Previous studies showed that many childhood cancers are initiated during fetal life or early infancy through exposure to atmospheric carcinogens. Places of birth were associated with industrial sources of oil combustion products, volatile fuels, and solvents: and with high local emissions of specific chemicals associated with oil fuels. Four such substances (1,3-butadiene, benzene, benzo(a)pyrene, dioxins) are known carcinogens and the first two are associated with industrial sources of oil combustion gases rather than with volatile fuel evaporation. All these effects were evident at the shortest measurable ranges, as expected from ground level discharges, but the coarse resolution of available “emissions hotspots” maps created uncertainties. The railway data, obtained through manual digitisation, were also inadequate for making the matter to higher resolutions; and detailed road data—necessary for any comprehensive ICE related examination—were not then available.

This study tackles these limitations by extracting exact road, rail, and other data from the national digital mapping archive held by the Ordnance Survey (OS) and by re-examining the ICE exhaust hypothesis on a fine geographical scale.

METHODS

The cancer cases analysed here are those described in a previous report: all children who died between 1955 and 1980 in Great Britain before their 16th birthdays and who had been born in the same period. Postcodes (PCs) of their home addresses at birth and at death were converted to map references through the Central PC Directory. Less reliable addresses and map references were excluded. The resulting database consisted of 12 017 children.

Urban PC map references represent actual addresses within 100–200 m with a mean error of 50–100 m. Rural PCs are generally larger and the probable errors are not definable. The cancers were originally classified into 10 diagnostic subtypes but earlier studies showed similar geographical proximity relations for each cancer subtype, as well as for two main groups: the reticuloendothelial cancers (leukemias and lymphomas), and the other “solid” tumours. These main groups were re-examined here, confirming their similarity. Apart from this, the main results shown below relate to all cancers/leukemias together.

Coordinates of mapped hazards were obtained from a subset of the OS national digital mapping archive, through the “Digimap” facility hosted by Edinburgh University. Of the several digital files, the subset “strategic” proved to be the most suitable. Its content is limited, corresponding roughly to that of the 1:200 000 OS motoring atlas, but the recorded features are specified to a precision of 1 metre. Unlike the higher resolution files, it is conveniently downloadable in only two large “tiles”, north and south of 400N. It includes motorways, A class roads (single and dual), B class roads (single and dual), minor roads (>4 m wide and <4 m wide), canals, rivers, railways, and railway stations. Point features are given as single coordinate pairs and linear features as separated sets of coordinates representing “vertices”, with

Study objectives: To locate geographical sources of engine exhaust emissions in Great Britain and to link them with the birth addresses of children dying from cancer. To estimate the cancer initiating roles of nearby roads and railways and to measure effective ranges.

Design: Birth and death addresses of all children born between 1955 and 1980 in Great Britain, and dying from leukemia or other cancer during those years, were linked to locations of railway stations, bus stations, ferry terminals, railways, roads, canals, and rivers. Nearest distances to births and deaths were measured, and migration data relating to children who had moved house were analysed. Excesses of close to hazard birth addresses, compared with each to hazard death addresses, indicate a high prenatal or early postnatal risk of cancer initiation.

Setting and subjects: Child cancer birth and death addresses and their map references were extracted from an earlier inquiry. Map references of putative hazards were downloaded from the Ordnance Survey national digital mapping archive of Great Britain. These data are recorded to a precision of one metre and have ground accuracies around 20 metres.

Main results: Significant birth excesses were found within short distances of bus stations, railway stations, ferries, railways, and A,B class roads, with a relative risk of 2.1 within 100 m, tapering to neutral after 3.0 km. About 24% of child cancers were attributable to these joint birth proximities. Roads exerted the major effect.

Conclusions: Child cancer initiations are strongly determined by prenatal or early postnatal exposures to engine exhaust gases, probably through maternal inhalation and accumulation of carcinogens over many months. The main active substance is probably 1,3-butadiene.
assumed linear interpolations. Details are presented in the appendix.

