Spatial Analysis of Childhood Leukemia in Relation to 25-Hz and 60-Hz Magnetic Fields Along the Washington – New Haven Rail Line

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Prepared for

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ABSTRACT

The failure to observe increased leukemia in laboratory animals with chronic exposures to a wide range of power frequency (50/60 Hz) magnetic field intensities contrasts with an apparent association between proxies for magnetic field exposure above 0.3 or 0.4 μT and childhood leukemia in case control studies. These contradictions have prompted the investigation of other characteristics of 'real world' magnetic field exposures, as both epidemiologic and long-term animal studies to date have largely focused on exposures to continuous 50/60 Hz magnetic fields. The Northeast Corridor (NEC) rail line runs between Washington, DC and Boston, MA along the densely populated eastern coastline. Power supplied to run electric trains at 25 Hz on electrified portions of the NEC generates magnetic fields quite different in primary frequency, harmonic content, and intermittency from those produced by power lines. This study compared the age-specific rates of childhood leukemia in census tracts crossed by the NEC rail line to background rates observed in these states where power to passenger trains was supplied by 25 Hz, 25/60 Hz, or diesel power sources. The analysis also assessed the presence of any association or clustering of the cases about the electrified sections of the rail line. Leukemia rates in census tracts crossed by the rail line were not statistically different from state background rates. Score tests for clustering provided no statistical evidence for higher leukemia rates in census tracts with higher estimated magnetic field exposures. The power of the test to detect a relative risk ≥ 2.5 was 76%. No clustering of leukemia cases in railroad census tracts related to potential confounders such as nearby interstate

highways or to median household income was observed. The study provides no statistical support for an association between magnetic field exposure and increased risk of childhood leukemia. While some of the limitations of general geographic studies were overcome, the relatively small fraction of the wayside population with potential exposure to magnetic fields from the rail line, and the relatively weak magnetic fields produced by the catenary-track circuit could help to explain the absence of a detectable effect of magnetic fields on childhood leukemia rates.

INTRODUCTON

Over the past 20 years considerable effort has been directed towards the investigation of associations between exposures to power frequency electric and magnetic fields and cancer, particularly in children (NIEHS, 1998; IARC, 2001). The common sources of exposure to these fields in the community are electric power lines, interior wiring and grounding systems, and appliances whose fields oscillate at 50/60 hertz (Hz) (Zaffanella, 1993). Associations have been reported between childhood cancers and various surrogates for magnetic field exposure including power line characteristics and distance to residence (wire codes), spot measurements, and calculated values based on historical power flows. Several large studies report no, or slightly elevated but imprecise associations, between measured and calculated magnetic fields and childhood leukemia in the US (Linet et al, 1997), Great Britain (UKCCS 1999, 2000) and Canada (McBride et al, 1999). Nonetheless, data pooled from the bulk of the published studies have suggested an association with exposures to magnetic fields greater than 0.4 μT even though most of the cases supporting this association were contributed from the Linet et al study (Ahlbom et al, 2000; Greenland et al, 2000). The literature provides little support for associations between magnetic or electric fields and other types of cancer in children or any cancer in adults (IARC, 2001).

Despite improvements in the design and exposure assessment of such studies, the strength of associations has not notably increased in studies that have reported associations with estimates of time-weighted-average (TWA) 50/60 Hz magnetic fields and other indices of exposure (Angelillo and Villari, 1999). Multiple long-term studies of animals exposed to sinusoidal 50/60 Hz magnetic fields provide no experimental support for an association between leukemia and magnetic fields (Boorman et al, 1999; McCormick et al, 1999; Morris et al, 1999). These contradictions among studies that used estimates of the TWA field as the exposure metric have prompted investigation of other characteristics of 'real world' magnetic field exposures including frequency, intermittency, and resonance with dc magnetic fields (NIOSH, 1994; Bracken et al, 1997). These other aspects of magnetic field exposure have been less well studied; epidemiologic and long-term animal studies have largely focused on potential effects of sinusoidal, continuous, 50/60 Hz magnetic fields.

