STATE OF CONNECTICUT

SITING COUNCIL

Re: Petition 754
2006 Revision of the Electric and Magnetic Field
Best Management Practices — March 9, 2007

COMMENT OF THE CONNECTICUT LIGHT AND POWER COMPANY
On
COMMENT OF PETER VALBERG, PhD, d. March 2, 2007

In the "Additional Note" appended to his March 2, 2007 Comment concerning the Joint Submission of CL&P/UI and The Connecticut Department of Health, and the Comments of the Attorney General with respect to that Joint Submission, Dr. Valberg refers to magnetic field levels associated with the Amtrak Northeast corridor trains. The Council may be interested to know that similar fields are associated with the operation by the State of Connecticut, Department of Transportation of the New Haven Line of Metro North Railroad. Attached hereto is an excerpt from "Health and Low-Frequency Electromagnetic Fields," by William R. Bennett, Jr., a professor of physics at Yale University, which provides detailed information with respect to the magnetic field levels associated with the Amtrak and New Haven Line trains. Dr. Bennett notes that these fields "represent the maximum widely distributed magnetic fields encountered in the common environment studied here." *Id.,* p. 646. In a ride on the New Haven Line, Dr. Bennett measured fields in the passenger compartment in which he was riding that were typically "about 40 to 60 mG throughout the trip" and "varied during acceleration from about 90 to 145 mG." *Id.*, pp. 43, 44.

Respectfully submitted,

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Health and Low-Frequency Electromagnetic Fields

William Ralph Bennett, Jr.

be seen by the application of Stokes's theorem (or from Ampere's law), the near presence of the return wire automatically reduces the magnetic field at distances from the wires that are large compared with their spacing. If the currents flowing in opposite directions in two parallel wires are equal, the line integral of the field taken around the pair is zero, because no net current is enclosed within the loop. Closer to the pair of wires, there is only partial cancellation of the field. It is of interest to examine what happens to the field near the wires in a few representative cases.

We may easily extend the single-wire solution to determine the magnetic field from two parallel wires, or any number of parallel wires, by using the principle of superposition. Because Maxwell's equations are linear, any linear combination of separate solutions to them must also be a solution. But it is the *vector* sum of the separate fields from the separate wires that concerns us here. Let us rewrite eq. (18) treating the current **I** as a vector. The magnetic flux at a point **P** from a group of n parallel wires is then given by

$$\mathbf{B} = C \sum_{i=1}^{n} (\mathbf{I}_i \times \mathbf{r}_i)/r_i^2, \tag{20}$$

where $\mathbf{r}_i = \mathbf{P} - \mathbf{W}_i$. The constant $C = 2$ mG-m/A; the vector $\mathbf{W}_i$ points to the location of the i^{th} wire; and **P** is a vector defining a particular point in space from a common origin in a plane perpendicular to the wires.

Figures 2.2 and 2.3 were computed from equation (20) for wires 2 m apart with the midpoint 10 m above the ground, carrying 500 A in opposite directions. The current and height are the same as in figure 2.1 for the single-wire example, but there is substantial cancellation of the magnetic field near the ground level in comparison with the single-wire line. The cancellation at ground level does not differ significantly between the two double-wire configurations. Power companies often use the vertical geometry with much closer spacing on the low-voltage (240/120 V), high-current distribution lines from power transformers to residential houses; the horizontal configuration is more frequently used in high-voltage, low-current lines.

