PB99-130908

SURVEY AND ASSESSMENT OF ELECTRIC AND MAGNETIC FIELD (EMF) PUBLIC EXPOSURE IN THE TRANSPORTATION ENVIRONMENT

Contract No. DTRS-57-96-C-00073

Prepared for:

DOT - RSPA
Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142

Prepared by:

Electric Research
P.O. Box 165
State College, PA 16804
814-238-6887

Principal Investigators:

Fred M. Dietrich
William L. Jacobs

March 1999

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

PB99-130908

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
SURVEY AND ASSESSMENT OF ELECTRIC AND MAGNETIC FIELD (EMF) PUBLIC EXPOSURE IN THE TRANSPORTATION ENVIRONMENT

5. FUNDING NUMBERS
Contract No. DTRS-57-96-C-00073

6. AUTHOR(S)
Fred M. Dietrich
William L. Jacobs

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Electric Research and Management Inc.
PO Box 165
State College, PA 16804

8. PERFORMING ORGANIZATION REPORT NUMBER
None

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Aviva Brecher
Volpe National Transportation Systems Center
RSPA DOT
Kendall Sq., Cambridge, MA 02142-1093

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
None

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the National Techical Information Service, Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This research, conducted under the support of the Federal Electric and Magnetic Field Research and Public Information Dissemination (EMF RAPID) Engineering Program, characterized the extreme-low-frequency (ELF) electric and magnetic fields (ELF) which a traveler might encounter while using various forms of transportation. Extemsive measurements of field level, frequency, temporal variability and spatial variability are reported for: conventional internal-combustion cars, trucks and buses; electric cars, trucks and buses; commuter trains; ferry boats; jetliners; airport shuttle trams; and escalators and moving sidewalks. Static magnetic field levels are also reported. Where possible, the source of the fields is identified.

This effort extends extensive past work which investigated fields in electrified trains, subways, light rail vehicles, and a magnetically levitated train by using similar protocols to characterize the complex ELF (3 Hz to 3000 Hz) electric and magnetic fields found in virtually all transportation systems.

14. SUBJECT TERMS electric field, magnetic field, electric and magnetic field, EMF, extreme-low-frequency, ELF, power-frequency, 60 Hz, electric vehicle (EV), conventional vehicle, car, truck, bus, commuter train, electrified train, ferry, boat, jetliner, etc.

15. NUMBER OF PAGES
242

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	

ACKNOWLEDGMENTS

This research effort was funded under the United States Department of Energy EMF Research and Public Information Dissemination (EMF RAPID) Engineering Research Program via transfer to the United States Department of Transportation's John A. Volpe National Transportation Systems Center. Project design and technical management were administered by Dr. Aviva Brecher, assisted by Volpe Center contracting officers.

The work discussed herein would not have been possible without the cooperation of several automobile manufacturers and transportation system operators. The authors acknowledge and thank the following automakers for access to their electric vehicles, use of their test facilities, as well as the enthusiastic participation of their engineering staff:

- Daimler Chrysler;
- Ford Motor Company;
- General Motors; and
- American Honda Motor Company, Inc.

Access to transportation facilities was provided by:

- Allegheny County Department of Aviation;
- Massport Authority;
- New Jersey Transit;
- New York Waterways;
- Paul Revere Transportation;
- Port Authority of Allegheny County;

and a domestic air carrier, which preferred to remain anonymous. The participation and assistance of those organizations and staff is acknowledged and sincerely appreciated.

The authors would also like to acknowledge the following Electric Research and Management, Inc. personnel for their assistance in performing the measurement tasks for this project:

- David W. Fugate;
- Terrance R. Whittemore; and
- Robert K. Kulp.

Table of Contents

List of Figures

List of Tables

1.0 EXECUTIVE SUMMARY

This research was conducted under support of the Federal Electric and Magnetic Field Research and Public Information Dissemination (EMF RAPID) Engineering Research Program. The goal was to characterize the electric and magnetic fields that a person might encounter while using various forms of transportation. It builds upon extensive past work to characterize the electric and magnetic field environment within electrified guided ground transportation systems such as electrified intracity trains, urban mass transit systems, and magnetically levitated trains [1], using standardized test protocols developed by Electric Research and Management, Inc. This effort focused on popular modes of transit such as personal cars and trucks, mass transit buses, commercial jetliners, ferry boats and electric-powered people movers, such as those which a traveler might use in an airport. The field environment of electric vehicles of the latest design was also closely examined. Electric-powered, self-contained commuter rail vehicles using variable frequency alternating current (ac) drive were also characterized to round out the previous work on electrified rail systems.

The measurement and data analysis procedures employed in this research effort were similar to those which proved successful in preceding transportation measurements [1], but were expanded to provide more complete coverage of the extreme low frequency (ELF) band (3 Hz to 3 kHz). An improved, free-body, electric field sensor was also added to obtain greater sensitivity and avoid perturbation of the electric field by the measuring device.

This effort demonstrated that complex (variable in time and space) ELF magnetic fields are present in every transportation system examined. The frequency and intensity characteristics of the magnetic field vary markedly between systems, at different places within each vehicle, and at different times at the same location, thus making it difficult to provide concise comparisons between transportation systems. But, if one averages the ELF magnetic field data across time, location within each vehicle, and multiple vehicles within a class, one finds the average field levels as indicated in Figure 1-1. To more fully comprehend the differences in magnetic field characteristics among transportation systems and to gauge the variability within each class of vehicles, one must examine the summary data for each transportation system reported in the body of this document. Figure 1-2 gives an expansion of Figure 1-1 showing how sub-bands of the ELF band contribute to the average field levels.

Time-varying electric fields are essentially non-existent in all of the transportation systems examined except the commuter rail system. On board that vehicle, 60 Hz electric fields from the 27.5 kV overhead catenary supply system averaged 2.3 V/m.

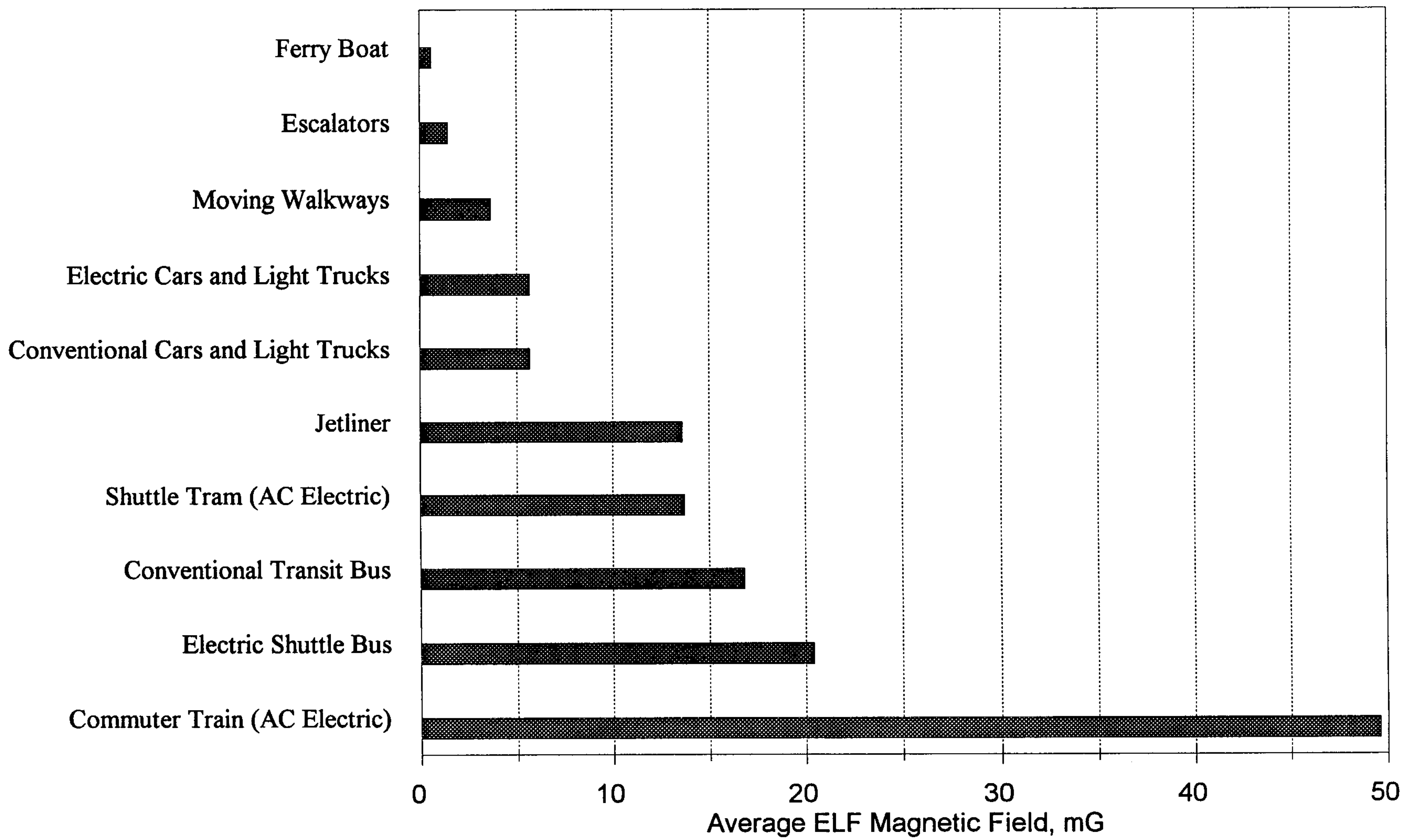


Figure 1-1 Average Extremely Low Frequency (ELF) Magnetic Field Levels Found in Ten Transportation Systems.

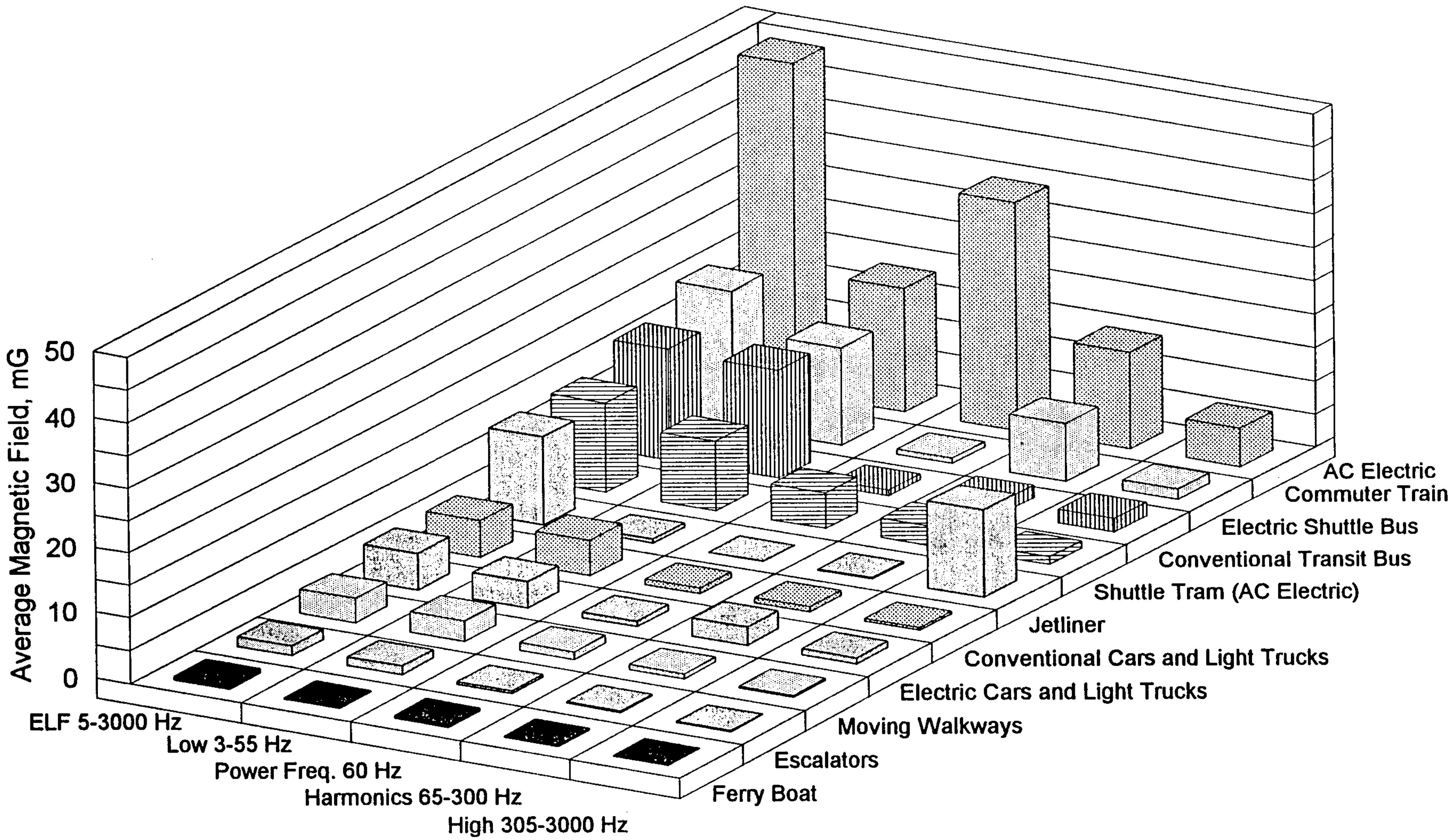


Figure 1-2 Average, Time-Varying Magnetic Field Levels in Ten Transportation Systems for Selected Frequency Bands.

ELF magnetic field levels in electrically powered vehicles using modern technology were not materially different than those in comparable systems using internal combustion power. Electric-powered personal highway vehicles (cars and light trucks) had average magnetic field levels similar to their internal combustion counterparts. Low frequency fields from similar sources are the dominant component in both types of vehicles. Magnetic field components at frequencies greater than 60 Hz are, on average, only a minor part of the total field environment in either conventional or electric cars and light trucks; however, higher frequency EMF levels are markedly higher in the electric vehicles.