Electric rail lines are sources of electric and magnetic fields that span a wider range of frequencies, are spatially more complex, provide more intermittent exposures than do power lines (DOT/FRA, 1993a,b), and have not been investigated as thoroughly. While power may be delivered to electric rail systems at 50/60 Hz, it has been common to deliver power to vehicles at other frequencies. In Europe some rail systems are powered at $16^{2/3}$ Hz. In Germany the $16^{2/3}$ Hz rail system has been identified as a source of magnetic field exposure to wayside populations similar in magnitude to power lines (Schüz et al, 2000). The first case-control study of magnetic fields from rail lines in relation to childhood leukemia reported a weak and imprecise association with residential exposure to $16^{2/3}$ Hz magnetic fields, but only few cases had exposures $\geq$0.1 μT and no exposure-related trend was present (Schüz et al, 2001). The authors concluded that the data neither support nor exclude the possibility of a small risk of leukemia from electrified rail.

A study of general clustering of childhood cancer near rail lines and other facilities in Great Britain reported fewer cases with death addresses within 0 – 0.3 km of rail lines but an excess at greater distances out to 4 km (Knox and Gilman, 1997). The power source of the locomotives on the rail lines was not specified but the authors commented that the attribution of risk to proximity to rail lines might reflect geographical proximity to chemical hazards from a variety of industrial sources.

In the U.S. most inter-city railroad lines are powered by diesel, not electric, locomotives. A notable exception is a 298-mile section of the Northeast Corridor (NEC) that connects Washington, D.C. to New Haven, CT (Figure 1). Between Washington, D.C. and New York City, electric locomotives supplied with power at 25 Hz pull most passenger trains. Between New York City and New Haven, CT, power to locomotives is supplied at 60 Hz. Diesel locomotives on the NEC pull passenger trains on the remaining 156 miles of the NEC route between New Haven and Boston, MA and all freight trains on the NEC. As of 2000, the New Haven, CT to Boston, MA segment has also been electrified at 60 Hz for high speed (Acela Operation). The unique frequency and intermittent magnetic field exposure characteristics of the electrified portion of the NEC and its long route along the densely populated eastern coastline prompted the Federal Railroad Administration (FRA) to sponsor an investigation of the feasibility of conducting either a cohort or case-control study of magnetic field exposures of electrified portions of NEC. As part of this investigation, the authors compared the rates of childhood leukemia along the entire NEC to rates in similar census tracks not along the railway, and assessed whether cases clustered near electrified sections of this rail line.