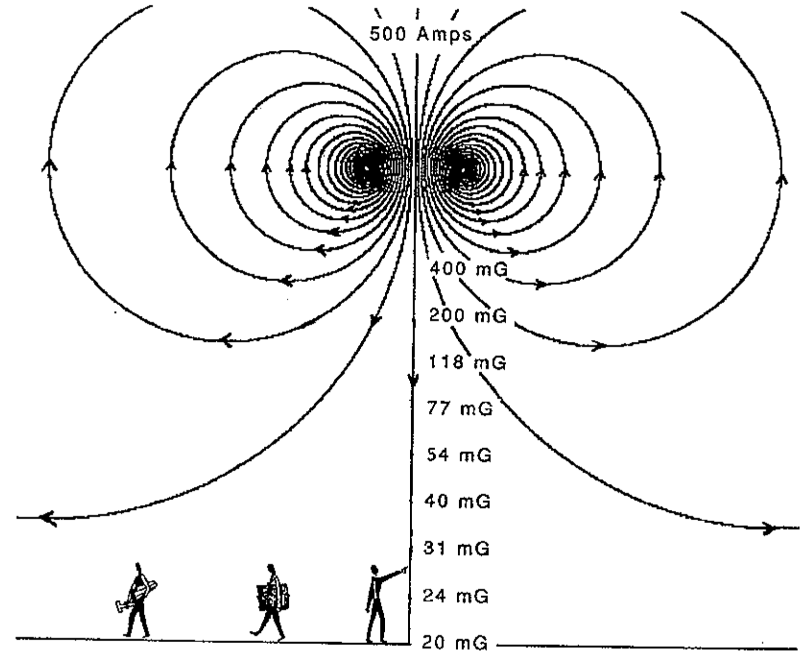

Figure 2.2. Magnetic fields from a two-wire, single-phase distribution line 10 m above ground with a horizontal spacing of 2 m. *Note:* 500 A flows into the diagram at the left and out at the right. (Two-wire single-phase lines are mainly used in rural areas or on short runs, as opposed to the more common three-phase distribution lines used in urban areas.)

From the density of the flux lines in figures 2.2 and 2.3, it is evident that the near cancellation of the magnetic field at large distances is compensated for by a large increase in the field between the two wires. In general, the smaller the separation between the two wires, the more exaggerated the difference. Although the field from a single long, straight wire falls off as $1/r$ (where r is the distance from the wire), the field from two (or more) wires carrying equal and opposite currents in both directions falls off as $1/r^2$ when the distances are large compared with the wire separation.

Magnetic Fields from Electrified Railroads

Three-wire single-phase power lines are used in electrified trains, trolley cars, and subways. Each of two parallel-current return lines (the rails,

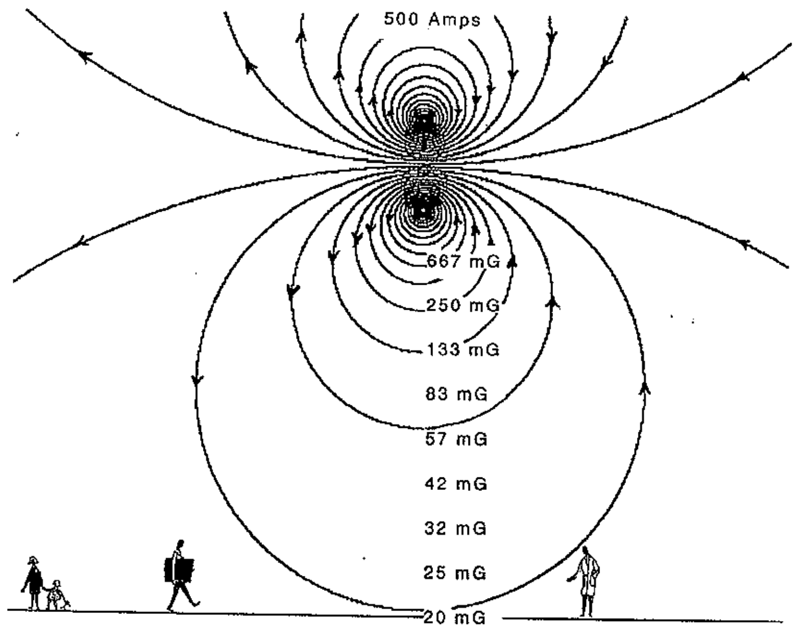

Figure 2.3. Magnetic fields from a two-wire, single-phase distribution line with a midpoint at 10 m above ground and a vertical spacing of 2 m. *Note:* 500 A flows into the diagram at the top and out at the bottom.