The electric bus tested had similar low-frequency ELF fields to that of its diesel counterpart, but also had a significant (8.9 mG average) field in a higher frequency range which was well in excess of that in the diesel bus. As a result, the average ELF field in the electric bus was about 21% higher than that in the conventional bus.

The average ELF magnetic field levels in the self-powered ac-drive commuter rail vehicles was well in excess of that seen in smaller and lighter electric-powered vehicles. While the propulsion equipment under these cars contributed to the field levels within the vehicles, the total average field (49.6 mG) was well within the range of average magnetic field levels previously measured in coaches of conventional electrified railroads (19 to 134 mG) [1] where the traction power equipment was only in the locomotives.

2.0 OVERVIEW

2.1 Introduction

Over the past two decades there has been growing public concern that low level electric and magnetic fields (EMF) may represent a public health concern. Much of the public attention has focused on fields from electric powerlines. Powerline fields occur primarily at the power frequency (60 Hz in North America or 50 Hz in many other countries), and smaller fields also occur at harmonics or integer multiples of the power frequency (120 Hz, 180 Hz, etc.). Much attention has focused on all fields in the extremely low frequency (ELF) band of fields at frequencies between 3 Hz and 3000 Hz.

In response to mounting public concern, the federal government initiated a multi-year research effort to research the possible health implications of ELF field exposure, identify and characterize sources of public exposure, and provide objective information to congress and the public regarding actual levels of risk. That federal effort is known as the Electric and Magnetic Field Research and Public Information Dissemination (EMF RAPID) Program.

Federal statistics [2] indicate that in 1996, the most recent year for which data is available, approximately 176 million cars and light trucks were registered in the United States. Americans used those vehicles to travel 3.6 trillion passenger miles. Assuming average speeds appropriate for the roadway classes for which data are reported, Americans appear to spend approximately 100 billion hours per year in their cars and light trucks. With a United States population of 270 million people, the time spent in cars, vans, and pickup trucks averages 370 hours per year or roughly one hour per day.

Because of the ubiquity of motor vehicle use in America and the significant portion of the day that the average American spends in a car or light truck, field exposure during those times can materially contribute to one's overall magnetic field exposure.

At the present time, electric vehicles have not significantly penetrated the personal vehicle market. Should they do so in the future, they could represent an important source of human exposure to electric and magnetic fields. The ELF field environment of today's market-ready electric vehicles has not been previously characterized.

Many Americans spend significant portions of their time commuting by transit systems other than automobile and light truck. In 1996, Americans traveled 19 billion miles [3] by motor bus. While that does not average much time over the population as a whole, it is significant for those who use that system. The average bus trip is

18 minutes [3] so the commuter who travels by bus twice a day accumulates an average 36 minutes on that system. Transit time spent on other systems is even longer. The average one-way trip on a commuter rail system is 43 minutes [3]. Ferry boat trips average 55 minutes [3] each.

The research reported in this document was funded under the EMF RAPID Engineering Research Program to investigate and characterize the ELF electric and magnetic fields encountered in transportation systems. Previous Electric Research and Management, Inc. (hereafter referred to as Electric Research) work for DOT/FRA focused on conventional and emerging electric-powered rail systems such as inter-city trains, subways, light rail transit systems, and a prototype magnetically levitated train [1]. This work was intended to extend that effort to a broader range of commonly used transportation systems and to examine emerging transportation technologies such as electric vehicles (EVs).

Systems examined in this effort included the following:

Conventional Vehicles

- Cars
- Pickup Trucks
- Vans
- Diesel Mass Transit Buses
- Commercial Aircraft
- Ferry Boats
- People Movers including Shuttle Trains, Escalators, and Moving Sidewalks at Airports

Vehicles Employing Emerging Electric Technology

- Electric Cars
- Electric Vans
- Electric Pickup Trucks
- Electric Buses
- Commuter Rail Vehicles with AC Drive

2.2 Report Organization

This overview section provides a brief introduction to the motivation for the research effort and a discussion of general methods of data acquisition and analysis applied to all of the transportation systems examined.

Chapters 3 through 9 focus on specific transportation systems. Each chapter briefly describes the transportation hardware and the specific measurement procedures employed in that system. Summary data are presented and discussed focusing upon such characteristics as field intensities, frequency spectra, and temporal and spatial variability. Comments about the sources of the observed fields are also offered where that information is known or can be deduced from the field data.

The final chapter provides comparisons of average field levels measured in different transportation systems. Because of the complexity of the fields within many transportation systems, comparisons based on average intensity alone does not provide a complete comparison of possibly important field parameters. The reader is encouraged to refer to the individual chapters for a more complete comparison of the field environments in different systems.

2.3 Approach and Methods

The magnetic fields produced by the power system in North America consist primarily of a 60 Hz frequency component and, to a lesser extent, components at harmonics of 60 Hz. These discrete harmonic frequencies are small in number and have little temporal variability beyond that of the fundamental frequency. Furthermore, the relative intensity of the field components at these harmonic frequencies are not highly spatially dependent and the relative spatial distribution is not time dependent. Consequently, rather simplistic two-dimensional analysis is sufficient to document most interactions between time, frequency, intensity, and spatial factors for powerline magnetic fields.

Extreme Low Frequency (ELF) magnetic fields produced by transportation vehicles are far more complex than those produced by powerlines; therefore, analysis and presentation methods used for powerline magnetic fields are inappropriate. The most significant complications arise from the following characteristics of transportation systems.

> **Multiple Sources:** The magnetic fields inside or in the vicinity of a transportation vehicle arise from multiple sources both within and external to the vehicle, hence spatial distributions cannot be expressed as simple attenuation curves which are temporally stable.
>
> **Continuous Frequency Distribution:** The time varying component of the magnetic field that is produced by multiple sources within motorized vehicles often does not exhibit a discrete and temporally stable frequency distribution. Consequently, field intensities in various bands of finite width rather than fields at specific frequencies must be addressed.

In order to accommodate these characteristics, a data collection analysis, and reported procedure for complex magnetic fields was used. This procedure was initially developed by Electric Research for use in reporting on magnetic field testing in high speed magnetic levitation transportation systems [1].

2.3.1 Instrumentation

To adequately capture the wide range of magnetic field conditions in the ELF frequency band, all magnetic field measurements were made using triaxial fluxgate magnetometers (Bartington Model MAG 03). These instruments respond to fields from 0 to 8 kHz. Electric field measurements were made with a single-axis free body (fiber optically isolated) sensor (Electric Research Model MW2EFL01) having a frequency response from 3 Hz to 3 kHz.

Analog signals from the field sensors were recorded using *MultiWave®* digital waveform recorders (Electric Research). These recorders digitized the individual field waveforms from the sensors at a sufficient rate and for a sufficient duration to faithfully record fields over the frequency range from 0 to 3000 Hz and resolve the frequency content of those fields to a resolution of 5 Hz. Two versions of the *MultiWave®* recorder were used. For those tests which required no more than three simultaneous three-axis magnetic field and one electric field measurement, the *MultiWave®* System II (Model MW2SYS02) recorders were used. Tests in conventional and electric vehicles were conducted using a special *MultiWave®* recorder built for previous transportation measurements, which is capable of recording three-axis magnetic fields at 12 locations in addition to the electric field.

2.3.2 Data Sampling

Since it is impractical to record and analyze continuous analog data from a large number of sensors within the cabins of transportation vehicles it was necessary to sample the field conditions at discrete points in time and space.

Spatial sampling was accomplished by deploying field sensors at locations which are well defined in terms of the traveler's body. To accomplish that goal, plastic sensor holders were built which could be easily placed in a passenger seat. The plastic holders are sized to represent an average American adult and are articulated at locations representing the neck, hips, and knees. Hence, when the sensor is placed in a seat, it assumes the position of a passenger with its "feet" on the floor and "head" erect. Figure 2-1 shows a photograph of the sensor holder mannequins in the front seat of a compact pickup truck. Fluxgate magnetometers are mounted in the mannequin at points

Figure 2-1 Electric and Magnetic Field Sensors Held by the Plastic Sensor Holders in the Front Seat of an Electric Vehicle.

representing the head, waist, and ankle of the seated passenger. Figure 2-2 shows the orientation of the magnetometers.

Electric field measurements were made at a position representing the passenger's chest along an axis normal to the chest.

Sensor holder mannequins were placed in the principal passenger seats of the vehicle under investigation. In a six passenger car, for example, two front and two rear seats were instrumented as illustrated in Figure 2-3. In many tests, the vehicle required a driver; therefore, a sensor mannequin could not be placed in the driver's seat. In those cases, the magnetometers were attached to a hat worn by the driver, strapped to his waist at the normal belt buckle locations, and strapped to his right ankle. In vehicles which accommodate many passengers, a limited number of seats spatially distributed throughout the vehicle were selected for sampling.

Temporal sampling of the analog field data was accomplished by digitally recording a "snapshot" of the analog field waveforms every 10 to 15 seconds. All sensors at a seat position were sampled simultaneously to ensure no confusion between temporal and spatial variability. Each snapshot was of 0.2 or 0.33 second duration, thereby permitting resolution of field frequencies in increments of .5 or 3 Hz, respectively. An attempt was made to capture on the order of 100 field samples per test condition to provide a reliable statistical description of the field variability over time. That was not possible on some systems such as the electric bus and commuter train which made frequent stops. In those cases, recordings continued from one station stop to the next to capture a full range of operating conditions.

2.3.3 Data Analysis

Each digitized electric and magnetic field waveform snapshot documents the frequency and amplitude characteristics of the field in a particular direction, at a particular location, at a particular time. The data analysis employed in this project seeks to preserve the maximum amount of information about amplitude and frequency as well as the temporal and spatial variability of those field parameters. Orthogonal magnetic field recordings at each location contain information about the spatial orientation of the magnetic field, but analysis of that parameter was beyond the scope of this project.

Each field waveform recording contains information about the amplitude of the field as a function of time. Those waveforms demonstrate, by their complexity, that the frequency characteristics of the ELF fields produced by transportation vehicles are quite different than the frequency characteristics of

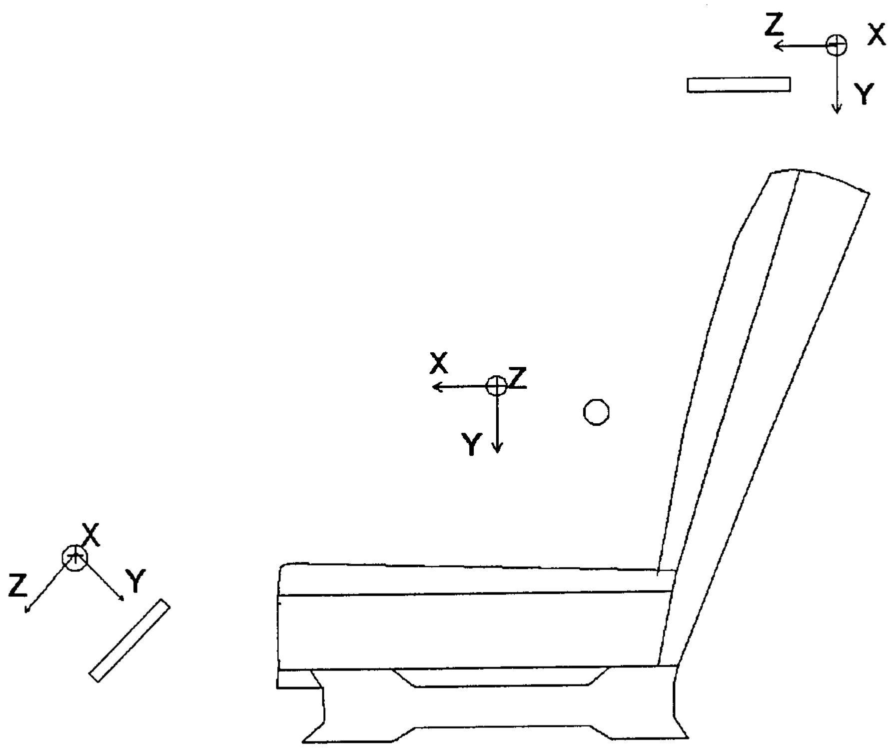


Figure 2-2 Location and Orientation of Sensors on a Single Seated Passenger.

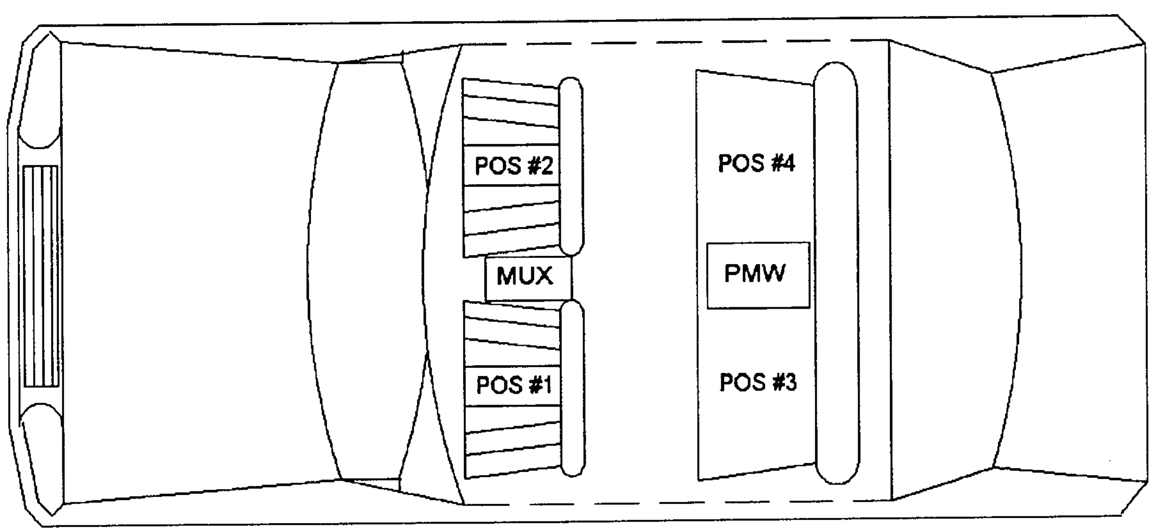


Figure 2-3 Passenger Positions for the In-Vehicle Measurements of the Six-Passenger Cars.

the ELF fields produced by most other environmentally relevant sources. Hence, it is important that the data analysis and presentation method applied to the data does not obscure this potentially important frequency information. Therefore, it was decided that the most comprehensive presentation of the repetitive waveform data collected at each measurement location would be a pseudo-three-dimensional plot of the magnetic flux density as a function of frequency and time. Electric fields related to the transportation system were only detected on the commuter train. Those fields were sinusoidal and, therefore, did not require as complex of an analysis.