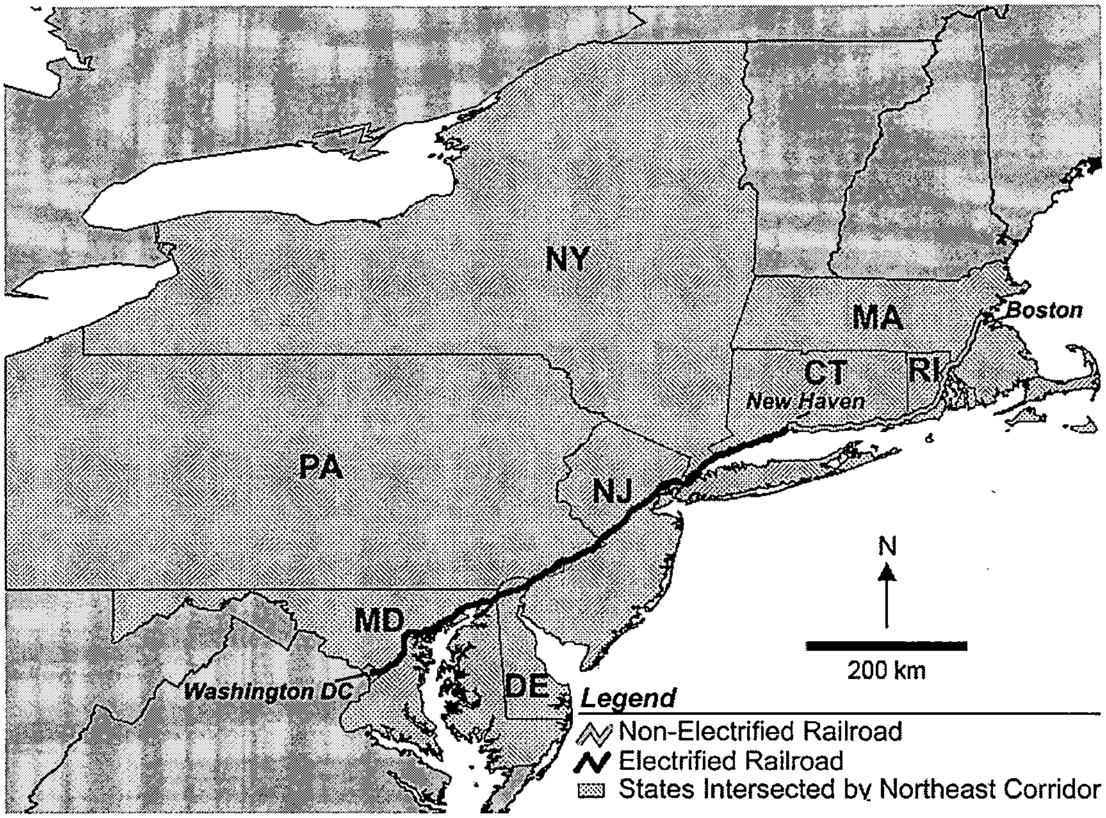

Fig. 1. Northeast Corridor rail line showing sections between Washington, D.C. and New Haven where power is supplied to passenger train locomotives at 25 Hz or 60 Hz by overhead catenary wires. Passenger trains between New Haven and Boston are diesel powered.

METHODS

A geographic correlation study was conducted using incident cases of childhood leukemia, diagnosed within the period 1984-1997. The advances in the treatment of childhood leukemia (Smith et al, 1999) make recent mortality data unsuitable for investigations as described here. Cases were ascertained from population-based tumor registries. Childhood leukemia rates in census tracts crossed by the rail line were compared with state background rates, and clustering was evaluated based upon magnetic field exposure. The analysis for clustering did not control for possible confounders. However, two potential risk factors for childhood leukemia, proximity to high traffic density roads (Savitz and Feingold, 1989), and socioeconomic status (Sharp et al, 1999) were compared among the exposed and unexposed populations.

Case Population

The analysis was restricted to cases diagnosed between 1984 and 1997 at ages 0 – 14 years with leukemia (International Classification of Diseases for Oncology; ICD-0-2 morphology codes 9800-9940 – Percy et al, 1990) listed in population-based cancer registries.

Calculation of Leukemia Incidence Rates

The geographic coordinates (latitude and longitude), political boundaries of case addresses, and census data were obtained by a geographic information system (GIS) program (Maptitude®, version 4.1, Caliper, Inc., Newton, MA). The expected accuracy of the residence location is about 100 m (Rushton and Lolonis, 1996). Addresses not coded by this program were manually checked by a variety of electronic resources including Microsoft Streets 98 (Microsoft Corporation, Redmond, WA) and Mapquest.Com, Inc (www.mapquest.com). Fewer than four percent of case addresses could not be georeferenced in this fashion and were not be included in the analyses. Leukemia rates in census tracts intersected by the NEC rail line were calculated by dividing the number of observed cases by the population at risk (ages 0-14 years) reported in the 1990 census. The census tract was chosen *a priori* as the primary unit of analysis to avoid the dilution of any local effect of the rail line within a geographical area the size of a county or the small numbers and resulting unstable rates of small block groups. The population of children aged 0-14 years in census tracts crossed by the NEC varied from 0 to 4,600. The total population in these tracts was just under 357,000.

The coverage of the state cancer registries was not complete for years 1984-1997. For example, the Maryland did not have coverage until 1992, while New Jersey and New York data were available only for 1985-1996. Therefore, leukemia incidence rates were calculated separately within each state. Confidence intervals for rates were determined by an exact Poisson distribution method (cases < 20) or by an approximation based on the normal distribution (Ahlbom, 1993).

Statistical Analysis

Pearson's chi-square test was used to test the hypothesis that the rate of cases in the at-risk population of a state's census tracts was the same for populations intersected by the NEC as for populations not intersected by the NEC. Based on population sizes of census tracts and observed leukemia rates within each state, the power of the Chi-square test to detect elevations in relative risks of 3.0 or greater was calculated to be above 80% in all states. Census tracts in PA, NJ and CT provided sufficient statistical power to detect at least a two-fold elevation in risk.