which are about 5 ft. [1.52 m] apart) laid at ground level carries half the current. The high-voltage feed comes either from a single overhead line or from an insulated third rail. (New York City subways and the San Francisco BART lines use DC transmission on the third rail and are excluded from this study.) At least eight railroads in the United States use 11,000-V AC power lines to supply engines with continuous ratings of 4,000–6,800 horsepower. In many instances, step-down transformers and DC rectifiers are used within the locomotive to drive DC motors. The overhead power line must supply about 300–500-A AC to run just one engine. Although 60-Hz power lines with rectification inside the engine and DC motors are commonly used today, some of the earlier lines (such as the New York, New Haven, and Hartford Railroad) formerly used a line frequency of 25 Hz to drive AC motors directly (Partridge 1967). Twenty-five Hz is still used on the Pennsylvania branch of Amtrak.

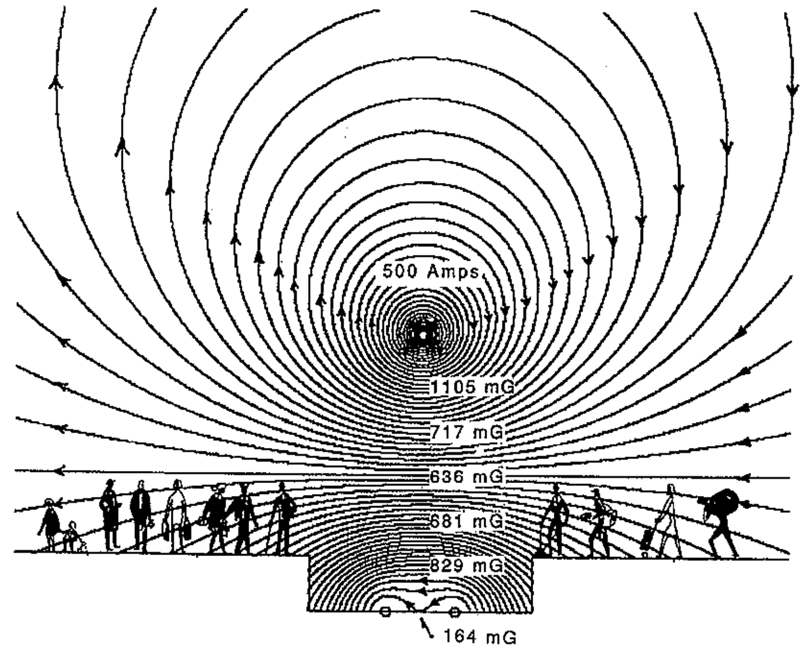

Figure 2.4. Magnetic fields from electrified trains. *Note:* 500 A flows into the diagram in the overhead wire and is returned in equal amounts by the two rails.

Figure 2.4 illustrates the magnetic-field lines produced by a 500-A current flowing in the overhead wire and being returned in equal amounts by the two rails. The rms field magnitudes are shown in table 2.2. These data correspond approximately to field measurements during maximum bursts of acceleration on the 25-Hz branch of Amtrak between Washington, D.C., and New York City. People need not be on the train to experience the field as long as they are between the power source and the engine. In this geometry, the gap between the opposing currents includes the level where people would be located, both on the station platform and inside the train. There they would be exposed to fields substantially stronger than the ones illustrated earlier. Here, the magnetic fields are of about the same magnitude as the earth's static magnetic field. Although considerable shielding from the magnetic field would result inside an iron or steel train, relatively little distortion of these fields would be expected in a train made

Table 2.2. Worst-Case RMS Magnetic Fields near an Electrified Railroad (mC)

y (m)	x (m) 0	2	4	6	8	10	20	40	60	80
6	10,164	483	213	121	77	53	15	4	2	1
5	1,105	497	232	129	81	55	15	4	2	1
4	717	471	242	135	83	56	15	4	2	1
3	636	460	245	137	84	56	15	4	2	1
2	681	483	245	135	83	56	15	4	2	1
1	829	543	237	130	81	54	15	4	2	1
0	164	556	217	121	76	52	15	4	2	1

Note: The overhead wire is ≈ 6.1 m above the track; y is the height above the track, and x is the horizontal distance from the wire. It is assumed that a current of 500 A rms flows through the overhead wire and is returned in equal amounts by the rails.