Lists of hazard coordinates were scanned against all addresses for points of nearest approach. Where appropriate, perpendiculars were dropped to lines connecting vertices. In practice, the vertices were so tightly set that this made little difference to the results of initial essays using the vertices alone. Railway stations were additionally inspected using the OS online “get-a-map” facility to estimate the compass bearing (to 5 degrees, using a protractor against the computer screen map) of the track passing through the station. In addition to the station, with idling diesel locomotives, this permitted calculation of risk estimates around the fume rich acceleration zones on either side. Perpendiculars were dropped to varied line extensions (0.2, 0.4, 0.6, 0.8, and 1.0 km); and, for comparison, this was repeated transversely to the track. Underground stations, tramways, tramway connections, and recently built stations were omitted. The latter were ascertained through reference to a 1992 railway atlas. Bus and coach stations were identified from national timetables and located visually on OS maps to a precision of 0.1 km. Those marked by symbols on OS maps, mainly town centre stations, were listed and tested separately.

Vehicle ferry terminals, civil airports, and holiday resorts, were added to the lists of point features using similar visual methods, for purposes to be described later.

RR at different distances from the nearest hazard points were estimated among children who moved house. For short distances the short range birth-death ratio serves as an estimator of RR. Its validity depends upon the premise of a short term migration equilibrium between different areas among the general child population. Against such a background, with an expectation of equal outward and inward movements relative to any nominated point, an excess of short range birth addresses represents a cancer hazard selection. Absolute numbers of cancer initiations attributable to hazard proximities are estimated as the difference between numbers of nearby births and nearby deaths.

Estimates of RR based on birth/death ratios can be sharpened by restricting them to children crossing a specific circumferential boundary around a point hazard (or lines parallel to a linear feature). This procedure excludes those children who migrated entirely within (or between) near field or far field locations or over very short radial distances. Ratios between such outward and inward movements are characterised below as “traverse limited”. These approaches are illustrated in the last two columns of tables 1 and 2.

An elaborated version of the boundary crossing technique, especially useful for examining simultaneous exposures to several hazard types, designates multiple lines at 50 metre intervals around the hazards, providing a contour map of exposure intensities. It permits synthesis of a sequence of different traverses. This is a comparatively efficient approach, retrieving additional information, and results from its application are shown below (for example, in table 3).

RESULTS
The 12 017 reliably located post-1954 birth and death records included 5663 children who moved house by more than 0.5 km. The primary analyses are based upon this group and table 1 distributes the 5663 births and deaths according to their distances from individual map features. The last two columns give cumulative values corresponding with the first three (0.0–0.3 km) and the first four columns (0.0–0.5 km), but restricted to those who traversed these limiting boundaries in either direction. Table 2 shows results obtained by combining pairs or larger groups of features, or by separating overlapping relations. These tabulations were repeated separately for the 2806 reticuloendothelial and the 2857 “solid” cancers. The results were indistinguishable and subsequent findings refer to the combined set.

Bus/coach stations
These results confirmed the high RRs already shown around 455 bus stations located in national timetables.4 RR within 0.5 km was 5.79. The excess risk tapered as far as 1.0 km, accumulating an attributable set of 479 additional cancer births (8.5% of 5663). Bus stations marked on OS maps (302), mainly in busy city centre sites, accounted for 375 excess cancers and the traverse limited RRs were 8.28 within 0.3 km and 7.12 within 0.5 km. Non-OS bus terminals showed weaker RRs (3.42 and 3.15) but still contributed substantially with 105 extra cancer births: 1.9% of migrants.

A similar analysis was performed for approach roads or waiting areas at vehicle ferry terminals, including those with foreign destinations and those crossing estuaries and sea passages within this country. There were few births within 1.0 km of these sites but there was a birth/death ratio of 82/41 (2.00) within 2.0 km and 168/108 (1.56) within 3.0 km.