The score test derived by Waller et al (1992) and Lawson (1993) was used to evaluate localized clustering of leukemia about the NEC. Additional details are provided in the

Appendix. The test statistic U compares the number of cases observed in each census tract crossed by the NEC within the states MD, DE, PA, NJ, NY, CT, RI, and MA to the expected number of cases based on the overall rate of leukemia observed in children aged 0-14 years in the rest of the state.

The statistical power of the score test to detect focused clustering about the NEC was computed by Monte Carlo simulations of the number of cases in each census tract assuming independent Poisson distributions for disease counts and considering observed to expected ratios of 1.0 (the null hypothesis), 1.5, 2.0, 2.5, 3.0 and 3.5, for 10,000 trials at each risk level and each of the four exposure definitions (described below). For a nominal value of alpha (α) = 0.05, the probability of observing a difference even when the null hypothesis true, the test rejected the null hypothesis about 6% of the time when the null hypothesis was in fact true. The power of the test was modest for observed/expected ratios of 1.5 or 2.0. For ratios ≥ 2.5 the power of the test was 76% or greater for g_i (defined as the calculated relative magnetic field intensity in the ith census tract), and above 60% when exposures were adjusted for passenger train frequency. Few, if any, statistical tests could be expected to provide greater discriminatory power for the alternatives evaluated here (Waller and Lawson, 1995; Waller, 1996).

The score test was also used to assess the clustering of leukemia cases around interstate highways (traffic-related emissions) or by socioeconomic factors represented by census tract median income. For these analyses the inverse distance to the nearest highway and the inverse of median income of census tracts were used as weighting factors. Some census tracts reported zero median income and so these values were replaced with median incomes of 1$ or $2000 in the analyses. The outcome was the same so only the score analyses that used 1$ as a replacement value are reported.

Magnetic Field Exposure

The major source of the magnetic field from the NEC is the current flowing in the circuit formed by the overhead catenary wires that provide power to electric locomotives via a pantograph from the overhead catenary and the rails on which current returns to substations. The magnitude of the field at any point along the electrified section of the NEC is largely determined by the current drawn by electric trains on the powered section of track, termed the electrification block, between substations (25-Hz section) or autotransformers (60-Hz section) to the north and south of the point of interest. Trains draw power from the catenary largely within the electrification block where they are present, with lower or no power drawn from adjacent blocks. The field is generally highest when trains are within the electrification block opposite the location of interest. Thus, magnetic field exposure of wayside populations is a function of the current drawn by passing trains and of the number of trains passing.

No historical information on current flow at specific locations was available but the magnitude of the magnetic field decreases with distance from the track in proportion to $1/(\text{distance})^2$. This theoretical relationship was used to determine the relative magnetic field exposures of census tracts near electrified sections of the NEC (see Appendix) and has been confirmed by measurements (DOT/FRA, 1993a).

Four measures of exposure, all relating to the magnitude of the magnetic field, were computed for each case. The first measure was the relative magnitude of the magnetic field for the population within a census tract, g_i defined as $1/d^2_i$, where d_i is the distance between the geographic centroid of the ith tract and the NEC line. The next measure adjusted the exposure value g_i based on the annual number of passenger trains passing over the rail segment closest to the census tract occupied by each case, on the presumption that the magnetic field is appreciably higher when a train is present in the electrification block than not. This adjusted value was defined as $g_i = (t_i/d^2_i)$, where t_i is the number of passenger trains using rail lines in tract i during a given year and provides an estimate of integrated annual exposure from the rail line. As a first approximation, the trains were treated as independent sources even though the total field produced by multiple trains in an electrification block may not be strictly additive.