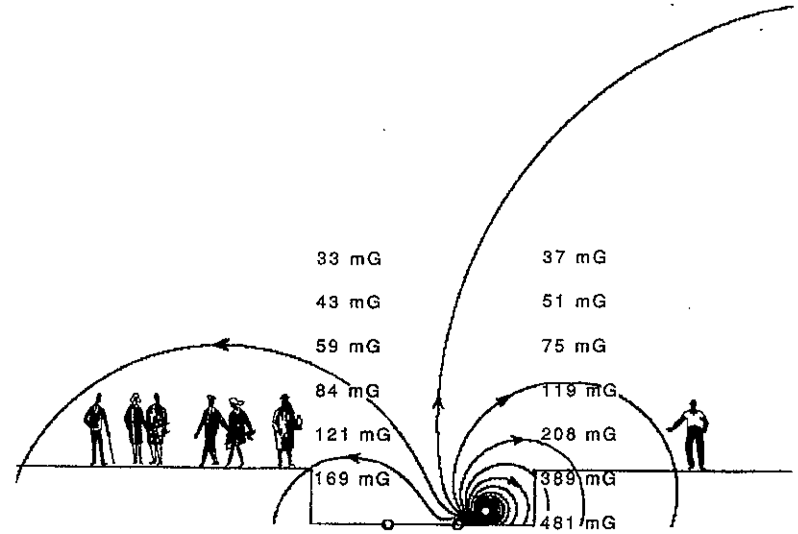

Figure 2.5. Magnetic fields from subway trains. *Note:* 500 A flows into the diagram at the right through the "third rail" and is returned in equal amounts by the two other tracks.

of nonmagnetic stainless steel or magnesium-aluminum alloys. (Flat structural sections made of regular steel at the bottom of the cars would have relatively little effect on the horizontal field lines at seat level.) In the case of metal outer walls, electrical conductivity of the wall material would result in some minor reduction of AC magnetic fields because of eddy currents induced by the Faraday effect. (These induced, opposing fields increase in proportion to the line frequency.) The metal conducting body of the train would provide quite substantial shielding from external electric fields, however.

In figure 2.5 we see a similar set of magnetic-field lines, calculated for a subway environment incorporating a "third rail" near ground level. For purposes of comparison, the fields were again computed for a 500-A current. That value of the current is unrealistic for subways in the United States, however, for they all operate on relatively low-voltage, high-current DC.

In table 2.2 we saw the rms magnetic fields that would be produced from the overhead-wire electrified train, assuming a current of 500-A rms. In

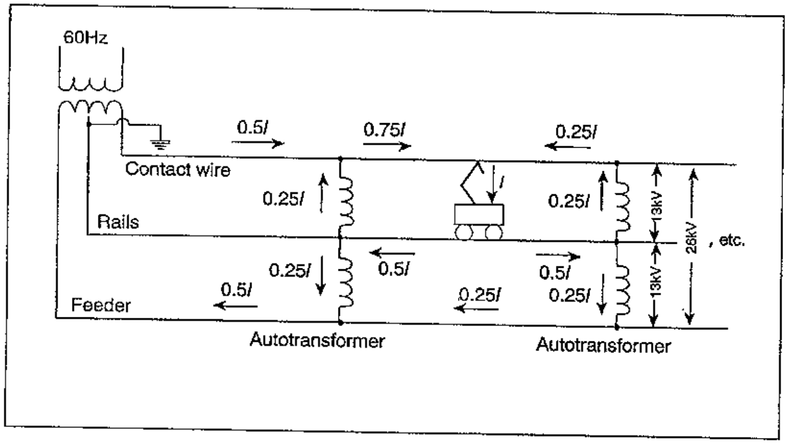

Figure 2.6 Wiring configuration for the post–1986 60-Hz New York–New Haven railroad (courtesy Metro-North commuter railroad)

this "worst-case" wiring geometry, the field does not drop off to 1 mG until about 80 m from the track. The calculation assumes that there is no significant source of magnetic shielding.