To produce plots of field versus frequency and time, each time domain waveform sample has been converted to the frequency domain by computing the Fourier Transform using the Fast Fourier Transform (FFT) capability of the *MultiWave*® analysis software package. Each of the orthogonal components was converted separately and the total rms value of the flux density at each frequency was then computed by the root-sum-square of the three orthogonal rms values at the same frequency. The pseudo-three-dimensional graphs showing the effect of time on flux density and frequency were constructed by placing frequency spectra information derived from successive repetitive waveform samples behind one another.

Figure 2-4 shows an example of a pseudo-three-dimensional plot. Note that in the figure, the flux density is represented as a surface above the plane of the time and frequency variables. For data collected from the fluxgate sensors, the ac frequency range spans from 2.5 Hz to 3002.5 Hz and the time spans the duration of the measurement period. The plot in the figure only displays frequency components up to 1000 Hz. This is because there were no field components above approximately 950 Hz . The three-dimensional graph was simply redrawn focusing on the lower frequencies and showing the major field components in more detail than would be available if the graph had been drawn displaying frequencies up to 3 kHz.

The three-dimensional analysis of field dependency upon frequency and time presents the available data in the most comprehensive yet concise form available. However, further reductions in the complexity of the data are necessary in order to progress with the spatial, temporal and statistical analysis of the repetitive waveform data. One obvious approach is to collapse the data across the frequency domain and do an analysis of "total ELF magnetic field". However, in doing so, one completely obliterates the frequency information. Another approach is to collapse the data across the time axis by computing mean values in each frequency band. That approach not only sacrifices the information on temporal variability, but it also adulterates the frequency by washing out peaks in the individual frequency spectra which vary from

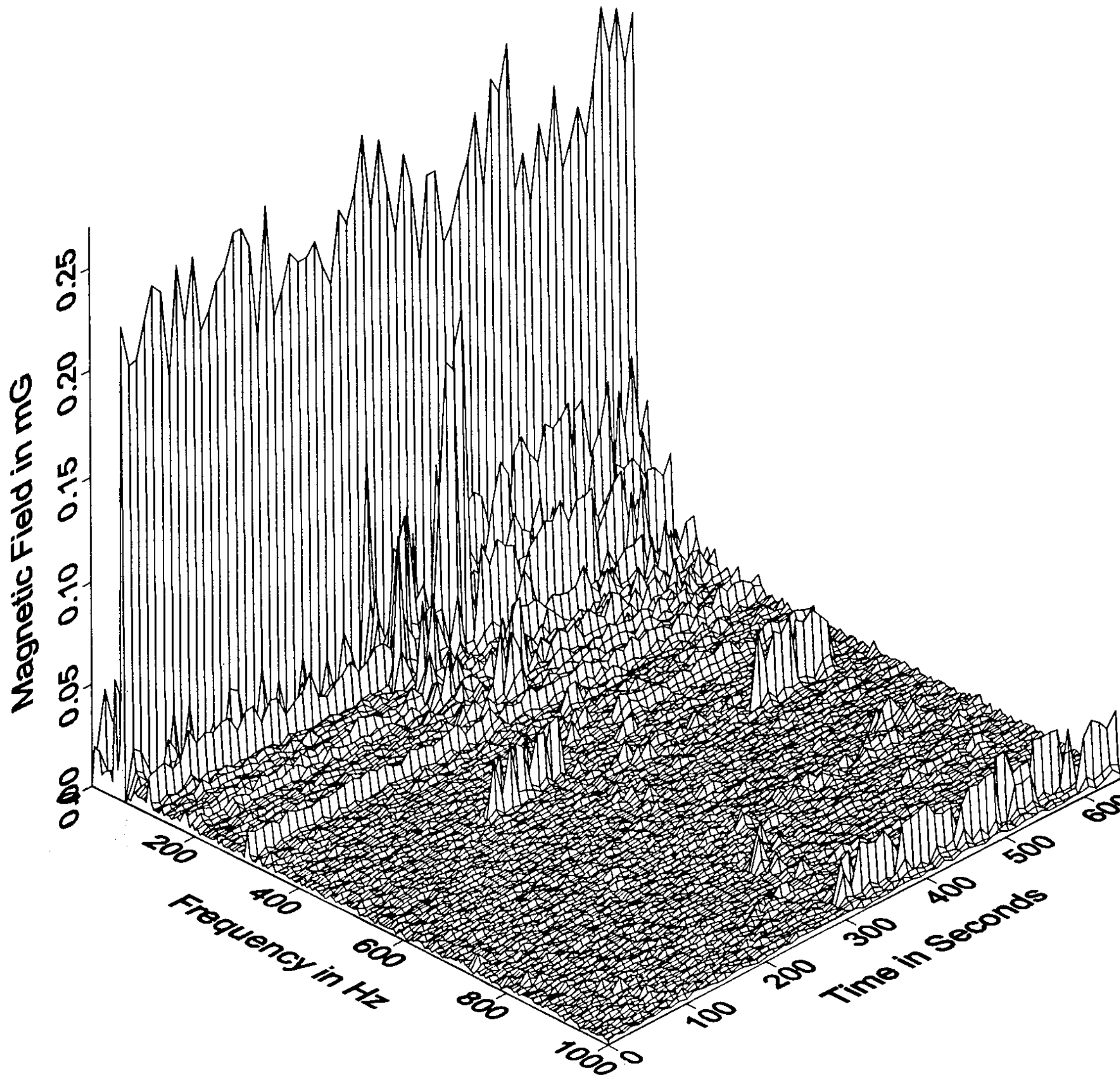


Figure 2-4 Example of a Pseudo-Three-Dimensional Plot Showing Field Level vs. Frequency and Time.

frequency to frequency over time. It was concluded that the essential features of these data could best be preserved by collapsing the data across the frequency domain but rather than producing just one value for total field strength, several values are produced that are indicative of the total field within specific ranges of frequency. In this way, some measure of the frequency characteristics are preserved and numerical values are produced which can be compared to magnetic field levels from other sources having similar ranges of frequency.

The frequency ranges selected for the further analysis are as follows:

Static: This is the component of the magnetic field measured by the fluxgate sensor which did not vary in intensity or orientation over the time of the waveform snapshot.

Low Sub-Power Frequencies: This quantity represents the total ac field in frequencies below the frequency used for electric power systems in North America. The range of FFT components included is from 5 Hz to 55 Hz, but the actual bandwidth is from 2.5 Hz to 57.5 Hz.

Power Frequencies: This is the strength of the 60 Hz component of the magnetic field produced by the electric power system in North America. The actual bandwidth is from 57.5 Hz to 62.5 Hz.

Power Frequency Harmonics: This band which extends from 62.5 Hz to 302.5 Hz includes the first few harmonics above the power frequency. This range also includes many of the components created by the various sources within the vehicles. The range of components combined to obtain this quantity is from 65 Hz to 300 Hz.

High ELF Frequencies: This quantity represents the magnetic field components in the upper part of the frequency range measured, from 302.5 Hz to 3002.5 Hz. This is the range of frequencies where power systems do not produce any significant magnetic fields. By examining the FFT components from 305 Hz to 3000 Hz, those small fields can be quantified accurately without being obscured by the larger fields present at lower frequencies.

All ELF Frequencies: This value is the total time varying field measured with the fluxgate sensors. For digital frequency analysis purposes, the bandwidth is 2.5 Hz to 3002.5 Hz. Since each FFT component of the data from the probes represents the energy within a 5 Hz bandwidth, the band center frequencies for this total ac field band are from 5 Hz to 3000 Hz.

Internal ELF Frequencies: This category is sometimes used to identify the total time varying field produced by the vehicle when there is a significant 60 Hz ambient field present from other sources. It covers the same frequency range as the total ac field, with the 60 Hz component removed.

The final step of the analysis and compression of the repetitive waveform data involved computing mean values of the magnetic flux density in each frequency band at each measurement location. Standard deviations and coefficients of variation for the flux density were also computed. This process produces "single number" measures of the strength of the magnetic field at the cost of losing virtually all of the time and frequency characteristics of the magnetic field.

The Fourier Transform is commonly used to convert data from the time domain to the frequency domain as has been done in the analysis reported herein. For the transform to be perfectly valid, it is required that the time domain waveform be periodic and that the data in the time domain represent exactly an integer number of periods. In practice this condition is rarely met and can not be met with transportation magnetic field data which is inherently nonperiodic. As a result of this condition, various frequency spectra are sometimes blurred through a phenomena known as "leakage". Some of the energy that belongs in a specific frequency bin is smeared to adjacent bins. A related situation exists when the period of the underlying fluctuation is longer than the waveform record, in this case 0.2 s. That would occur from field components having frequencies well less than 5 Hz. Although those fields properly belong in the 0 Hz frequency band (0 to 2.5 Hz), some of the energy leaks into the higher frequency bins. Producing an apparent frequency spectrum with exponentially decreasing intensity as frequency increases. This situation occurs often in the measurement of magnetic fields in the transportation environment due to the vehicle traveling through regions of inhomogeneous geomagnetic field. Although not precisely accurate, these components are preserved in the analysis as indicative of time-varying field activity in the transition region between static fields and 5 Hz fields.

2.4 Data Archiving

A vast amount of magnetic field waveform data was collected during this project. Within the constraints of this report, only an overview and summary analysis can be presented. It is recognized that others may wish to extract from the data more specific details about certain ELF field characteristics in particular transportation systems. To archive the data and facilitate its availability to other investigators, as much of the raw and partially processed data as practical will be submitted to the National EMF Database.

The EMF Measurements Database for the RAPID Program (NIEHS and DOE) is administered by T. Dan Bracken, Inc., and can be contacted by writing to:

EMF Measurement Database
T. Dan Bracken, Inc.
5415 S.E. Milwaukie Ave., Suite 4
Portland, Oregon 97202

You may also contact the Database by telephone at (503) 233-2181, by e-mail at info@emf-data.org, or by visiting the web site at URL: http://www.emf-data.org. The RAPID Program URL is: http://www.niehs.nih.gov/emfrapid/.

3.0 CONVENTIONAL CARS, TRUCKS, AND BUSES

Cars, light trucks, and buses powered by internal combustion engines are ubiquitous in American society. Most people spend more time in those vehicles than any other transportation system. Even though internal combustion vehicles are not considered likely sources of electric or magnetic field exposure, their heavy use justifies investigation of their field environments. Moreover, field levels in a universally accepted transportation system such as conventional highway vehicles can serve as a rational baseline against which to compare the fields of other systems. This chapter only summarizes the measurements in conventional vehicles. The measurement procedures and results have been previously reported in greater detail [4].

3.1 Conventional Vehicle Characteristics

In an effort to characterize personal passenger and mass transit vehicles, four personal passenger vehicles and one mass transit bus were chosen for testing. The vehicles chosen included a 1993 six-passenger car, a 1997 six-passenger car, a 1997 minivan, a 1996 pickup truck, and a 1996 mass transportation bus. All tested vehicles were produced by domestic manufacturers. The particular personal passenger vehicles used in the study were chosen to best represent the broad range of personal passenger vehicles that are available in today's market. The bus used in the study was typical of late model buses used in public mass transportation systems in this country.

3.2 Test Conditions

Before any road test data was collected, a pretest was performed on each vehicle. The pretest involved fitting the vehicle with the instrumentation and parking it in an area with known low background magnetic fields. While recording data in this area, the vehicle was placed in a number of different states. These states included: everything off, headlights on, audio system on, ventilation system on, engine on, among others. The pretest data was recorded for the purpose of characterizing the effects of the electric and magnetic fields within the vehicle without regard to the motion of the vehicle or to the environment in which it was traveling. It also enabled the investigators to identify some of the sources of fields within the vehicle itself.

In the pretest, field measurements were made in as many seat positions in each vehicle as was practical. For the cars, four seat positions were monitored. For the minivan, six seat positions were used. For the pickup, sensors were placed in two seat positions. For the mass transit bus, measurements were made in eight seat positions, four in the front half and four in the rear half. At each seat position, repetitive three-axis magnetic field waveform measurements were made at positions representing the head, waist, and ankles of a seated passenger. Single-axis, electric-field waveform measurements were made at a position representing the chest of the front seat passenger in the personal vehicles and at the chest position of two passenger seats in the bus.

When trying to characterize the EMF environment experienced by passengers in these types of vehicles, it is necessary to consider the environment through which the vehicle travels. There are two reasons for such consideration. First, the environment itself contains many sources of electric and magnetic fields. Second, the vehicles themselves may exhibit different field characteristics during travel in different environments, due to such factors as vehicle speed, engine speed, direction of travel, and use of accessories.

In order to accurately characterize the environment, nine road types were defined. The road types include: rural roads, rural secondary roads, suburban roads, suburban residential roads, arterial highways, urban streets, interstate spurs into the city (beltways), commercial roads, and interstates and turnpikes outside of the city. These road types differ in such factors as speed limits, number of lanes, type and density of building structures in the surrounding area, and type and density of external field sources.