The third and fourth exposure measures were also defined as $g_i = (t_i/d^2_i)$, but in these cases, t_i represented annual numbers of freight, and freight and passenger trains, respectively. During the years studied, passenger trains on the NEC were electrically powered in MD, DE, PA, NJ, NY, and part of CT; passenger trains in part of CT, RI and MA were powered by diesel locomotives. Freight trains are powered exclusively by diesel locomotives and were considered as a control for the electrically-powered passenger trains. To the extent that the use of the NEC by passenger trains limits usage by freight trains, there was some justification for also considering the combined annual traffic of both passenger and freight trains. Any clustering of childhood leukemia with the number of freight trains passing a population would not be related to magnetic fields from the NEC. Data on frequency of trains was provided by the VOLPE National Transportation System Center from the Fall/Winter 1996/97 National Timetable.

RESULTS

Table 1 summarizes the characteristics of the leukemia cases with diagnosis addresses in census tracts crossed by the NEC from MD to MA. The distribution by age and sex is roughly similar to that reported in the literature (Sharp et al, 1999: Reis et al, 2001).

Category	No.
Total	185
Sex	
Male	117
Female	68
Age (years)	
0-4	109
5-9	32
10-14	44

Table 1. Age and sex of leukemia cases 0-14 years of age in census tracts crossed by the NEC between Maryland and Massachusetts, 1984-1997.

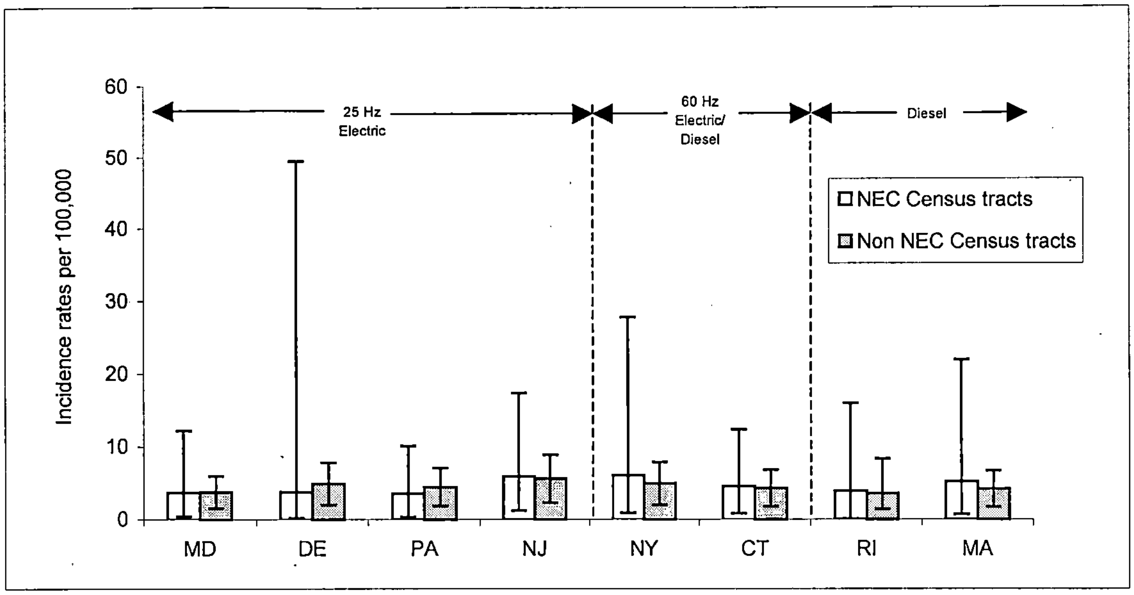

Fig. 2. Age-specific childhood leukemia rates in census tracts crossed by NEC rail line and other non-NEC census tracts by state. The power supplied to NEC passenger train locomotives is 25-Hz electrical power, 60-Hz electrical power or diesel fuel as indicated.

Figure 2 compares the age-specific leukemia rates of census tracts crossed by the NEC with rates for other census tracts within the same state. Regardless of the type of power used by locomotives on particular sections of track, there is no statistical evidence of elevated rates of leukemia among 0-14 year olds in the tracts crossed by electrified rail lines (MD, DE, PA, and NJ), by non-electrified rail lines (MA, RI) or by both (NY, CT) compared to census tracts not containing rail lines in these states.

The results of score tests performed to detect localized clustering about the NEC based on four exposure definitions and exact *p*-values are shown in Table 2. There was no statistical evidence for greater than expected rates of leukemia in census tracts subject to higher spatially averaged magnetic field exposures as estimated by $1/d^2$.