Railway stations
Railway stations showed a similar tapering pattern with RRs of 2.11 (CI = 1.76 to 2.53) and 2.44 (2.16 to 2.76) at 0.3 and 0.5 km and lesser excesses as far as 1.0 km. This was less than for bus stations, but more children were involved and the 842 birth excesses within 1.0 km exceeded those for bus stations or ferry points, representing 14.9% of the 5663 migrants. Major bus stations are often adjacent to railway stations and their associated birth distance distributions are far from independent so a joint list of both features was examined (section 1: table 2). It showed an excess of 869 cases within 1.0 km of either: raising jointly attributable cancers to 15.3% of all migrants.

Departure track extensions
Railway station through-tracks were extended each way in steps of 0.2 km up to 1.0 km along their compass bearings. Birth/death ratios within 0.3 km of these extensions increased from an initial 1.74 (347/199) for no extension to 1.93 for the 0.4 km extension (882/457); but then decreased (section 2 of table 2). Numbers of attributable cancers increased from an initial 148 to 425 at 0.4 km and decreased thereafter.

The stations were extended similarly along an imaginary line drawn at right angles to the track. Surprisingly, the rise and fall patterns were similar and there were even more attributable cases for the 0.4 km extension (477) than for the tangential one. This presumably results from adjacent hazards such as bus stations, bus stops, road traffic, car parks, shopping areas, and other commercial and industrial activities. It will require other evidence to show how much is attributable to the railways and the locomotives themselves.

Railway lines
Birth/death excesses here were concentrated within 0.5 km and (including stations) showed a ratio of 2457/1707 (1.44:1.34 to 1.54). The excess of 750 amounted to 13.2% of all migrants. Railway lines remote from the extended station tracks were examined separately. Results for near points where there was no station closer than 0.5 km are shown in section 3 of table 2. The RRs at 0.3 and 0.5 km were only 1.12 and 1.20 but the respective cancer excesses were 60 and...
Table 1  Shortest distances from births and deaths to selected map features

<table>
<thead>
<tr>
<th>Distances (km)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.5</th>
<th>1.0</th>
<th>&gt;1.0</th>
<th>0-0.3*</th>
<th>0-0.5*</th>
</tr>
</thead>
</table>

1. Bus stations
Births | 12   | 113  | 92   | 224  | 374  | 4848  | 215    | 423    |
Deaths | 3    | 14   | 18   | 52   | 249  | 5327  | 33     | 73     |
B/D ratio | 4.00 | 8.07 | 5.11 | 4.31 | 1.50 | 0.91  | 6.52   | 5.79   |

2. Railway stations
Births | 23   | 113  | 261  | 656  | 1350 | 3260  | 376    | 926    |
Deaths | 23   | 65   | 111  | 308  | 1054 | 4102  | 178    | 380    |
B/D ratio | 1.00 | 1.74 | 2.35 | 2.12 | 1.28 | 0.79  | 2.11   | 2.44   |

3. Railways
Births | 257  | 490  | 476  | 1058 | 1316 | 2066  | 974    | 1509   |
Deaths | 175  | 350  | 376  | 685  | 1443 | 2634  | 652    | 814    |
B/D ratio | 1.47 | 1.40 | 1.23 | 1.54 | 0.91 | 0.78  | 1.49   | 1.85   |

4. Motorways
Births | 9    | 18   | 17   | 61   | 290  | 5268  | 37     | 88     |
Deaths | 6    | 18   | 33   | 97   | 284  | 5225  | 50     | 137    |
B/D ratio | 1.50 | 1.00 | 0.52 | 0.63 | 1.02 | 1.01  | 0.74   | 0.64   |

5. A roads
Births | 23   | 113  | 261  | 656  | 1350 | 3260  | 376    | 926    |
Deaths | 23   | 65   | 111  | 308  | 1054 | 4102  | 178    | 380    |
B/D ratio | 1.00 | 1.74 | 2.35 | 2.12 | 1.28 | 0.79  | 2.11   | 2.44   |

6. B roads
Births | 509  | 579  | 513  | 704  | 1130 | 2066  | 974    | 1509   |
Deaths | 289  | 531  | 424  | 716  | 1251 | 2462  | 791    | 977    |
B/D ratio | 1.76 | 1.09 | 1.21 | 0.98 | 0.90 | 0.91  | 1.45   | 1.35   |