A road test course was selected in and around Pittsburgh, Pennsylvania. The physically compact nature of the city with its clearly delineated urban, industrial, suburban, and close-in rural areas facilitated the selection of a course which incorporated all of the desired road types, yet was not prohibitively long.

Electric and magnetic field waveform measurements were made every ten seconds while driving the course. This design produced approximately 100 field samples at the seat and body positions described above while driving on each type of road. Limitations on available instrumentation prevented monitoring more than four seats at a time so the minivan and bus were run twice around the course to collect data at 6 and 8 seat locations, respectively. Driving the minivan around the course twice to monitor a total of 6 seats permitted measurements of fields in 2 of the seats during both circuits of the course. Those data were examined to verify the repeatability of the testing procedures.

3.3 Magnetic Field Characteristics

This section summarizes the key findings regarding magnetic field characteristics recorded in the conventional vehicles. Readers interested in more detail about the field characteristics are referred to an earlier data report [4] and the EMF RAPID Database [5].

3.3.1 Car 1

Car 1 is a 1993 model year, six-passenger sedan with front wheel drive. Stationary pretest measurements in this vehicle revealed three significant magnetic field sources in the front of the vehicle. Time-varying field levels measured at the driver's ankle during the pretest are plotted in Figure 3-1. Table 3-1 identifies the state of the vehicle accessories and engine at various times during the pretest. Data from this location is not representative of field levels elsewhere in the car, but is selected because it shows the field characteristics of two localized sources near this measurement location. The left-hand frame of Figure 3-1 shows no significant time-varying fields present in Car 1 before 100 seconds, except the ambient 60 Hz field at the test site. That ambient field is removed in the right-hand frame to facilitate evaluation of the vehicle fields. As indicated in Table 3-1, the pretest protocol called for turning on the headlights first between 100 seconds and 150 seconds, again between 250 seconds and 299 seconds, between 350 and 399 seconds for a third time, and finally between 550 and 599 seconds. Figure 3-1 shows the presence of a magnetic field of approximately 63 Hz and harmonics thereof each time the headlights are on. The source of the field was determined to be a headlight control behind the dashboard above the driver's ankles.

Another weaker field component of about 580 Hz appears in Figure 3-1 at 300 seconds and continues to the end of the data record. As indicated in Table 3-1, that is the time when the engine is running. The speed of the engine changed at 400 seconds on the graph but the frequency of the field did not change. Though not identified, the source is clearly not the ignition system or rotating magnetized engine parts and is only present when the engine is running.

Figure 3-2 shows the magnetic field levels measured at the head of the right rear passenger during the pretest. This is the most distant measurement point from the magnetic field sources identified at the front of the car. It can be compared with Figure 3-1 to bracket the range of field levels measured at all of the other locations in Car 1 during the pretest. In this figure, removal of the ambient 60 Hz field was even more important to see the weak fields of the vehicle. (The weak ambient power harmonic fields present at the test site, principally 180 Hz and 300 Hz, have not been removed from the data in the right-hand frame and should be ignored in the following discussion.) Observing the right-hand frame, one sees that the fields from the headlight control are still discernable as is the field at 580 Hz associated with the engine. One also sees

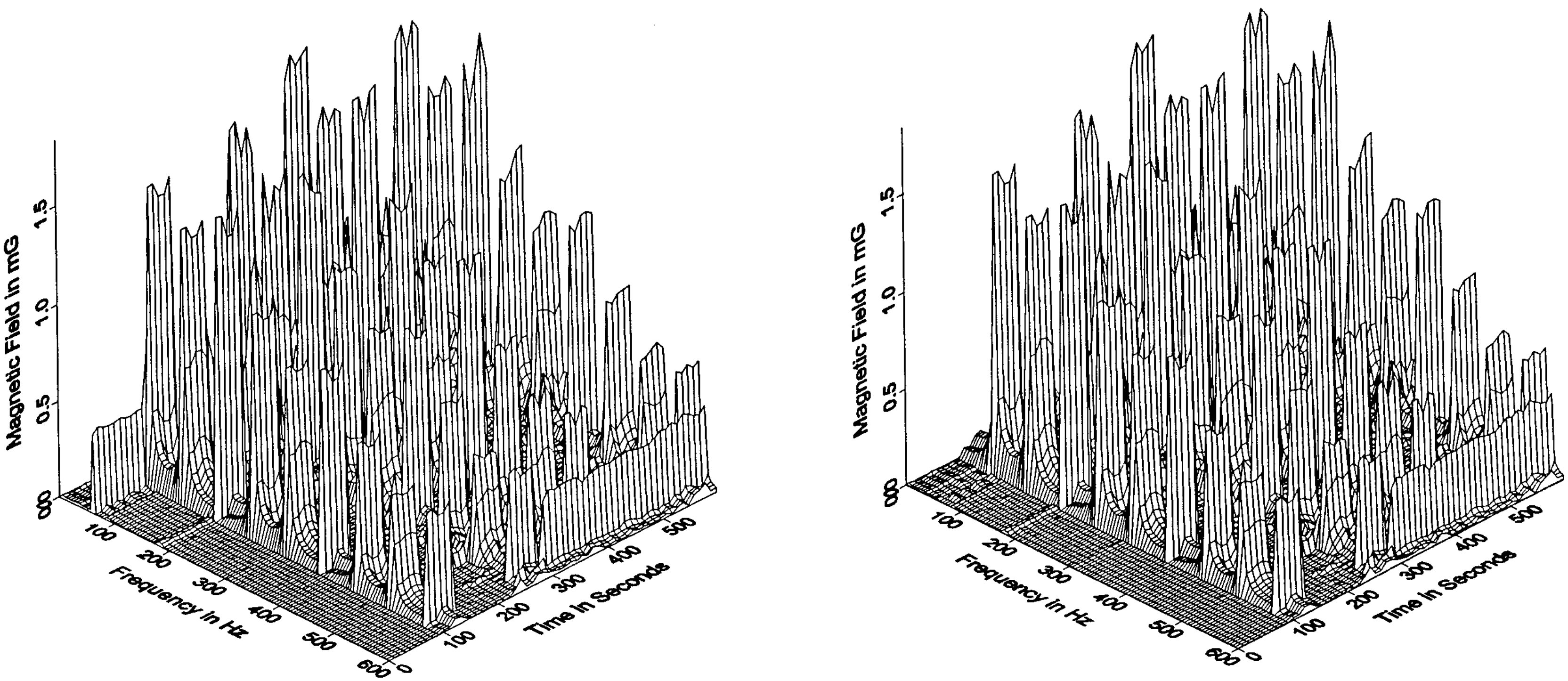


Figure 3-1 **Example of Pretest Magnetic Field Data Recorded in Car 1 from the Sensor Mounted on the Driver's Ankle. The Plot on the Left Shows Raw Data. The Plot on the Right Shows the Same Data after the 60 Hz Ambient Field has been Removed.**

Table 3-1
State of Vehicle Engine and Accessories at Various Times During the Pretest

Time (Seconds)	State
0-49	All Off
50-99	Electrical System
100-149	Headlights
150-199	Audio System
200-249	Heater, Fans
250-299	All Accessories
300-349	Engine at Idle
350-399	Engine, Headlights
400-449	Engine at 2000 RPM
450-499	Engine, Audio System
500-549	Engine, Heater, Fans
550-599	Engine, All Accessories

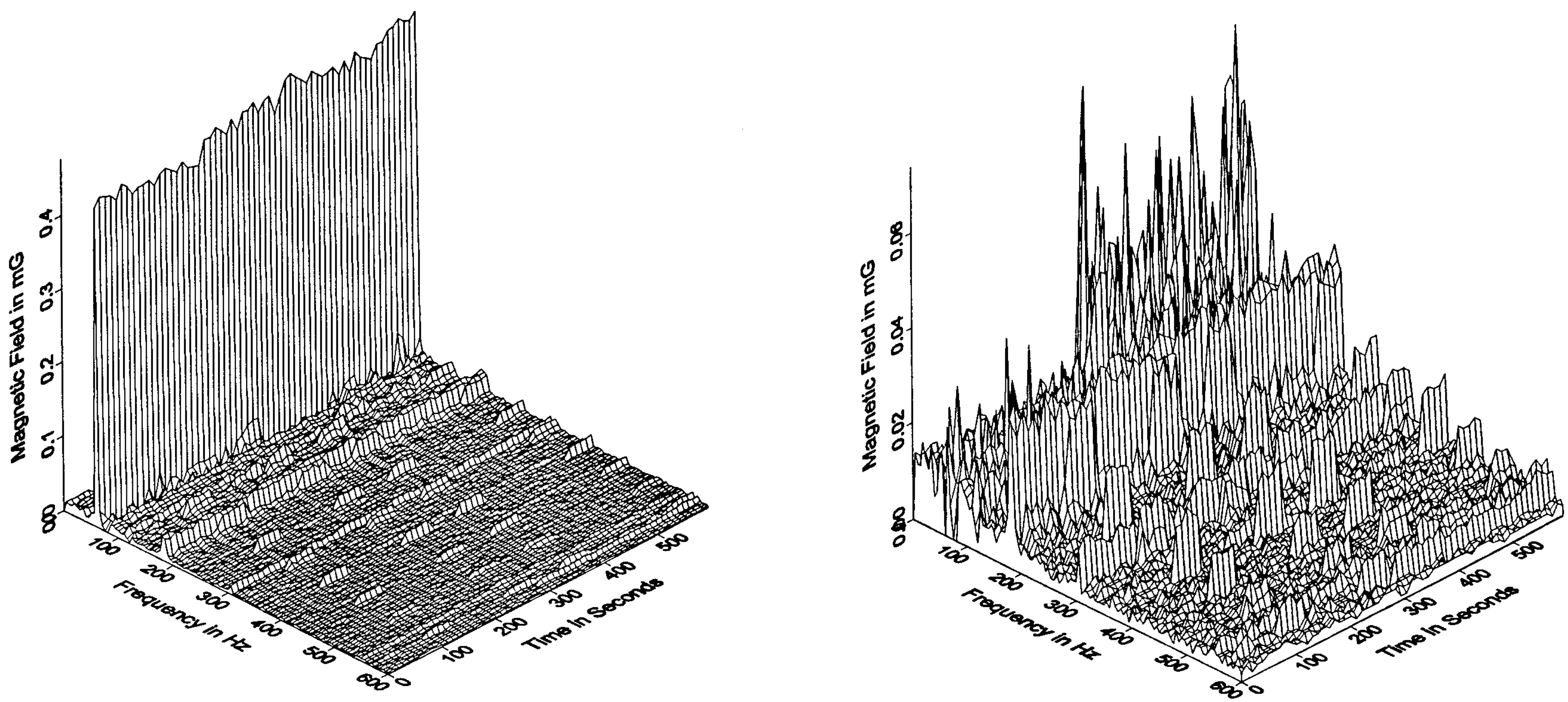


Figure 3-2 Example of Pretest Magnetic Field Data Recorded in Car 1 from the Sensor Mounted to the Head of the Right Rear Passenger. The Plot on the Left Shows Raw Data. The Plot on the Right Shows the Same Data after Removal of the 60 Hz External Component.

the presence of low frequency field components of differing frequency and intensity which begin at 300 Hz when the engine is started. (Those fields are also present in Figure 3-1, but obscured by the larger fields from the near by headlight control.) These low frequency fields appear to arise from the rotation or other movement of steel engine or other parts which have a small amount of residual magnetism. The apparent chaotic behavior is the result of interaction of field components from multiple sources. Movement of magnetized engine parts represent the third main field source within this vehicle when stationary.

Magnetic field waveform data was collected at 10 second intervals throughout the road tests. Figure 3-3 shows data measured at the front seat passenger's ankle while driving on suburban and suburban residential roads. In this and other conventional vehicles, the headlights, radio, and fan were on through the road tests.

Fields from the sources observed during the pretest are still present throughout the time depicted in this graph, but small due to the distance from the highly localized sources near the driver's ankle. They appear as ridges running across the graph at fixed frequencies, but the influence of four other important field sources is apparent.

The predominant field components throughout much of the time period illustrated in Figure 3-3 are low frequency components at frequencies well less than 60 Hz. Although these fields have the same characteristics as those produced by rotating magnetic engine components observed in the pretest, their magnitudes are larger and clearly related to motion of the vehicle. Investigation revealed that these fields arise from rotation of magnetized drive train parts, principally magnetized steel belts in radial-ply tires.

