs. The PAHs that comprised the first principal component do not vary across different production conditions in road paving. They represent an overall PAH exposure common to all road paving workers. The identity of the underlying source of these PAHs is unclear. The PAHs in the second principal component and benzo(a)pyrene both appear to represent tar use and PAHs in bitumen fume. These two variables are very good predictors of benzo(a)pyrene exposure levels. We were unable to test whether the second principal component is related to changes in bitumen vapour exposure levels, since no bitumen vapour measurements were collected during the use of tar. However, a comparison of the patterns of regression coefficients in bitumen vapour and benzo(a)pyrene models (see the discussion below) indicates that changes in total benzo(a)pyrene exposure may mimic, to some extent, those in bitumen vapour.

Mastic laying. Bitumen fume and vapour exposures arising during mastic laying were 2–13 times higher than those observed in association with hot mix paving. This corroborates findings of other researchers, who have indicated that mastic laying results in much higher bitumen fume exposure levels than other paving activities (Brandt et al., 1985; Hansen, 1991; CROW, 1992). In mastic laying elevated bitumen fume and vapour exposures can be expected, since the source of exposure (that is, the application mixture) is closer to the exposed person’s breathing zone owing to the fact that mastic is habitually applied by hand. It has been reported that up to a twofold decrease in inhalable dust exposure levels during paving can be explained by an increase in distance between the exposed person’s breathing zone and the source of exposure (Claydon et al., 1984). Furthermore, higher temperatures of mastic mixes can lead to more fuming. In fact, it was not possible to separate the effects of application temperature from those of mastic laying in the models. Differences in composition and physical properties of bitumen used in mastic pav-
ing may also account for this effect. ‘Worst case’ mastic laying corresponded to applying mastic asphalt in indoor environments (for example a covered parking lot). The apparent fivefold to sixfold difference between indoor and outdoor exposures observed in our models is the same order of magnitude as those reported by Brandt et al. (1985). It would also appear that the industrial hygienist who conducted the surveys entered into the AWE database was able to consistently identify indoor mastic laying as a ‘worst case’ scenario.

The association of mastic laying with a fourfold to eightyfold increase in PAH exposure relative to hot mix paving is rather surprising, since coal tar is not supposed to be used in the formulation of mastic mixes. The explanation for the observed effect may lie with the fact that even though PAH content of mastic emissions may be low, the overall amount of these emissions is so high that it results in PAH exposure comparable to that incurred during the use of coal-tar-containing materials. This hypothesis is supported by: (a) the high correlation between levels of mastic fume or vapour and benzo(a)pyrene exposures reported earlier; and (b) patterns of coefficients in statistical models. However, owing to the controversy about cancer risk in mastic laying and the uncertainty about the contribution of the underlayer with coal tar to PAH exposures during mastic laying (Wong et al., 1992), this issue deserved further attention. If the source of PAHs in mastic laying is the underlayer with coal tar (Wong et al., 1992), then owing to the fact that coal tar is no longer used in paving, we can assume that the high PAH exposures resulting from mastic laying are a thing of the past. However, if the mechanism we have suggested is correct, then high PAH exposures (and the associated health risks) due to mastic laying may still be present, especially in indoor environments.

Re-paving or in situ recycling. Re-paving or in situ recycling operations have been associated with elevated bitumen fume and benzo(a)pyrene exposure. This may be due to the fact that coarse particulate is generated during recycling operations in the course of grinding the old asphalt layer. These particles may absorb bitumen fume and vapour generated in heating old asphalt, resulting in elevated bitumen fume rather than vapour exposures. It is not clear as to what defined worst case scenarios in recycling operations. However, there are some indications that the re-paving technique in which old asphalt is heated with a propane burner (hot in situ recycling) produced these high exposure situations (CROW, 1992). An alternative to hot in situ recycling is milling and recycling at ambient temperatures. Since bitumen vapour was not monitored during these operations, the effect of milling and recycling on bitumen vapour exposure was not possible to estimate. As in the case of mastic laying, it would appear that industrial hygienists conducting the surveys of recycling operations were able to identify a fivefold increase in exposure as ‘worst case’. The association between PAH levels and recycling operations may be due to the correlation between fume and PAH concentrations. It is also possible that the same mechanism that leads to elevated fume levels during recycling operations is also responsible for preferential absorption of heavier PAH, such as benzo(a)pyrene, by particles comprising fume. This would lead to elevated PAH content of fume during recycling/re-paving operations.