7. Minor roads >4 m wide
Births | 846  | 1037 | 819  | 915  | 754  | 1130  | 2228   | 1148   |
Deaths | 726  | 1165 | 886  | 1044 | 807  | 3995  | 414    | 1106   |
B/D ratio | 1.17 | 0.88 | 0.92 | 0.88 | 0.89 | 0.78  | 1.92   | 2.26   |

8. Minor roads <4 m wide
Births | 135  | 162  | 154  | 283  | 632  | 4297  | 322    | 472    |
Deaths | 126  | 148  | 183  | 435  | 1090 | 3681  | 676    | 802    |
B/D ratio | 2.01 | 1.75 | 2.03 | 1.48 | 1.45 | 0.98  | 1.71   | 1.44   |

9. Canals
Births | 58   | 64   | 79   | 166  | 466  | 4830  | 176    | 301    |
Deaths | 28   | 49   | 73   | 154  | 339  | 5020  | 125    | 237    |
B/D ratio | 2.07 | 1.31 | 1.08 | 1.08 | 0.96 | 1.41  | 1.27   | 1.27   |

10. Estuaries
Births | 9    | 14   | 18   | 69   | 204  | 5349  | 38     | 98     |
Deaths | 4    | 16   | 13   | 47   | 141  | 5442  | 30     | 68     |
B/D ratio | 2.25 | 0.88 | 1.38 | 1.47 | 0.98 | 1.27  | 1.44   | 1.44   |

11. Other rivers
Births | 172  | 287  | 370  | 812  | 1393 | 2629  | 663    | 1051   |
Deaths | 169  | 286  | 355  | 747  | 1587 | 2519  | 644    | 968    |
B/D ratio | 1.02 | 1.00 | 1.04 | 1.09 | 0.88 | 1.04  | 0.98   | 1.09   |

*Cumulative birth-death ratios in the last two columns are “traverse limited” and refer to subsets of migrants who crossed the nominated distance boundary, either a circumference or a pair of parallel lines.

Table 2  Combinations and separations

<table>
<thead>
<tr>
<th>Distances (km)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.5</th>
<th>1.0</th>
<th>&gt;1.0</th>
<th>0-0.3*</th>
<th>0-0.5*</th>
</tr>
</thead>
</table>

1. Bus and railway stations combined
Births | 30   | 217  | 307  | 685  | 1289 | 3135  | 558    | 1117   |
Deaths | 23   | 74   | 120  | 329  | 1113 | 4004  | 200    | 402    |
B/D ratio | 1.30 | 2.93 | 2.56 | 2.08 | 1.16 | 0.78  | 2.79   | 2.78   |

2. Rail acceleration tracks: ≤0.4 km
Births | 253  | 259  | 371  | 644  | 1243 | 2893  | 1153   | 1552   |
Deaths | 126  | 148  | 183  | 435  | 1090 | 3681  | 676    | 802    |
B/D ratio | 2.01 | 1.75 | 2.03 | 1.48 | 1.14 | 0.79  | 1.71   | 1.94   |

3. Railways excluding acceleration tracks
Births | 134  | 276  | 256  | 578  | 837  | 3582  | 581    | 971    |
Deaths | 113  | 228  | 265  | 467  | 1063 | 3527  | 521    | 806    |
B/D ratio | 1.19 | 1.21 | 0.97 | 1.24 | 0.79 | 1.02  | 1.12   | 1.20   |

4. Bus stations, rail acceleration tracks, and other railways
Births | 444  | 594  | 573  | 960  | 1204 | 1888  | 1012   | 1626   |
Deaths | 254  | 380  | 401  | 711  | 1472 | 2445  | 499    | 800    |
B/D ratio | 1.75 | 1.56 | 1.43 | 1.35 | 0.82 | 0.77  | 2.03   | 2.03   |

5. A roads and B roads combined
Births | 1137 | 1246 | 832  | 890  | 949  | 609   | 1774   | 1419   |
Deaths | 592  | 1059 | 779  | 1129 | 1223 | 881   | 989    | 874    |
B/D ratio | 1.92 | 1.18 | 1.07 | 0.79 | 0.78 | 0.69  | 1.79   | 1.62   |

*Cumulative birth-death ratios in the last two columns are “traverse limited” and refer to subsets of migrants who crossed the nominated distance boundary, either a circumference or a pair of parallel lines.
165, showing some evidence of a railway proximity effect beyond the reach of the station-related acceleration and transverse zones.