A second prominent field characteristic in Figure 3-3 is high peaked fields occurring at approximately 80 seconds into the record. These fields, characterized by high intensity at only one sample point and frequency spectra having exponentially decreasing intensity with increasing frequency, result from the automobile passing through a region where the geomagnetic field is highly perturbed. From the frame of reference of a passenger in the car, that condition represents a time-varying field. Each instant, the field is different because the car is in a different place where the perturbed geomagnetic field is different. The larger the spatial gradient in the geomagnetic field or the more rapidly the vehicle passes through it, the bigger the transient ELF field. Some of the largest transient fields observed in these tests were associated with entering or exiting bridges with steel beams or truss but smaller ones were

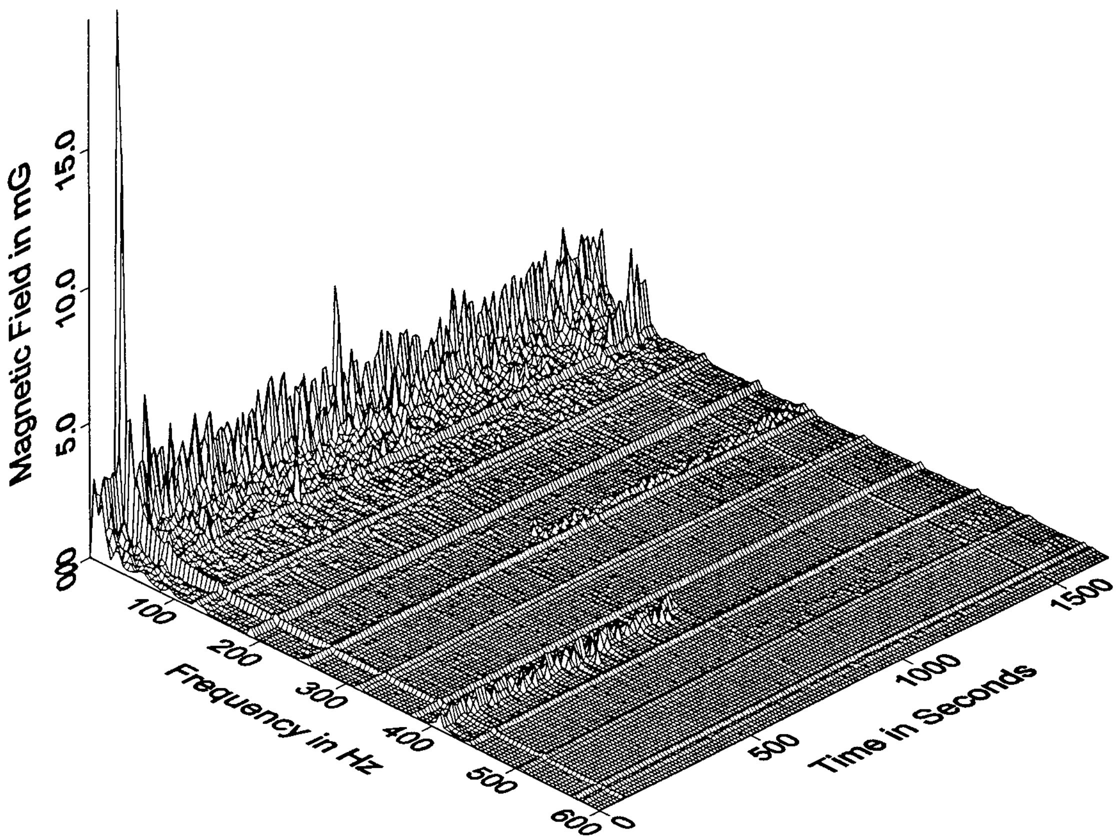


Figure 3-3 Example of Magnetic Field Data Recorded in Car 1 during the Suburban and Suburban Residential Road Tests. The Sensor was Mounted to the Ankle of the Front Passenger.

sometimes observed when passing other cars and steel structures adjacent to the roadway.

The geomagnetic field in the car is also significantly perturbed by the car body and chassis. This perturbation is constant when the car is traveling in a fixed direction through a uniform geomagnetic field. But, when the vehicle changes direction or passes through a region where the geomagnetic field is perturbed by another object, the amount of shielding produced by the chassis and body changes. Since that changes the geomagnetic field within the car in a time-dependant way, it also gives rise to low frequency time-varying fields.

A third field component visible in Figure 3-3 is a weak field which begins at about 400 Hz at the start of the record, abruptly changes to about 240 Hz at 750 seconds into the record, and continues at that frequency until the end of that record. That field is from the heater/air conditioner fan just in front of the front seat passenger's legs. Apparently, the driver turned the fan speed down which produced the abrupt frequency transition.

The fourth field component is the 60 Hz field from the electric power system along the roadway. Although much of route of travel depicted in Figure 3-3 is suburban residential streets with underground distribution, small 60 Hz fields from powerlines are occasionally visible throughout the record but most evident after 1500 seconds when the car is on a road with a larger distribution line. On other types of roads in the road test course, 60 Hz fields from nearby powerlines are the principal ELF field components in the car. Figure 3-4, which contains data measured on urban streets, illustrates such a situation. Not only are 60 Hz fields prominent, fields from odd harmonic current in the power system are evident at 180, 300 and 420 Hz.

Although Figure 3-4 depicts data measured at a rear seat passenger's head position and is well removed from moving parts of the engine and drive train, low frequency, speed dependant fields from the tires and other rotating components are present. The transient ELF fields produced by passing objects which perturb the geomagnetic field are also present in Figure 3-4 and considerably more frequent in this urban environment than in the suburban residential environment illustrated in Figure 3-3.

The various field sources discussed above contributed to a complex magnetic field environment in Car 1 which varied materially by seat position in the car, head, waist, or ankle position in the seat, and road type. The extensive body of data collected in Car 1 during both pretest and the road test is summarized in Table 3-2. Data measured at the 12 sensor locations have been pooled for computations of average field and standard deviation. Hence, those values

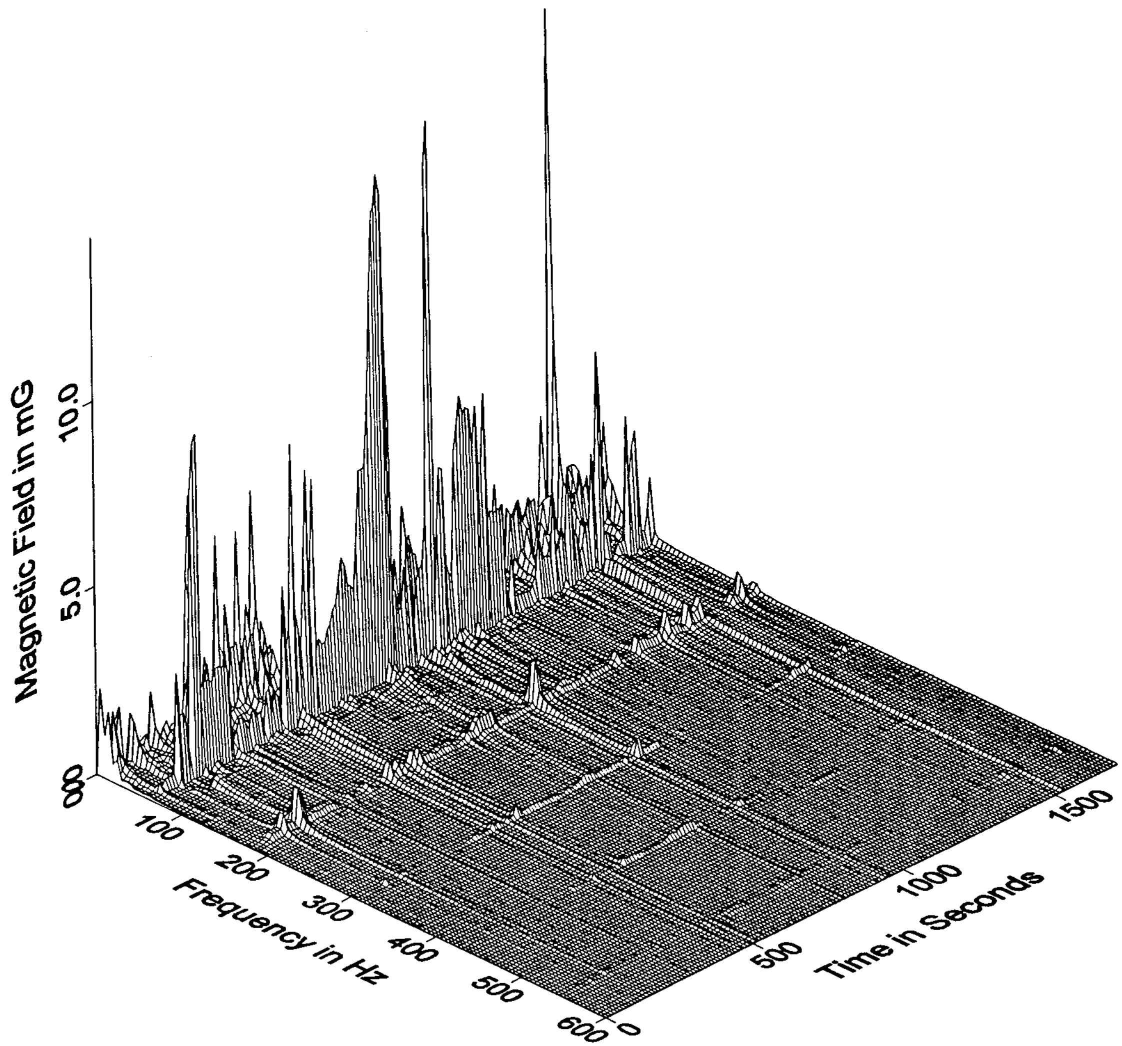


Figure 3-4 Example of Magnetic Field Data Recorded in Car 1 during the Urban Streets Test. The Sensor was Mounted on the Head of the Right Rear Passenger.

Table 3-2
Minimum, Maximum, and Average Magnetic Field Levels by Road Type and Frequency Band in Car #1

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
0 Hz	Pretest	60	137	508	381	95	25.0
Static	Rural	110	78	609	369	105	28.5
	Rural Secondary	80	84	606	369	106	28.6
	Suburban	94	96	570	362	90	24.8
	Suburban Residential	74	81	551	348	98	28.1
	Highway	91	109	790	370	105	28.4
	Urban	171	58	646	335	111	33.0
	Interstate	82	37	816	358	133	37.2
	Commercial	114	82	706	356	119	33.4
	Turnpike	114	61	690	359	97	27.1
	All Roads	930	37	816	357	109	30.4
5 - 55 Hz	Pretest	60	0.0	1.9	0.2	0.3	142.0
Sub-Power	Rural	110	0.5	36.5	2.9	2.4	82.4
Frequencies	Rural Secondary	80	0.4	22.2	2.5	1.8	71.8
	Suburban	94	0.2	55.6	2.6	3.1	122.2
	Suburban Residential	74	0.3	18.1	2.1	1.5	74.1
	Highway	91	0.5	75.5	7.9	8.4	106.4
	Urban	171	0.1	75.5	3.1	5.3	172.2
	Interstate	82	0.6	89.4	14.4	15.1	105.3
	Commercial	114	0.1	48.4	2.5	4.1	164.6
	Turnpike	114	0.5	99.7	10.8	10.0	92.2
	All Roads	930	0.1	99.7	5.2	8.1	154.9
60 Hz	Pretest	60	0.2	1.4	0.4	0.1	30.2
Power	Rural	110	0.1	3.8	1.0	0.7	65.6
Frequency	Rural Secondary	80	0.0	3.6	0.5	0.6	128.0
	Suburban	94	0.1	5.6	0.8	0.9	106.8
	Suburban Residential	74	0.0	3.1	0.5	0.5	85.2
	Highway	91	0.0	6.6	0.7	1.0	137.4
	Urban	171	0.0	19.4	2.5	2.6	102.9
	Interstate	82	0.0	5.4	0.6	0.6	98.7
	Commercial	114	0.0	6.3	0.7	0.6	81.9
	Turnpike	114	0.0	12.7	0.6	0.8	138.4
	All Roads	930	0.0	19.4	1.0	1.5	143.3
65 - 300 Hz	Pretest	60	0.0	3.7	0.3	0.6	218.0
Power	Rural	110	0.1	5.8	0.8	1.1	148.0
Frequency	Rural Secondary	80	0.1	4.7	0.7	1.1	161.2
Harmonics	Suburban	94	0.1	8.1	0.7	1.1	153.2
	Suburban Residential	74	0.1	5.0	0.6	1.0	157.8
	Highway	91	0.1	8.1	1.1	1.2	110.6
	Urban	171	0.1	9.7	0.9	1.0	116.0
	Interstate	82	0.1	13.6	1.5	1.7	108.2
	Commercial	114	0.1	7.1	0.7	1.0	142.1
	Turnpike	114	0.1	8.1	1.2	1.3	102.6

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
	All Roads	930	0.1	13.6	0.9	1.2	130.5
305 - 3000 Hz High ELF Frequencies	Pretest	60	0.0	2.9	0.2	0.4	194.4
	Rural	110	0.1	3.8	0.5	0.8	160.1
	Rural Secondary	80	0.0	3.3	0.5	0.8	169.1
	Suburban	94	0.0	3.5	0.5	0.8	158.4
	Suburban Residential	74	0.0	2.9	0.4	0.7	175.7
	Highway	91	0.1	3.9	0.6	0.8	126.0
	Urban	171	0.0	4.7	0.5	0.7	144.1
	Interstate	82	0.0	6.2	0.8	0.9	112.1
	Commercial	114	0.0	3.4	0.4	0.7	163.5
	Turnpike	114	0.1	4.3	0.7	0.8	116.6
	All Roads	930	0.0	6.2	0.5	0.8	144.5
5 - 3000 Hz All ELF Frequencies	Pretest	60	0.3	4.9	0.7	0.7	104.7
	Rural	110	0.6	37.2	3.4	2.5	71.2
	Rural Secondary	80	0.5	22.2	2.9	2.0	68.2
	Suburban	94	0.3	56.2	3.1	3.3	103.7
	Suburban Residential	74	0.4	18.9	2.5	1.8	71.0
	Highway	91	0.6	76.0	8.2	8.3	101.3
	Urban	171	0.2	75.9	4.9	5.3	108.5
	Interstate	82	0.7	89.7	14.6	15.2	104.2
	Commercial	114	0.1	48.7	3.0	4.1	135.5
	Turnpike	114	0.6	100.0	11.0	10.0	90.7
	All Roads	930	0.1	100.0	5.9	8.0	135.6
5 - 3000 Hz (Excluding 60 Hz) Internal ELF Frequencies	Pretest	60	0.1	4.8	0.4	0.8	171.5
	Rural	110	0.5	37.1	3.2	2.5	79.6
	Rural Secondary	80	0.5	22.2	2.8	2.0	71.2
	Suburban	94	0.2	56.2	2.9	3.3	113.2
	Suburban Residential	74	0.3	18.9	2.4	1.8	74.9
	Highway	91	0.6	76.0	8.1	8.4	104.1
	Urban	171	0.2	75.6	3.4	5.3	155.0
	Interstate	82	0.7	89.6	14.6	15.2	104.3
	Commercial	114	0.1	48.7	2.8	4.2	149.0
	Turnpike	114	0.6	99.9	11.0	10.0	91.1
	All Roads	930	0.1	99.9	5.5	8.1	147.2

represent field levels in the car interior as a whole. Road test data are summarized by road type and pooled under the "all roads" category to give summary data for all of the road test data.