Fields from Modified Wiring on Electrified Railroads

The magnetic fields in figure 2.4 and table 2.2 are proportional to the total current in the overhead wire and represent worst-case limits for wiring configurations used earlier in the twentieth century. Some rail lines use more elaborate wiring configurations of the type shown in figure 2.6, which reduce the magnetic fields significantly. The specific system shown in the figure was adopted by the Metro-North commuter railroad in September 1986 when it converted from 25 to 60 Hz on the New York–New Haven route.[4] This lower-field configuration was partly adopted to minimize 60-Hz interference with telephone communication lines.

Single-phase 60-Hz power is supplied from a 26-kV secondary winding of a transformer that has a grounded center tap connected to the rails. One outer terminal of the secondary winding is connected to the overhead contact wire (trolley line), which is 13 kV with respect to the rails. The other outer

terminal provides an out-of-phase 13-kV supply to a feeder line mounted at the edge of the track above the trolley wire. At intervals of a few miles along the route, the feeder line provides power to the trolley wire and the rails through a series of center-tapped autotransformers. The current going to the engine connected between the trolley wire and the rails is split up into several branches.

The configuration reduces the current flowing through the rails and the contact wire by a factor of about two over the earlier wiring system assumed in figure 2.4. There is additional magnetic-field cancellation because of the current flow parallel to the track in the out-of-phase feeder line. The higher voltage supplied also permits drawing lower current for the same engine power. Table 2.3 represents the calculated field magnitudes for the wiring configuration in figure 2.6, assuming the engine power to be the same as in table 2.2.

The situation is more complicated when multiple-unit commuter trains are used. Again using the Metro-North commuter railroad as an example, one of these self-propelled nonmagnetic stainless-steel cars draws about 80 A for maximum acceleration and about 40 A for steady, rapid travel. But the current is conducted from the pantograph in opposite directions along the car and down to the rails at each end, providing further reduction of the field inside the car. Commuter trains consist of three to ten of these cars, several of which may have their pantographs connected to the trolley wire. Thus, maximum currents could reach 800 A, although typical values for travel on a commuter express are mostly below 300 A.

Spot measurements of the magnetic fields from both Metro-North commuter trains and Amtrak express trains were made on this line using a three-coil magnetometer (a Field Star 1000, made by the Dexsil Corporation). This microprocessor-controlled unit has a range from about 0.04 mG to 1,000 mG and can display the resultant magnitude from simultaneous measurements of all three field components at 1-s intervals.

In the first car of a four-car express Metro-North Metroliner from New Haven to Bridgeport, Connecticut, the fields at chest level varied during acceleration from about 90 to 145 mG, were typically in the range from

Table 2.3. RMS Magnetic Fields for the Wiring Configuration Shown in Figure 2.6 (mG)

	x (m)									
y (m)	0	2	4	6	8	10	20	40	60	80
Location a										
6	6,602	278	102	51	30	19	5	1	1	0
5	633	266	109	55	32	21	5	1	1	0
4	378	238	112	57	33	21	5	1	1	0
3	315	222	111	58	34	21	5	1	1	0
2	322	224	108	56	33	21	5	1	1	0
1	381	243	102	54	32	21	5	1	1	0
0	84	242	92	49	30	20	5	1	1	0
Location b										
6	2,342	170	97	60	40	28	8	2	1	1
5	339	181	102	63	41	28	8	2	1	1
4	254	181	106	64	42	29	8	2	1	1
3	245	186	108	65	42	29	8	2	1	1
2	277	203	109	64	41	28	8	2	1	1
1	348	235	107	61	40	27	8	2	1	1
0	60	248	100	57	38	26	8	2	1	1