**Roads**
A roads, B roads, minor roads > 4 m wide, and minor roads < 4 m wide, displayed reducing birth/death ratios with diminishing traffic-class and with increasing distance. The respective 0.3 km traverse limited RRs for the four classes of road were 1.92 (1.75 to 2.10), 1.45 (1.32 to 1.60), 0.93 and 0.80. Urban streets are not recorded here so most minor roads, and locations distant from the A,B roads, represent rural areas. There was an excess of 785 births within 0.3 km of A,B roads together, amounting to 13.9% of all migrant cancers. Rural birth locations, represented by the minor roads, were strongly “protective”. There were no birth excesses near motorways; indeed, very few addresses of any kind. Many motorways did not exist at that time and their current locations often represent low population rural areas.

**Waterways**
Canals displayed few nearby addresses and the weak relation with cancer births is probably attributable to adjacent features rather than canal traffic. Lower reaches of main rivers, shown in table 1 as “estuaries”, and coded to the centre of the waterway, showed few nearby addresses and no clear cancer initiating effects. Other river classes, taken together, showed nothing.

**Locomotive effects**
Many rail lines in south east England have for many years used third rail electrification (750 V DC) although this did not reach the coastal towns until about 1970. Proximity studies were performed separately for hazards east of 480.0E and south of 175.0N (a useful defining point near Reading). Studies were performed separately for hazards east of 480.0E and south of 175.0N (a useful defining point near Reading). Railway station acceleration tracks here showed birth/death asymmetries of only 113/96 (1.36) at 0.3 km compared with 752/361 (2.08) elsewhere (p<0.01). The difference suggests a direct locomotive effect.

**Times and places**
Ratios between “near” and “far” birth addresses relative to different hazards, were examined in different years and in different seasons. A first study sought secular changes in near rail B/D ratios that might be related to the introduction of diesel locomotives. There were irregularities, some years showing unexplained excesses or deficits over adjacent years, but there was nothing that clearly corresponded with known equipment changes or strikes or other rail stoppages. The railway system underwent major changes after the “modernisation plan” of 1956, and a major retrenchment after the Beeching economic review in 1963, and cancer death sequences themselves were affected by improving survival. An intrinsic “rail diesel effect”, if it existed, failed to show through these complexities.

A second study sought seasonal road related proximity changes in places with high summer holiday traffic, including the ferries mentioned above, civil airports, and a list of traffic-notorious holiday resorts. “Surrounding zones” were defined within various radii (5.0 km, 10.0 km) and seasonal near-road B/D ratios inside these zones were compared with the same ratios outside. Rail proximity effects were likewise examined. No local seasonal near/far variations were found.

**Combined effects**
Aggregation of birth and death distributions around combined map features, as in table 2, raised problems. There was double counting in some combinations, while differing effective ranges could result in conflicting migration pola-
rities, and it was difficult to show the marginal effects of one hazard over another. It was here that an examination of successive exposure contours proved useful. Distance contours were set at 50 m intervals around the component hazards, within their individual effective ranges. For each child the contour intervals were scanned from nearest to farthest, examining all the listed hazards within each exposure band before proceeding to the next band. The

![Table 3](image-url)

**Policy implications**
There is an urgent need to monitor and control ICE exhaust emissions, especially with respect to 1,3-butadiene. The controls need to be comprehensive covering road, rail, and marine sources and possibly oil fired space heating systems and furnaces. The controls should be directed specifically towards emissions from known sources.
Key points

Childhood cancer birthplaces are strongly and closely associated with A and B class roads, railways, bus/coach stations, railway stations, vehicle ferry ports, and the commercial and industrial environments surrounding these features. The effects are evident at ranges down to 100 metres, decaying rapidly with increasing distance, and the relevant pollutants are evidently discharged at low level. This, and the close range potency of vehicles and certain volatile fuels (for example, diesel buses), shows that the main carcinogens are associated with engine exhausts. The chief carcinogen is probably 1,3-butadiene and it is probably inhaled and accumulated by the mother over a prolonged period. It probably accounts for most childhood cancer initiations although the clinical onset of leukaemia, in particular, may sometimes be precipitated by an infection.