For all of the road types identified in Table 3-2, the largest contributor of the total ELF magnetic field in Car 1 is the low frequency fields. Those field components arise from rotating magnetized parts in the vehicle drive system and from changes in the geomagnetic field. Since those sources depend on motion of the car, they were not present during the stationary pretest measurements. Data in 3-2 confirms that expectation. The largest low-frequency fields were found in the highway, interstate, and turnpike road categories where the vehicle traveled most constantly at high speed. Average low-frequency field levels were similar in the other road classes.

Sixty-hertz fields from powerlines along the road averaged 2.5 mG inside Car 1 while driving on urban roads but averaged 1 mG or less on other types of roads. This trend was observed in the other vehicles as well.

3.3.2 Car 2

Car 2 was also a six-passenger sedan, but of model year 1997. This car was equipped with daytime running lights which could not be turned off. Figure 3-5 shows magnetic fields measured at the driver's ankle during the pretest measurements. The pretest schedule was as indicated in Table 3-3 with two exceptions - daytime running lights were on whenever the car was running, and one additional 50-second test was included at the end with the engine idling but the accessories off. This car did not have the ELF field waveform associated with the headlights, but had fields from most of the other sources discussed for Car 1. Notable in Figure 3-5 are:

- 450 Hz fields from 200 to 300 seconds and 500 to 600 seconds from the fan;
- 980 Hz fields independent of engine speed while the engine is on; and
- Lower frequency fields whose frequencies correlate with engine speed.

During the road test of Car 2, fields were observed from the sources identified in the pretest. But, like Car 1, the largest fields came from sources present only when the car was moving.

The low-frequency fields from rotating tires were larger in Car 2 than in Car 1. Those fields were especially prominent at waist level in the rear seats which are very near the rear tires. Otherwise, comments about magnetic fields in Car 1 apply to this car as well.

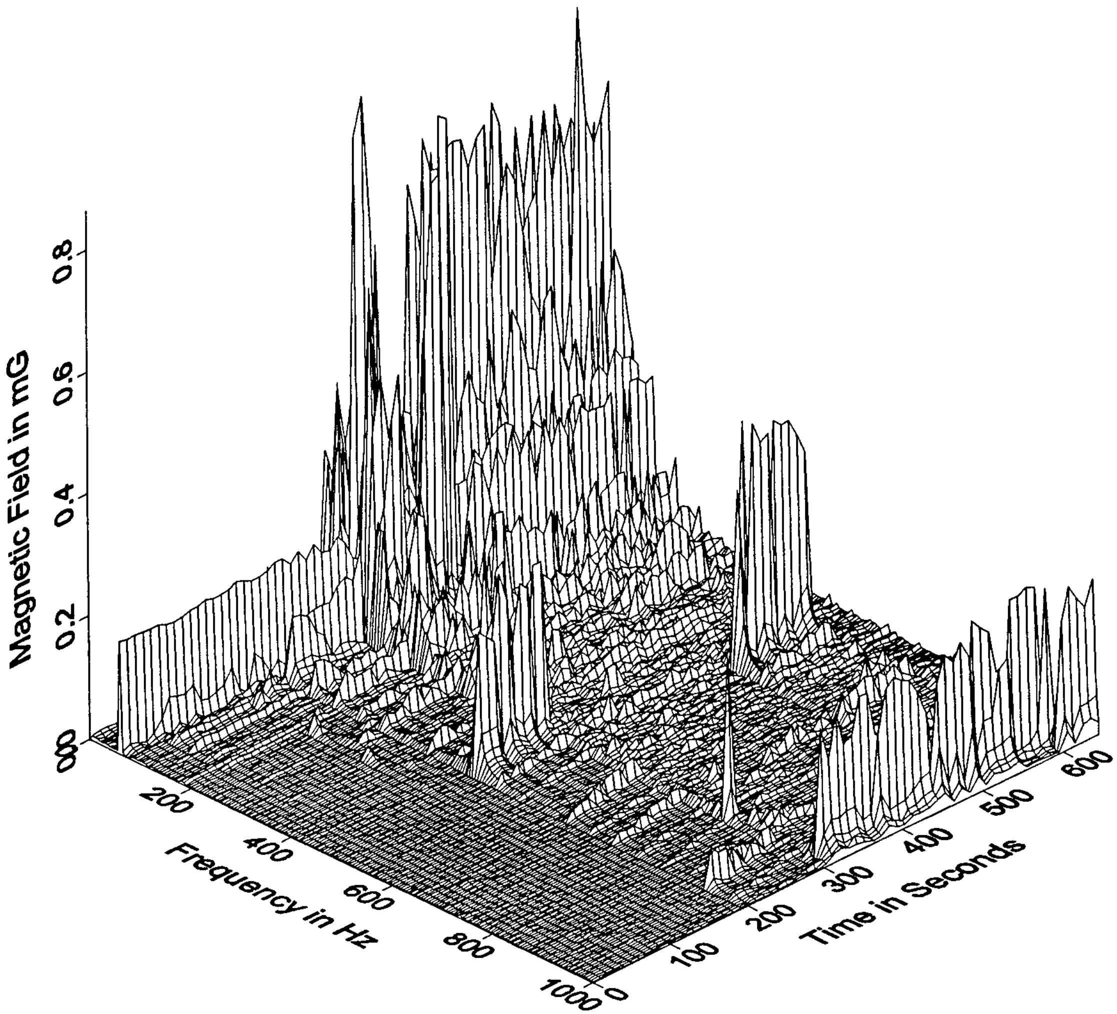


Figure 3-5 Example of Pretest Magnetic Field Data Recorded in Car 2 from the Sensor Mounted on the Driver's Ankle.

Table 3-3
Minimum, Maximum, and Average Magnetic Field Levels by Road Type and Frequency Band in Car #2

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
0 Hz Static	Pretest	65	233	500	346	75	21.8
	Rural	114	41	593	312	100	32.1
	Rural Secondary	76	45	570	278	109	39.2
	Suburban	88	16	527	211	89	42.4
	Suburban Residential	98	26	588	275	109	39.7
	Highway	89	31	636	254	121	47.7
	Urban	121	9	637	260	118	45.5
	Interstate	74	17	581	263	103	39.1
	Commercial	96	18	601	283	111	39.2
	Turnpike	109	62	595	328	93	28.4
	All Roads	865	9	637	276	111	40.4
5 - 55 Hz Sub-Power Frequencies	Pretest	65	0.0	1.7	0.2	0.3	153.5
	Rural	114	0.3	31.0	7.8	7.4	95.1
	Rural Secondary	76	0.5	29.8	7.3	7.1	97.3
	Suburban	88	0.1	27.6	6.4	6.5	100.9
	Suburban Residential	98	0.3	27.5	5.7	5.9	103.0
	Highway	89	1.2	123.2	12.2	10.9	89.4
	Urban	121	0.1	124.2	6.8	8.1	120.1
	Interstate	74	1.5	107.7	18.8	16.7	88.7
	Commercial	96	0.1	70.1	6.3	8.4	134.9
	Turnpike	109	1.3	96.5	14.3	11.5	80.0
	All Roads	865	0.1	124.2	9.3	10.3	111.0
60 Hz Power Frequency	Pretest	65	0.1	0.9	0.2	0.0	17.7
	Rural	114	0.0	2.7	0.8	0.4	52.0
	Rural Secondary	76	0.0	4.8	0.4	0.4	116.8
	Suburban	88	0.1	3.6	0.6	0.5	80.2
	Suburban Residential	98	0.1	2.8	0.5	0.3	57.4
	Highway	89	0.0	4.6	0.7	0.7	103.5
	Urban	121	0.0	17.1	2.2	2.5	112.4
	Interstate	74	0.1	4.5	0.7	0.6	88.7
	Commercial	96	0.0	5.5	0.9	0.9	95.3
	Turnpike	109	0.0	7.3	0.6	0.7	115.0
	All Roads	865	0.0	17.1	0.9	1.2	138.9
65 - 300 Hz Power Frequency Harmonics	Pretest	65	0.0	1.4	0.1	0.2	163.6
	Rural	114	0.1	4.2	0.7	0.7	97.3
	Rural Secondary	76	0.0	3.9	0.7	0.7	105.1
	Suburban	88	0.1	3.5	0.7	0.7	98.8
	Suburban Residential	98	0.1	3.6	0.5	0.5	104.0
	Highway	89	0.1	8.9	1.2	1.1	89.6
	Urban	121	0.1	9.6	0.8	0.7	89.3
	Interstate	74	0.1	12.3	1.6	1.5	94.5
	Commercial	96	0.1	9.3	0.8	0.9	116.5
	Turnpike	109	0.1	9.5	1.3	1.2	85.9

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
	All Roads	865	0.0	12.3	0.9	1.0	106.3
305 - 3000 Hz	Pretest	65	0.0	0.5	0.1	0.1	83.7
High ELF	Rural	114	0.1	2.0	0.3	0.3	94.3
Frequencies	Rural Secondary	76	0.0	1.8	0.3	0.3	99.5
	Suburban	88	0.0	1.6	0.3	0.3	94.2
	Suburban Residential	98	0.0	1.5	0.2	0.2	93.1
	Highway	89	0.1	4.2	0.5	0.5	92.3
	Urban	121	0.0	4.7	0.3	0.3	99.4
	Interstate	74	0.1	5.8	0.7	0.7	99.6
	Commercial	96	0.0	4.5	0.3	0.4	122.8
	Turnpike	109	0.1	4.5	0.6	0.5	88.8
	All Roads	865	0.0	5.8	0.4	0.4	109.3
5 - 3000 Hz	Pretest	65	0.2	2.0	0.4	0.4	91.6
All ELF	Rural	114	0.4	31.0	8.0	7.4	93.1
Frequencies	Rural Secondary	76	0.6	29.8	7.4	7.1	96.6
	Suburban	88	0.4	27.6	6.6	6.5	98.7
	Suburban Residential	98	0.3	27.6	5.8	5.9	101.3
	Highway	89	1.3	123.4	12.4	11.0	88.6
	Urban	121	0.4	124.5	7.9	7.9	100.0
	Interstate	74	1.5	107.7	18.9	16.8	88.5
	Commercial	96	0.4	70.9	6.7	8.3	124.6
	Turnpike	109	1.3	96.5	14.4	11.5	79.6
	All Roads	865	0.3	124.5	9.6	10.3	107.0
5 - 3000 Hz	Pretest	65	0.0	1.9	0.3	0.4	139.0
(Excluding	Rural	114	0.3	31.0	7.9	7.5	94.9
60 Hz)	Rural Secondary	76	0.6	29.8	7.3	7.1	97.1
Internal ELF	Suburban	88	0.2	27.6	6.5	6.5	100.5
Frequencies	Suburban Residential	98	0.3	27.6	5.8	5.9	102.6
	Highway	89	1.3	123.4	12.3	11.0	89.2
	Urban	121	0.1	124.5	6.9	8.1	118.1
	Interstate	74	1.5	107.7	18.9	16.8	88.5
	Commercial	96	0.1	70.8	6.3	8.5	133.3
	Turnpike	109	1.3	96.5	14.4	11.5	79.8
	All Roads	865	0.1	124.5	9.4	10.4	110.5

3.3.3 Minivan

The 1997 eight-passenger minivan was the third vehicle tested. Because sensors were to be positioned in 6 seats for this vehicle, two complete test were necessary.

For the first test, sensors were positioned on the driver, front seat passenger, and middle seat passengers. For the second test, sensors were again positioned on the driver and front seat passenger, in addition to the two rear seat passengers. This resulted in duplicate measurement in the driver's and front passenger's seat positions.

Pretest measurements in the minivan revealed fields from the accessories similar in nature to those seen in Car 1 but differing somewhat in amplitude and frequency. Figure 3-6 shows pretest magnetic fields at the ankle of a passenger sitting on the right side of the middle seat. Fields from the headlight controller and fan are small at this location. The fundamental frequency of the headlight controller is 130 Hz, but the fields are rich in harmonics. The field from the fan is about 520 Hz. When the engine starts, however, fields of several milligauss appear from two apparently independent sources. One source produces fields at approximately 120 Hz but second, third, and fourth harmonic components are clearly present. The other field source has a frequency of approximately 920 Hz. Neither of these field sources varied in frequency depend upon engine speed. The source of these fields is not known.

Summary descriptions of field values measured in the minivan during the two tests are presented in Tables 3-4 and 3-5. Data from both tests were not pooled for analysis because samples were not taken simultaneously. Statistical summaries of duplicate data taken in the driver's and front passenger's seats during the two tests were compared and found to have very good agreement. Statistical summaries from all 4 seats during the two tests have some differences due to the differences in measurement locations. Average values differ most noticeably in the harmonic frequencies and high ELF frequencies where values were consistently higher in the first set of tests. That difference results from elevated fields in the middle seat area from sources identified beneath the floor in that area during the pretest. Otherwise, field characteristics and apparent sources during the road tests are similar to those discussed for Car 1.