Note: The overhead trolley wire was 6.1 m above the track; the out-of-phase feeder line was assumed to be directly above and 50 percent higher than the trolley wire; y is the height above the track and x is the horizontal distance away from the center of the track. The engine current was assumed to be 440 A. Location a is to the left of the engine, and location b to the right in figure 2.6. Including the two rails, currents flow in four parallel conductors.

about 40 to 60 mG throughout the trip, and went down to roughly 20 mG when the train was coasting or braking. The minimum field encountered was 1.6 mG when the train went through a steel trestle bridge. The fields on the station platform at Bridgeport during commuting hours were typically 20 to 30 mG, and from the fluxmeter readings I could easily detect an arriving train long before it was visible. (With such a meter, you don't need to put your ear on the rail!) The return trip on the third car of a six-car, very slow Metroliner local yielded much lower fields: about 30 to 90 mG during acceleration, with typical values of about 20 mG. Indeed, larger fields on the order of 50 mG were encountered within the local when express trains passed from the opposite direction. I obtained similar results on electric commuter trains between Philadelphia and Bryn Mawr, Pennsylvania, where I used a correction for the meter response at 25-Hz.

I recorded the time variation of the magnetic field at chest level at 2-s intervals while seated in the rear car of a nine-car Amtrak Metroliner pulled by an electric locomotive during an entire six-and-a-half-hour trip from Washington to New Haven. Data for the 25-Hz fields from Washington to New York are shown in figure 2.7a and those for the 60-Hz fields on the New York–New Haven leg of the trip are shown in figure 2.7b. As is evident from both figures, these trains are driven by short bursts of power during acceleration — where the peak fields are encountered — but they spend most of their time either coasting or receiving just enough power to overcome friction. The 25-Hz fields during the Washington to New York branch of the trip were the largest. There, peak fields of up to 646 mG were encountered inside the train at sporadic intervals of one or two minutes' duration, with an average value over the four-and-a-half-hour trip of 126 mG. The peak observed field agrees with the maximum calculated values shown in figure 2.4 and table 2.2. Because of the different wiring arrangement that we saw in figure 2.6, peak 60-Hz fields on the New York–New Haven run amounted to only about 300 mG, with an average value over the whole two-hour trip of about 35 mG. The peak 60-Hz field shown in figure 2.7b agrees well with the values calculated in table 2.3.

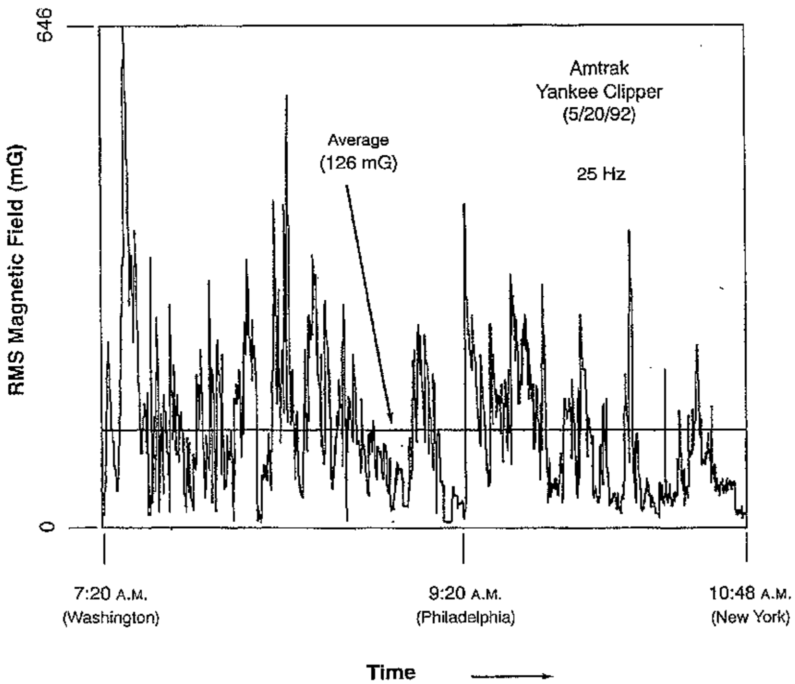

Figure 2.7a Time variation and average rms magnetic field at chest level for a person seated in the last car of a nine-car Amtrak Metroliner pulled by an electric locomotive, Washington to New York. *Note:* Measurements were made at 2-s intervals using a Dexsil Field Star 1000 three-coil magnetometer throughout the trip. (The locomotive and magnetometer batteries were changed in the New York station.)