Discussion

These results confirm the prior hypothesis that many childhood cancers are initiated by short range exposure of the fetus or infant to exhaust fumes from ICEs. Earlier migration analyses had shown that ICE associated 1,3-butadiene was the probable agent. Other reported investigations of ICE proximities have mainly used case-control comparisons and the conclusions have varied, but several have produced proximities that are mainly used case-control comparisons and the conclusions have varied, but several have produced proximities that are probably inhaled and accumulated by the mother over a prolonged period. It probably accounts for most childhood cancer initiations although the clinical onset of leukaemia, in particular, may sometimes be precipitated by an infection.

What proportion of all child cancers might be initiated by exhaust gas exposures? Firstly, we can suppose that exposed non-migrants suffered to the same degree as migrants; or more so if there is a postnatal component. Secondly, we can suppose that the measured proximities supply only a very crude indicator of all maternal/child exposures. More specific measures of exposure (for example, including their own cars) must be capable of explaining many more than the 24% found here; and ICE exhaust exposure can probably be regarded as the major initiating cause of these diseases in this country during these years. It was a more powerful hazard than medical radiation, which resulted in about 6% of cases, and much more powerful than any effects of exposure to non-ionising electromagnetic radiation.

However, this negative finding leads to the important inference that exhaust gas inhalations must be effective after varying intervals, smoothing out seasonal exposure variations. This implies that the mother probably accumulates toxic materials over long periods, concentrating low ambient levels of carcinogen through a “biological magnification” process. Such processes have been recognised in other contexts: for example, in food chain concentrations of DDT, or the dietary toxin pathways responsible for endemic neurodegenerative disease on the island of Guam. The possibility deserves examination here.

Acknowledgements

The cancer data were supplied by the late Professor A M Stewart.

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Conflicts of interest: none declared.

The author is Emeritus Professor, University of Birmingham, UK.
APPENDIX

Digimap featurecodes and numbers of coordinates in each category:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Codes</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus/coach stations</td>
<td>(direct map reading)</td>
<td>455</td>
</tr>
<tr>
<td>OS bus stations</td>
<td>(direct map reading)</td>
<td>302</td>
</tr>
<tr>
<td>Railway stations</td>
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<td>2531</td>
</tr>
<tr>
<td>Railways</td>
<td>5510, 5511, 5512, 5513</td>
<td>7837</td>
</tr>
<tr>
<td>Motorways</td>
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</tr>
<tr>
<td>A class roads</td>
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<td>146943</td>
</tr>
<tr>
<td>B class roads</td>
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<td>164227</td>
</tr>
<tr>
<td>Minor roads &gt; 4 m wide</td>
<td>5350</td>
<td>382817</td>
</tr>
<tr>
<td>Minor roads &lt; 4 m wide</td>
<td>5405</td>
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</tr>
<tr>
<td>River, main, lower</td>
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<td>15505</td>
</tr>
<tr>
<td>Other rivers</td>
<td>5211, 5212, 5221, 5222, 5230</td>
<td>857107</td>
</tr>
</tbody>
</table>

Map data were downloaded in DXF format and hazard lists were extracted using specially written PASCAL programs. Coordinates are specified to one metre precision but OS warns that this is not a meaningful statement of ground accuracy. OS quoted tolerances on their 1:250 000 printed maps, derived from these data, suggest maximum ground errors of 25 metres for points and vertices (0.1 mm on map) and 50 metres for interpolations (0.2 mm). Mean errors are probably around 20 metres.

REFERENCES