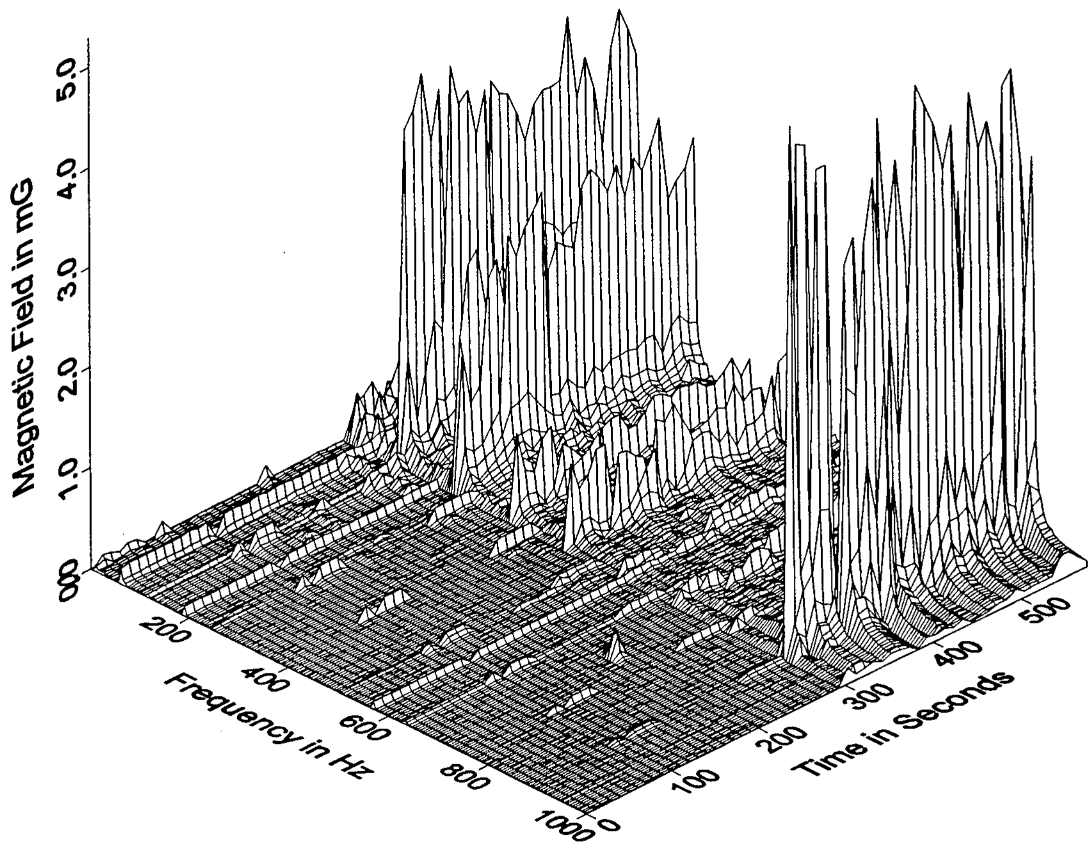


Figure 3-6 Example of Pretest Magnetic Field Data Recorded during the First Test of the Minivan from the Sensor Mounted on the Ankle of the Passenger on the Right Side of the Middle Seat.

Table 3-4
Minimum, Maximum, and Average Magnetic Field Levels by Road Type and Frequency Band for the First Test in the Minivan

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
0 Hz	Pretest	58	45	671	262	141	54.0
Static	Rural	94	59	934	282	142	50.2
	Rural Secondary	76	50	959	312	157	50.3
	Suburban	83	55	865	321	138	42.9
	Suburban Residential	94	50	964	325	170	52.2
	Highway	94	23	764	247	98	39.6
	Urban	140	56	846	314	143	45.6
	Interstate	83	57	719	320	137	42.6
	Commercial	100	25	762	289	141	48.8
	Turnpike	108	43	885	265	145	55.0
	All Roads	872	23	964	297	144	48.7
5 - 55 Hz	Pretest	58	0.0	6.8	0.3	0.4	168.2
Sub-Power	Rural	94	0.2	47.9	1.7	3.1	186.4
Frequencies	Rural Secondary	76	0.2	77.9	1.4	3.0	218.0
	Suburban	83	0.1	19.2	1.2	1.3	111.5
	Suburban Residential	94	0.2	28.7	1.4	2.2	156.1
	Highway	94	0.2	77.7	4.8	6.5	133.8
	Urban	140	0.1	26.0	2.3	3.1	135.8
	Interstate	83	0.3	111.6	10.7	12.8	119.2
	Commercial	100	0.1	38.6	2.2	3.9	181.2
	Turnpike	108	0.3	61.8	6.9	6.4	93.4
	All Roads	872	0.1	111.6	3.6	6.3	176.4
60 Hz	Pretest	58	0.0	0.4	0.2	0.0	17.5
Power	Rural	94	0.0	4.5	0.8	0.6	72.4
Frequency	Rural Secondary	76	0.0	3.9	0.2	0.3	147.6
	Suburban	83	0.1	4.0	0.5	0.4	85.1
	Suburban Residential	94	0.1	4.6	0.5	0.4	71.8
	Highway	94	0.0	8.8	0.5	0.7	161.4
	Urban	140	0.1	11.9	1.7	1.7	99.9
	Interstate	83	0.0	2.7	0.4	0.4	97.5
	Commercial	100	0.0	3.9	0.6	0.5	82.0
	Turnpike	108	0.0	8.8	0.4	0.7	170.1
	All Roads	872	0.0	11.9	0.7	1.0	141.2
65 - 300 Hz	Pretest	58	0.0	5.1	0.4	0.9	229.0
Power	Rural	94	0.1	12.2	0.9	1.4	154.5
Frequency	Rural Secondary	76	0.1	13.3	1.0	1.6	160.2
Harmonics	Suburban	83	0.2	7.4	1.0	1.6	154.7
	Suburban Residential	94	0.1	7.9	1.0	1.5	154.1
	Highway	94	0.1	7.2	1.0	1.3	128.4
	Urban	140	0.1	10.5	0.9	1.2	130.0
	Interstate	83	0.1	8.6	1.4	1.6	113.7
	Commercial	100	0.1	7.3	0.9	1.3	150.5
	Turnpike	108	0.2	9.6	1.4	1.9	134.2

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
	All Roads	872	0.1	13.3	1.1	1.5	142.5
305 - 3000 Hz High ELF Frequencies	Pretest	58	0.0	5.6	0.4	1.0	254.0
	Rural	94	0.1	6.6	0.8	1.4	185.9
	Rural Secondary	76	0.1	7.8	0.7	1.4	184.8
	Suburban	83	0.1	5.2	0.7	1.3	182.6
	Suburban Residential	94	0.1	5.2	0.7	1.3	181.2
	Highway	94	0.1	6.5	0.9	1.6	171.6
	Urban	140	0.1	6.3	0.8	1.5	180.6
	Interstate	83	0.1	6.3	1.0	1.4	144.1
	Commercial	100	0.1	5.5	0.8	1.4	180.7
	Turnpike	108	0.1	5.8	0.9	1.4	161.0
	All Roads	872	0.1	7.8	0.8	1.4	174.5
5 - 3000 Hz All ELF Frequencies	Pretest	58	0.0	7.4	0.8	1.4	180.4
	Rural	94	0.4	50.0	2.5	3.6	141.0
	Rural Secondary	76	0.3	79.5	2.1	3.5	168.9
	Suburban	83	0.3	19.6	2.1	2.3	108.2
	Suburban Residential	94	0.3	29.4	2.2	2.8	127.4
	Highway	94	0.3	77.8	5.3	6.6	123.6
	Urban	140	0.3	26.5	3.7	3.5	95.0
	Interstate	83	0.4	111.7	11.0	12.9	116.8
	Commercial	100	0.2	38.6	2.9	4.2	146.6
	Turnpike	108	0.4	62.1	7.3	6.7	91.1
	All Roads	872	0.2	111.7	4.3	6.4	147.9
5 - 3000 Hz (Excluding 60 Hz) Internal ELF Frequencies	Pretest	58	0.0	7.4	0.7	1.4	211.8
	Rural	94	0.3	49.8	2.3	3.6	160.5
	Rural Secondary	76	0.3	79.4	2.0	3.5	173.2
	Suburban	83	0.3	19.6	1.9	2.3	118.6
	Suburban Residential	94	0.2	29.3	2.1	2.8	137.6
	Highway	94	0.2	77.8	5.2	6.6	127.1
	Urban	140	0.2	26.1	2.8	3.5	125.8
	Interstate	83	0.4	111.7	11.0	12.9	116.9
	Commercial	100	0.2	38.6	2.7	4.3	158.8
	Turnpike	108	0.4	62.1	7.3	6.7	91.7
	All Roads	872	0.2	111.7	4.1	6.5	158.3

Table 3-5
Minimum, Maximum, and Average Magnetic Field Levels by Road Type and Frequency Band for the Second Test in the Minivan

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
0 Hz Static	Pretest	60	128	525	315	118	37.4
	Rural	108	32	639	302	117	38.6
	Rural Secondary	90	49	714	285	120	42.1
	Suburban	90	76	646	269	98	36.5
	Suburban Residential	98	29	658	281	120	42.6
	Highway	99	33	562	270	94	34.8
	Urban	136	17	819	284	133	47.0
	Interstate	76	43	802	288	145	50.4
	Commercial	118	21	734	284	123	43.5
	Turnpike	111	25	705	303	121	39.8
	All Roads	926	17	819	286	121	42.2
5 - 55 Hz Sub-Power Frequencies	Pretest	60	0.0	6.4	0.3	0.4	156.2
	Rural	108	0.1	37.5	2.0	2.3	114.1
	Rural Secondary	90	0.2	34.3	1.8	2.0	114.3
	Suburban	90	0.2	25.0	1.6	1.4	87.5
	Suburban Residential	98	0.2	40.6	1.8	2.6	146.4
	Highway	99	0.1	84.5	4.4	5.4	121.9
	Urban	136	0.1	37.5	2.3	3.0	130.9
	Interstate	76	0.4	104.7	11.4	12.7	110.8
	Commercial	118	0.1	45.7	1.9	3.4	177.5
	Turnpike	111	0.3	64.6	6.9	7.0	101.1
	All Roads	926	0.1	104.7	3.6	5.9	166.3
60 Hz Power Frequency	Pretest	60	0.1	0.6	0.2	0.0	16.8
	Rural	108	0.1	3.8	0.6	0.5	74.8
	Rural Secondary	90	0.0	4.9	0.2	0.5	210.5
	Suburban	90	0.0	4.8	0.4	0.4	89.7
	Suburban Residential	98	0.0	4.4	0.4	0.3	77.2
	Highway	99	0.0	3.8	0.5	0.7	146.9
	Urban	136	0.0	10.0	1.7	1.6	97.1
	Interstate	76	0.0	3.7	0.4	0.5	112.3
	Commercial	118	0.0	4.9	0.6	0.5	87.7
	Turnpike	111	0.0	6.9	0.4	0.6	153.4
	All Roads	926	0.0	10.0	0.6	0.9	141.6
65 - 300 Hz Power Frequency Harmonics	Pretest	60	0.0	2.3	0.3	0.4	148.7
	Rural	108	0.1	8.3	0.6	0.6	104.5
	Rural Secondary	90	0.1	7.3	0.6	0.6	105.4
	Suburban	90	0.1	4.6	0.7	0.6	95.0
	Suburban Residential	98	0.1	10.1	0.7	0.8	112.3
	Highway	99	0.1	8.5	0.8	0.8	95.2
	Urban	136	0.1	9.7	0.8	0.8	89.8
	Interstate	76	0.1	10.9	1.3	1.4	102.8
	Commercial	118	0.1	7.5	0.7	0.7	101.3
	Turnpike	111	0.1	8.6	0.9	0.8	88.3

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
	All Roads	926	0.1	10.9	0.8	0.8	103.7
305 - 3000 Hz High ELF Frequencies	Pretest	60	0.0	2.2	0.3	0.4	159.8
	Rural	108	0.1	2.1	0.4	0.5	117.4
	Rural Secondary	90	0.1	2.3	0.4	0.5	118.2
	Suburban	90	0.1	2.2	0.4	0.5	116.2
	Suburban Residential	98	0.1	2.5	0.4	0.5	118.3
	Highway	99	0.1	4.1	0.5	0.6	109.0
	Urban	136	0.1	3.3	0.5	0.5	112.0
	Interstate	76	0.1	5.3	0.7	0.7	103.4
	Commercial	118	0.1	3.1	0.4	0.5	116.3
	Turnpike	111	0.1	4.2	0.5	0.6	103.9
	All Roads	926	0.1	5.3	0.5	0.5	114.1
5 - 3000 Hz All ELF Frequencies	Pretest	60	0.2	6.6	0.6	0.7	117.4
	Rural	108	0.4	38.4	2.4	2.3	96.1
	Rural Secondary	90	0.3	35.2	2.0	2.1	104.3
	Suburban	90	0.4	25.6	1.9	1.5	76.0
	Suburban Residential	98	0.3	42.1	2.1	2.7	127.3
	Highway	99	0.3	85.0	4.8	5.4	113.1
	Urban	136	0.4	38.3	3.5	3.1	88.9
	Interstate	76	0.5	104.9	11.6	12.7	109.8
	Commercial	118	0.3	46.5	2.4	3.4	140.8
	Turnpike	111	0.4	65.0	7.1	7.0	99.0
	All Roads	926	0.3	104.9	4.0	5.9	147.1
5 - 3000 Hz (Excluding 60 Hz) Internal ELF Frequencies	Pretest	60	0.0	6.5	0.5	0.7	140.5
	Rural	108	0.3	38.2	2.2	2.3	106.1
	Rural Secondary	90	0.3	35.1	2.0	2.1	106.5
	Suburban	90	0.4	25.5	1.8	1.5	82.4
	Suburban Residential	98	0.3	41.9	2.0	2.7	133.2
	Highway	99	0.2	85.0	4.6	5.4	118.0
	Urban	136	0.3	38.2	2.6	3.1	118.8
	Interstate	76	0.5	104.9	11.6	12.7	109.9
	Commercial	118	0.3	46.4	2.2	3.4	156.8
	Turnpike	111	0.4	65.0	7.0	7.0	99.7
	All Roads	926	0.2	104.9	3.8	5.9	157.1

3.3.4 Pickup Truck

The last conventional personal vehicle tested was a 1996 model-year compact pickup truck. This vehicle was equipped only with a bench style front seat. Consequently, measurements were made only at the head, waist, and ankles of the driver and front seat passenger.

During the pretest, this vehicle exhibited only very low magnetic fields when the engine was running. These included low-frequency fields from moving engine parts and perhaps the ignition system which varied in frequency proportional to engine speed and a smaller fixed-frequency field of about 800 Hz. ELF fields attributable to a headlight controller or fan were not observed.