Exposure Metric	U	p-value
$(1/d^2)$	-1.99	0.977
(number of freight trains per year)/d^2	-2.63	0.996
(number of passenger trains per year)/d^2	-1.51	0.934
(number of trains per year)/d^2	-1.51	0.935

Table 2. Score test results of clustering for magnetic field exposure metrics for electrified sections of the North East Corridor

Based on the size of the catenary tract circuit and assumed maximum current flow (FRA/VOLPE, 1994), it was estimated that exposures to magnetic fields of 0.1 μT or greater would only be encountered within about 200 feet of the NEC. Of the 100 cases of childhood leukemia identified in census tracts crossed by the NEC in states where all passenger trains are powered by 25 Hz or 60 Hz power, only 5 cases had residences at diagnosis within 200 feet of the NEC.

A proxy for total annual exposure (the number of passenger trains per year times relative magnetic field intensity) also showed no evidence of clustering. Score tests for exposures related to the annual number of freight trains, which are unrelated to 25 Hz or 60 Hz magnetic fields, also indicated no association with leukemia rates of census tracts. Given the small length of rail line supplied by 60-Hz power relative to that supplied at 25 Hz, and no evidence for clustering along the entire length of electrified tract, no separate analyses of census tract exposures by the specific frequency of the magnetic field were performed.

Two potential risk factors for childhood leukemia, proximity to high traffic density roads

(Savitz and Feingold, 1989), and socioeconomic status (Sharp et al, 1999) were also analyzed by the score test. For the census tracts crossed by the NEC, the number of cases was not higher than expected as weighted by inverse distance to interstate highways (U = -0.3721, p = 0.64). There was no statistical evidence for leukemia to cluster in NEC census tracts by socioeconomic status as indicated by score tests using the inverse of median income as an indicator variable (U = -0.3764, p = 0.65).

DISCUSSION

Given the extensive analytic epidemiologic research on magnetic fields from power line sources over the past 20 years, there is now no justification for another general ecologic study of childhood leukemia (Linet, 2000). However, the apparent association between several proxies for magnetic field exposure and childhood leukemia in case control studies (particularly for exposures above 0.4 μT) contrasts with the failure to observe increased leukemia in laboratory animals with chronic exposures to 50/60 Hz magnetic fields. This inconsistency in the data supports the search for some overlooked aspect of magnetic field exposures in residential settings that might be of etiologic significance. The power supplied to run electric trains at 25 Hz on the Northeast Corridor generates magnetic fields and public exposures quite different in primary frequency, harmonic content, and intermittency from those associated with stable loads from power lines. The spatially constrained and highly dynamic (spatially and temporally) exposures to magnetic fields from the electric rail line operating at 25 Hz and 60 Hz provides the opportunity to evaluate the potential importance of power frequency and other aspects of the rail line fields from an epidemiologic perspective. Although ecologic studies have well known limitations, as will be discussed below, *a priori* tests for focused clustering about a linear structure, such as the NEC, offer the opportunity to investigate hypotheses about potential health impacts of such unique magnetic field exposures. The contribution of ecologic studies to the identification of risk factors for leukemia is underscored by the results of ecologic studies of the clustering of childhood leukemia within small geographical areas. Such research has provided a firm basis to identify 'population mixing' as one of the few known risk factors for this disease (Doll, 1999).

Schüz et al (2001) have reported on measured residential magnetic exposures from rail lines to German children at $16^{2/3}$ Hz but observed no trend or statistically elevated odds ratios for leukemia, but both the prevalence and intensity of magnetic field exposures were low. Although the power supplied to electric trains on the NEC is not at the same frequency, the limitations regarding exposure are similar for this study. In the Schüz et al study only 4 % of the cases had measured peak magnetic exposures at $16^{2/3}$ Hz greater than 0.1 μT. In census tracts crossed by the NEC also only 4 % of the cases are estimated to have had peak exposures from the rail line above 0.1 μT.