Surface dressing and oil gravel paving. On the basis of limited data, CROW (1992) has concluded that surface dressing is associated with elevated fume and PAH exposure relative to hot mix paving. Our results indicate that there is no difference in bitumen fume exposure levels between surface dressing and hot mix paving. It is possible that small differences between these two types of applications do exist, but their magnitude is likely to be small (less than a factor of two), resulting in negligible contrasts in average fume exposure levels. Our observed association between surface dressing and bitumen vapour can be attributed to differences in modes of applying bitumen to road surfaces. In surface dressing, a liquid bitumen solution (cut-back or emulsion) is sprayed onto the road surface, while in other applications (with the exception of oil gravel paving) bitumen is deposited as a part of solid asphalt (a mixture of bitumen and mineral aggregate). It is possible that the spraying of liquid bitumen solution is more conducive to the formation of small droplets and vapour, which are preferentially absorbed by sorbent tubes. It is also likely that bitumen used in surface dressing has a higher proportion of volatile hydrocarbons, originating either from bitumen itself or from the cutbacks which are customarily added to bitumen solutions used in surface dressing. The process of vapour emission during surface dressing is governed by application temperature and vapour pressure of the constituents of the mixture. Given that we cannot expect all surface dressing mixtures to have the same composition, we can expect that application temperature per se will not account for the amount of vapour originating in surface dressing. The influence of bitumen composition on the relationship between the amount of bitumen fume emitted and temperature has been reported (Machado et al., 1993).

Oil gravel resulted in bitumen fume exposures, which were lower than those in the reference category (which includes hot mix paving). This was probably the case because fume formation requires bitumen to be heated (as in surface dressing). However, during oil gravel paving, binding material is applied at ambient temperatures, precluding the occurrence of evaporation and condensation pro-
cesses that lead to fume formation. The weak positive association between oil gravel paving and organic vapour levels is probably a result of the application method, similar to surface dressing, in which vapour and small aerosol droplets are generated during spraying of a liquid. It is also likely that volatile organic materials not present in hot mix asphalt or surface dressing mixtures evaporate during oil gravel paving, resulting in elevated vapour exposure.

The observed pattern of relationships between benzo(a)pyrene exposure and these two application methods suggests that it mirrors patterns of organic matter levels in fume and vapour.

**Effects of application temperature.** The dependence of bitumen fume, vapour and PAH exposure on application temperature has been reported by other investigators (Ekström, 1991; Brandt and Cordingley, 1992; Lien, 1993; Machado et al., 1993; Brandt and DeGroot, 1994; Kitto et al., 1997). The rationale for temperature dependence of the levels of asphalt emissions is that the emissions are formed via evaporation of the organic components of asphalt. This evaporation process is governed, at least in part, by the temperature of a given asphalt mix. In our data, application temperatures were most commonly extracted from production records, but in one survey they were measured at the location of a worker. Separate analysis by the method of assessing application temperature did not yield diverging results. We only observed the effect of application temperature, independent of mastic laying, on bitumen vapour. Despite some authors’ claims that application temperature is the primary predictor of bitumen fume and vapour exposure levels (Ekström, 1991; Brandt and Cordingley, 1992; Brandt and DeGroot, 1994), in the AWE data the application temperature alone accounts for 7–14% of variability in bitumen fume and vapour exposure levels (Fig. 2). However, the observed slope of the relationship is of the same order of magnitude as reported in the literature.

There are several possible explanations as to why we did not observe a very strong influence of application temperature on exposures in road paving. First, laboratory studies (Machado et al., 1993; Brandt and DeGroot, 1994; Kitto et al., 1997) do not take into account a multitude of factors that may and probably do influence personal exposure in the workplace. Thus, a variable can be expected to have lower predictive power in the ‘real world’ than it does under controlled laboratory conditions. Second, the model developed by Brandt and DeGroot (1994) in a set of laboratory experiments has been validated on a very small number of field observations, and thus its generalization remains uncertain. Third, two reports claiming that application temperature has a strong effect on bitumen fume and vapour exposure (Ekström, 1991; Lien, 1993) have not been published in peer-reviewed scientific literature, thus making it difficult to ascertain how the authors arrived at such a conclusion. Incidentally, the data from the last two reports are included in the AWE database and form part of the data set used to build the statistical models presented in this report.

From the point of view of exposure assessment in an epidemiological study, it is quite fortunate that we do not have to rely very heavily on application temperature in making inferences about exposure levels. Our experience has indicated that collecting accurate information about typical application temperatures in the past is difficult, with uncertainty on the order of 10–20°C. Thus, for example, if we had to assign a twofold change in exposure level for every 15°C, as suggested by Ekström (1991), a significant misclassification of exposure would have resulted.