As I shall discuss in detail later, any potential danger to health from such magnetic fields would arise primarily from electric fields induced in the body because of the Faraday effect. Such electric-field amplitudes occur in direct proportion to the frequency. Because the frequency ratio (60/25) roughly equals the field ratio between the data examined in figures 2.7a and 2.7b, there would be no significant difference in electric fields generated by the Faraday effect within the passengers on the two legs of the trip. The maximum fields in each case turn out to be smaller than thermal fields at the cell level by a factor of more than ten. These fields, however, do represent the maximum widely distributed magnetic fields encountered in the common environment studied here.

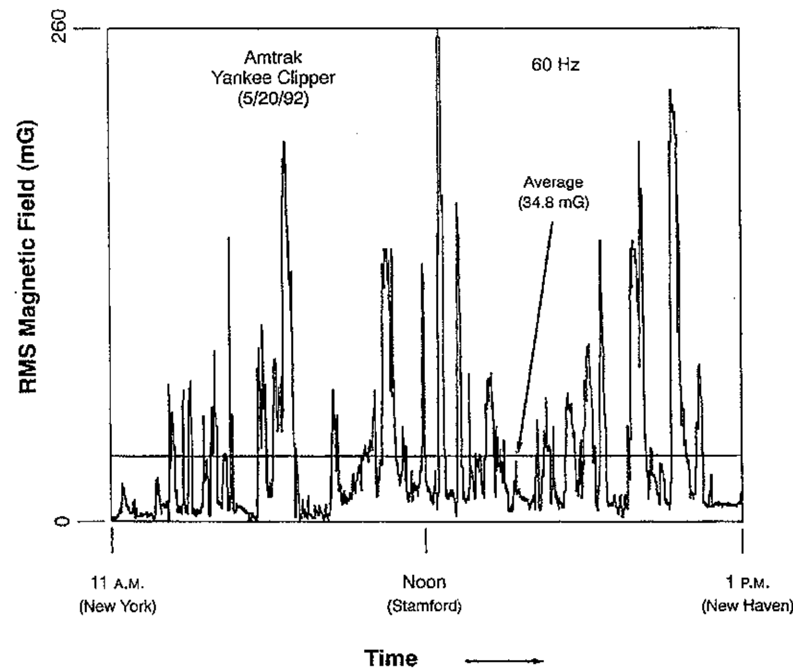

Figure 2.7b Time variation and average rms magnetic field at chest level for a person seated in the last car of a nine-car Amtrak Metroliner pulled by an electric locomotive, New York to New Haven. *Note:* Measurements were made at 2-s intervals using a Dexsil Field Star 1000 three-coil magnetometer throughout the trip. (The locomotive and magnetometer batteries were changed in the New York station.)

Magnetic Fields from Three-Phase Transmission Lines

Although a pair of wires carrying equal currents in opposite directions is commonly called a *single-phase* line, it could also be regarded as a two-phase system in which the phases differ by 180°. That distinction is useful for extending this discussion to three-phase lines.

For practical reasons — which involve the efficiency of AC generators and minimizing the loss from ohmic heating in the line — three-phase systems are generally used for long-distance power transmission (Robinson 1974, 595–597; Gönen 1988). Such three-phase systems have a minimum of three parallel wires carrying currents of the form

$$I_1 = I_{01} \cos(\omega t),\ I_2 = I_{02} \cos(\omega t + 120°),$$
$$I_3 = I_{03} \cos(\omega t + 240°). \qquad (21)$$