Background childhood leukemia rates varied considerably across census tracts in the eight states crossed by the NEC rail line (Figure 1), for reasons that are not known. However, available data were sufficient to determine that the leukemia incidence rates in these census tracts, potentially affected by any magnetic- or diesel-related exposure from the inter-city NEC rail line, were the same as in other census tracts within those states crossed by the NEC. More specific analyses for focused clustering about the electrified sections of the NEC failed to support the idea that leukemia rates are higher in census tracts nearest to the sections of the line that produce a 25-Hz magnetic field (MD, DE, PA, NJ), 25/60 Hz magnetic fields (NY), 60-Hz magnetic field in parts of CT, or no magnetic field (MA and RI)[1].

Given the often close proximity of the entire NEC corridor to a parallel interstate highway system, it seemed prudent to consider the possibility that the results may be confounded by traffic density, a surrogate for vehicle emissions. Although traffic density on local streets was not evaluated, the 100,000 or so vehicles that travel daily on nearby interstate highways were considered in a crude fashion by modeling exposure by inverse distance between the census tract crossed by the NEC and nearby interstate highways. Similarly, the frequent observation that rates of childhood leukemia vary by social class and socioeconomic status (Sharp et al, 1999) prompted testing for clustering of NEC census tracts by median family income. Neither distance to interstate highways nor median family income of census tracts crossed by the NEC were determined to provide a basis for clustering.

The absence of elevated childhood leukemia rates in populations of census tracts exposed to magnetic fields from the NEC could reflect that either such fields have little or no leukemogenic potential, or that the limitations of the study precluded the detection of an effect. While the score test had sufficient power to detect 2.0 - 2.5-fold elevations in leukemia risk in census tracts crossed by the NEC, none were observed. It must be

[1] Until the year 2000 for Acela passenger train operations.

recognized, however, that many residences in a census tract may have little or no exposure to magnetic fields from the NEC. In fact, perhaps only 4 % of cases in census tracts crossed by the electrified sections of NEC from DE to CT were close enough to the NEC for magnetic field exposure to have exceeded 0.1 μT. Ahlbom et al (2000) and Greenland et al (2000) have concluded that an association between childhood leukemia and exposure to 50/60 Hz magnetic fields may only be present at average field exposure levels greater than 0.3 or 0.4 μT.

The limitations of the study also include the lack of data about the specific historical magnetic field exposures of individuals, and the assumption that all children in a census tract have the same exposure. Like the study by Schüz et al (2001), the relatively small fraction of the population with potential exposure to magnetic fields from the rail line, and the relatively weak magnetic fields produced by the catenary-track circuit could help to explain the absence of a detectable effect of the NEC on leukemia rates. Yet, in spite of these limitations, the study provides no statistical support for any association between sub-power or power-frequency magnetic field exposure from electrified rail operations and childhood leukemia or a basis to recommend that the studies with more powerful designs be carried out to identify an association between 25 Hz magnetic fields and childhood leukemia.

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APPENDIX

Score Test

If O_i and E_i denote the numbers of cases observed and expected, respectively, in tract i, $i = 1, \ldots, I$, and where g_i denotes the exposure of the ith tract to the rail lines.

The score test statistic is:

$$U^* = \frac{\sum_{i=1}^{I} g_i (O_i - E_i)}{\sum_{i=1}^{I} g_i^2 E_i},$$

Waller et al (1992) show that such a test is a locally most powerful test of the null hypothesis:

H_0: $O_i \sim \text{Poisson}(n_i\lambda)$

where n_i, denotes the population size in tract i (here the number of children aged 0-14 years), and λ denotes the background leukemia rate estimated here by $(\sum_{i=1}^{I} O_i)/(\sum_{i=1}^{I} n_i)$, versus the alternative hypothesis:

H_1: $O_i \sim \text{Poisson}(n_i\lambda(1 + g_i\varepsilon))$

where ε is a small positive number related to the increase in risk due to exposure g_i. All residents of a census tract are assumed to experience the same exposure.

Magnetic Field

The magnetic flux density (B) in μT, simply referred to here as the magnetic field, at a horizontal distance d (m) from the track is given by

$B = 0.2\ I\ P/d^2$

where I is the current in amperes and P is the distance (m) between the catenary and the track. (The catenary-track circuit represents a linear dipole source with a simple expression for magnetic field strength.)