Even though application temperature may not affect the amount of bitumen fume emissions, it may influence their composition (Kitto et al., 1997). Norseth et al. (1991) found that health effects of bitumen fume exposure were associated with application temperature. This may indicate that the toxic properties of asphalt emission change with change in application temperature. Thus, one of the principal limitations of the AWE database and our predictive models becomes apparent: they do not take into account either bitumen composition or quality and quantity of non-bitumen components of the binder. Questions about bitumen composition are at present difficult to answer (CROW, 1992; Kitto et al., 1997) since bitumen is defined on the basis of its physical properties rather than its chemical composition. Therefore, the above-mentioned limitation is not an inherent fault of our data, but is merely a reflection of the overall poor current understanding of bitumen chemistry.

**Coal tar in paving mixes.** The strong relationship between coal tar use and PAH levels observed in our study supports our a priori assumption that an assessment of exposure to coal tar can be based on PAH measurements. Our results reveal that in the presence of coal tar, PAH exposures in road paving are elevated by a factor of five (that is, exp(1.68)). However, on the basis of the results of laboratory experiments, PAH content of tar can be assessed to be 100 or even 1000 times higher than that of bitumen (Lindstedt and Sollenberg, 1982; Brandt et al., 1985; Darby et al., 1986; Machado et al., 1993). This apparent difference in the observed effects of coal tar on PAH exposure levels in road paving can be explained by the observation that most benzo(a)pyrene levels were non-detectable, unless coal-tar containing materials were used in paving. Thus, the absolute magnitude of the observed coal tar effect is dependent on the treatment of non-detectable benzo(a)pyrene levels in statistical analysis. On the
other hand, some doubts have been raised about how representative laboratory-generated emissions are of those encountered in workplace (Niemeier et al., 1988).

**Time trend.** According to the time trend observed in the AWE data, bitumen fume, bitumen vapour and benzo(a)pyrene exposures have decreased by a factor of 2–3 each decade. The possibility that the time trend in benzo(a)pyrene levels was due to the manner in which we treated non-detectable values was rejected since there was no time trend in the values we used to replace the non-detectable benzo(a)pyrene exposure measurements. We have no technical data that would explain these patterns. The role of other factors that may affect the time trends, such as those related to social and economic conditions, is difficult to ascertain. The use of time trend for which we have no explanation will lead to biased estimates of exposure only if the time trends themselves are estimated with a bias. There is no reason to believe that our time trend estimates for the asphalt industry are biased. For unbiased exposure assessment for epidemiological purposes it is critical to explain how exposure levels have changed, not why they have done so.

A recent investigation of world-wide time trends in exposure data (Symanski et al., 1998a, b) has indicated that when occupational exposures decrease over time, they generally do so at a rate of 6–17% per year (statistically significant downward trends, \( P < 0.05 \)). Our results are in agreement with these trends. The limitations of the meta-analysis conducted by Symanski et al. (1998a) were the inability (a) to obtain individual measurements, and (b) to adjust time trends for the effects of sampling strategy (notably worst case versus representative) and sampling methods. Our estimates of time trends do not suffer from these limitations, since they are based exclusively on individual measurements (corrected for the effect of area sampling) and are adjusted for sampling strategy, analytical methods and production factors. Thus, our results provide additional evidence of the validity of the time trends obtained by Symanski et al. (1998a, b).

**Variability of bitumen and PAH exposures in paving operations.** Estimating an arithmetic mean exposure for a group of workers using multiple linear models presented in this report requires one to have an estimate of within-worker (day-to-day) variability of exposure (Tornero-Velez et al., 1997). Our estimates of within-worker variance presumably underestimate true day-to-day variability in bitumen and PAH exposures. This arises from sampling strategies employed in collecting repeated exposure measurements, in which exposures were monitored over the duration of one project on several consecutive days. Thus, the collected measurements cannot represent a variety of exposure circumstances (that is, projects) that paving workers experience in a given year. Nevertheless, the within-worker logarithmic variance for outdoor work, such as road paving, was of similar magnitude (1.40) in other data (Kromhout et al., 1993). The reason for this is possibly related to the fact that outdoor work is often not very different from one day to another. Consequently, exposure levels can be expected to be determined to a large extent by environmental factors such as wind and rain, which were not accounted for in either data set.

Our results suggest that the predictors of exposure present in our models are related to differences in exposure between workers. These predictors explain at least half of the variability in exposure concentrations between-workers. It has been suggested that process-related variables influence between-worker variance components (Kromhout et al., 1993). However, the grouping of workers solely on the basis of identified predictor variables will not result in uniformly exposed groups, since mean exposures for each worker in these groups can be expected to vary over a 13–70-fold range (as assessed by \( b_{R_0.95} \) values).

**Methods of measuring bitumen exposure.** Area samples of bitumen vapour were 10 times higher than personal ones. A possible explanation for the observed effect is that the stationary samples were placed in areas of high exposure (close to the source, such as the screed of a paving machine) which are avoided by workers. Even though area samples have been generally reported to underestimate personal exposures (Scheeper et al., 1995), the bias in area samples is probably highly dependent on their position. Thus, in estimating an individual’s exposure level, stationary sampling should be avoided.

Different sorbents have demonstrated varying affinities to bitumen vapour. It is not clear as to why this is the case. Given that the effect of sorbent choice on the measured bitumen vapour level can be substantial (a factor of 0.06 in the case of silica gel, as compared to XAD2), this issue should be the subject of further research.

The type of sampling head used to collect bitumen fume appears to have had a significant impact on the observed exposure levels. We have chosen the sampling head employed to collect the majority of samples (37 mm open face Millipore sampler) as a reference category, even though we are aware that its collection efficiency deviates significantly from the toxicologically relevant inhalable dust fraction (Kenny et al., 1997). However, these deviations for small particles, such as those that can be expected to form bitumen fume (\( < 40 \mu m \) in aerodynamic diameter), are not dramatic (Kenny et al., 1997). Nevertheless, the GGP sampler, a modified version of the GSP sampler whose collection efficiency better adheres to the inhalable convention (Kenny et al., 1997), would probably have formed a more
appropriate reference category. Unfortunately, the GGP sampler was used to collect only a limited number of samples, all of them from Germany, making the generalization of the effect of the GGP sampler somewhat questionable. Furthermore, the GGP sampler is expected to outperform the 37 mm open-face sampler mostly at low wind speeds (less than 4 m s\(^{-1}\)), but at high wind speeds both samplers deviate significantly from collecting inhalable dust (Kenny et al., 1997). According to the AWE database, wind speeds during road paving ranged between 0.5 and 33 m s\(^{-1}\) \((N = 303, \text{ AM } = 3.1 \text{ m s}\(^{-1}\), GM = 2.1 m s\(^{-1}\), GSD = 2.3). Under such variable wind conditions it is very difficult to predict how the collection efficiencies of samplers would be affected. Unfortunately, wind speed was not recorded during sampling with the GGP, making it impossible to correct the observed ‘sampler effect’ for wind speed. Thus, absolute levels of bitumen fume predicted by our model can underestimate levels of fume available for inhalation by a factor of approximately three. This has important implication for standard setting and risk assessment, indicating that relative performance of different samplers in outdoor environments should be the subject of further research.

In general, characterization of exposure to bitumen has suffered from a lack of standard methods, which have been demonstrated to collect physiologically and toxicologically relevant fractions of bitumen emissions.

Limitations of the predictive models

The AWE data for paving workers are unbalanced. We attempted to compensate for this by choosing the appropriate statistical model (restricted maximum likelihood algorithm) (Searle, 1988). Nevertheless, we cannot alter the nature of the data. Somewhat different subsets of the AWE data were used to construct predictive models for the three agents raising, the possibility that factors which operated in some subsets may not have been present in others. Consequently, the classical problem of unbalanced data is manifested by the fact that some effects cannot be estimated. Thus, the challenge of obtaining a data set which would allow one to conduct a comprehensive evaluation of the determinants of bitumen (fume and vapour) and PAH exposure remains.

There is a noticeable lack of dermal exposure measurements in the AWE database. This reflects the virtual absence of data on dermal exposure in the European asphalt industry, with the exception of one study which measured dermal deposition of PAH during road construction (Jongeneelen et al., 1988). Since the dermal route of bitumen exposure can potentially play a role in increasing the risk of adverse health effects among bitumen-exposed individuals, more research is clearly needed to increase our understanding of dermal exposure in the asphalt industry.

CONCLUSION

Changes in bitumen fume, bitumen vapour and PAH exposures are each associated with somewhat different factors in road paving. In assessing the intensity of exposure among road paving workers, adjustments for time period and the type of work they have performed must be made. Time trend and a small set of production parameters can be used to explain a substantial portion of variability in exposures among paving workers. Our models, despite their limitations, will help to make the assessment of exposures among road paving workers in a multicentric cohort study a data-driven, reproducible process. The models have also revealed a much more complex pattern of determinants of exposure than could have been ascertained, with any degree of certainty, from the review of published reports alone.

Acknowledgements—An IARC Special Training Award supported Igor Burstyn. The study was partially supported by a grant of the European Commission, DG-XII, Biomed-2 programme (Contract No. BMH4-CT95-1100), European industrial associations, EAPA, Eurobitume and CONCAWE. Pamela Cruise edited the manuscript. Wim Braun created SAS programs used in investigating the stability of models. Chava Perez provided valuable comments on the final manuscript.

REFERENCES


Darby, F. W., Willis, A. F. and Winchester, R. V. (1986)