Magnetic field levels measured during the road test of the pickup truck are summarized in Table 3-6. That data is consistent with that from the other conventional personal vehicles in that ELF fields are predominantly in the 5 to 55 Hz range and arise from rotating magnetic components of the drive train, especially the tires, and from moving through perturbations of the geomagnetic field. These fields tend to have the largest average values on roads where there is sustained driving at high speeds. Magnetic fields in the ELF frequency range above 60 Hz fields are small in this vehicle due to the lack of harmonic-rich fields from electronic devices like a headlight controller.

3.3.5 Mass Transportation Bus

The final vehicle tested was a 1996 mass transportation bus. Because the protocol required sensors to be positioned in 8 seats on the bus, two complete tests were performed. For the first test, sensors were positioned in 4 seats located near the front of the bus. For the second test, seats towards the rear of the bus were used.

Figure 3-7 shows the seating arrangement in the bus and the seats in which measurements were made during the first and second tests.

One sample of the magnetic field characteristics in the bus during the pretest is shown in Figure 3-8. These data were measured at the waist level of a center-facing seat in the rear of the bus (Test 2, Position 3, in Figure 3-7). Large low-frequency fields are seen whenever the engine is running (280 seconds and beyond).

Smaller fields are seen at 300 Hz, 350 Hz, and 2050 Hz. The field component at 2050 Hz changes frequency in proportion to engine speed. The other field components appear to remain constant in frequency regardless of engine

Table 3-6
Minimum, Maximum, and Average Magnetic Field Levels by Road Type and Frequency Band in the Pickup Truck

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
0 Hz	Pretest	55	312	614	420	95	22.5
Static	Rural	120	37	782	390	138	35.3
	Rural Secondary	89	64	739	354	154	43.4
	Suburban	85	52	778	339	181	53.5
	Suburban Residential	96	59	795	334	155	46.4
	Highway	100	36	890	393	220	55.9
	Urban	160	9	919	318	185	58.2
	Interstate	79	19	762	299	162	54.3
	Commercial	125	57	876	360	182	50.5
	Turnpike	113	124	968	423	151	35.6
	All Roads	967	9	968	358	176	49.1
5 - 55 Hz	Pretest	55	0.0	1.3	0.2	0.3	140.3
Sub-Power	Rural	120	0.1	11.3	2.6	2.0	77.3
Frequencies	Rural Secondary	89	0.2	6.4	2.2	1.5	70.1
	Suburban	85	0.2	13.5	2.7	2.0	75.4
	Suburban Residential	96	0.1	6.8	2.1	1.6	74.7
	Highway	100	0.1	63.2	5.2	6.2	118.9
	Urban	160	0.1	45.1	2.1	2.7	131.2
	Interstate	79	0.8	88.9	11.4	12.5	109.1
	Commercial	125	0.1	47.7	2.1	3.6	171.8
	Turnpike	113	0.6	80.3	7.3	6.6	90.5
	All Roads	967	0.1	88.9	3.9	5.8	148.6
60 Hz	Pretest	55	0.1	0.8	0.1	0.1	45.9
Power	Rural	120	0.1	3.9	1.0	0.7	70.3
Frequency	Rural Secondary	89	0.0	6.2	0.4	0.6	178.7
	Suburban	85	0.1	8.9	0.7	0.8	110.4
	Suburban Residential	96	0.1	1.7	0.4	0.3	60.1
	Highway	100	0.0	4.4	0.5	0.6	139.6
	Urban	160	0.0	17.5	2.7	2.5	92.1
	Interstate	79	0.0	3.3	0.4	0.4	92.9
	Commercial	125	0.0	11.3	0.9	1.1	121.2
	Turnpike	113	0.0	5.9	0.4	0.6	141.6
	All Roads	967	0.0	17.5	1.0	1.5	151.9
65 - 300 Hz	Pretest	55	0.0	1.1	0.2	0.2	123.8
Power	Rural	120	0.1	1.5	0.5	0.4	72.6
Frequency	Rural Secondary	89	0.1	1.4	0.4	0.3	84.8
Harmonics	Suburban	85	0.1	1.4	0.5	0.4	73.6
	Suburban Residential	96	0.1	1.6	0.4	0.4	85.2
	Highway	100	0.1	8.7	0.7	0.8	109.8
	Urban	160	0.1	3.0	0.7	0.4	58.0
	Interstate	79	0.1	9.7	1.1	1.1	98.5
	Commercial	125	0.1	4.6	0.5	0.5	91.1
	Turnpike	113	0.1	6.7	0.8	0.7	82.7

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
	All Roads	967	0.1	9.7	0.6	0.6	96.9
305 - 3000 Hz High ELF Frequencies	Pretest	55	0.0	0.3	0.1	0.1	68.0
	Rural	120	0.1	0.6	0.2	0.1	61.4
	Rural Secondary	89	0.1	0.4	0.2	0.1	64.2
	Suburban	85	0.1	1.0	0.2	0.1	66.0
	Suburban Residential	96	0.1	0.6	0.2	0.1	65.5
	Highway	100	0.1	4.2	0.3	0.4	121.7
	Urban	160	0.1	1.3	0.2	0.1	64.6
	Interstate	79	0.1	4.7	0.5	0.5	105.1
	Commercial	125	0.1	2.2	0.2	0.2	100.9
	Turnpike	113	0.1	3.3	0.3	0.3	86.0
	All Roads	967	0.1	4.7	0.2	0.3	106.5
5 - 3000 Hz All ELF Frequencies	Pretest	55	0.1	1.4	0.4	0.4	100.0
	Rural	120	0.2	11.5	3.0	1.9	64.1
	Rural Secondary	89	0.3	6.8	2.3	1.6	68.5
	Suburban	85	0.4	13.5	2.9	2.0	69.0
	Suburban Residential	96	0.3	7.0	2.2	1.6	70.1
	Highway	100	0.3	63.3	5.4	6.2	115.8
	Urban	160	0.3	45.2	4.1	3.1	76.0
	Interstate	79	0.9	89.0	11.5	12.5	108.6
	Commercial	125	0.2	48.0	2.6	3.6	136.6
	Turnpike	113	0.7	80.4	7.4	6.6	89.3
	All Roads	967	0.2	89.0	4.5	5.8	129.6
5 - 3000 Hz (Excluding 60 Hz) Internal ELF Frequencies	Pretest	55	0.1	1.4	0.3	0.4	120.6
	Rural	120	0.2	11.4	2.6	2.0	76.5
	Rural Secondary	89	0.3	6.5	2.3	1.6	70.1
	Suburban	85	0.2	13.5	2.7	2.0	74.7
	Suburban Residential	96	0.2	7.0	2.1	1.6	74.5
	Highway	100	0.1	63.3	5.3	6.2	118.3
	Urban	160	0.2	45.2	2.3	2.7	118.0
	Interstate	79	0.8	89.0	11.5	12.5	108.6
	Commercial	125	0.1	48.0	2.2	3.6	164.1
	Turnpike	113	0.6	80.4	7.4	6.7	90.1
	All Roads	967	0.1	89.0	4.0	5.8	145.6

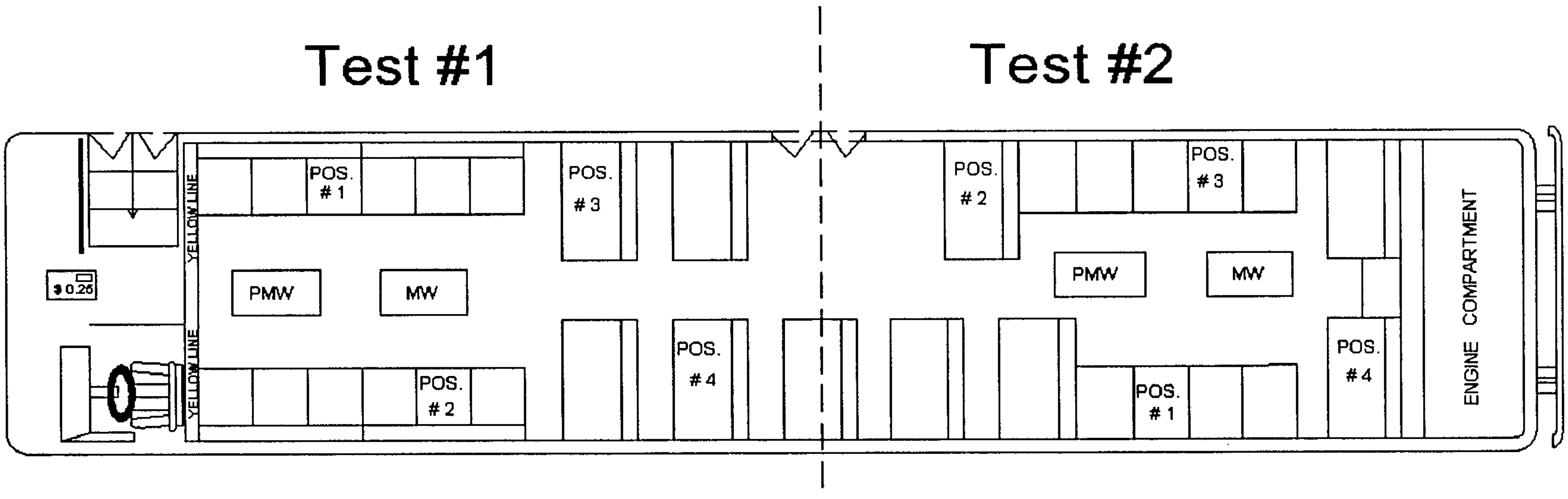


Figure 3-7 Passenger Positions for the In-Vehicle Mass Transportation Bus Measurements.

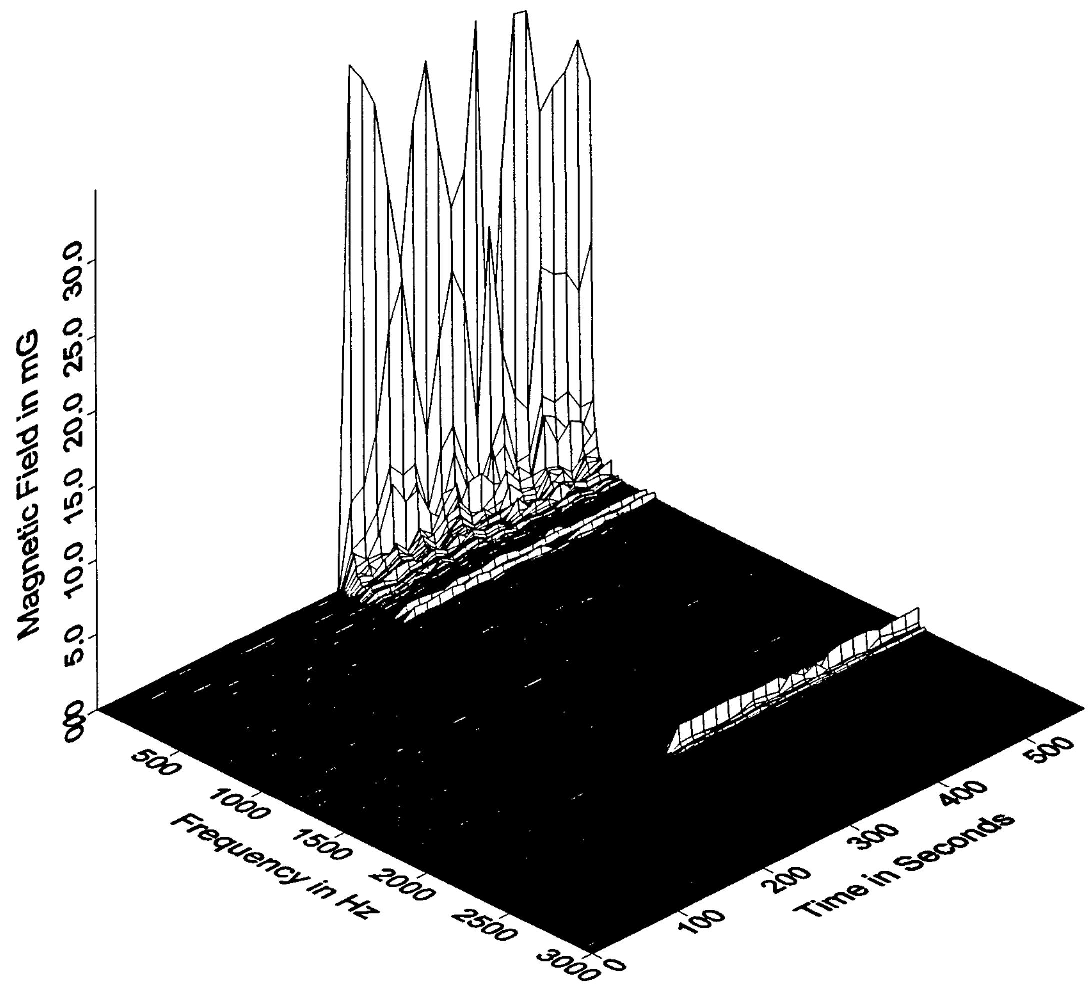


Figure 3-8 Example of Pretest Magnetic Field Data Recorded in the Mass Transit Bus from the Sensor Mounted on the Waist of a Passenger in a Center Facing Seat at the Left Rear of the Bus.

speed. Pretest measurements in the front of the bus revealed comparable levels of the 2050 Hz field but the lower frequency fields were about an order of magnitude smaller. Significant fields attributable to headlights, interior lights, or the public address system were not observed. The climate control in this vehicle was on all of the time when the engine was running and controlled automatically. It could not be turned on or off for the pretest.

The mass transportation bus was road tested over much the same course used to test the personal vehicles. The rural secondary roads were omitted because they do not represent a locale where mass transportation vehicles would operate. To obtain data for 8 seats, the bus was tested over the same route on two sequential days measuring fields at 4 seat locations (head, waist, and ankle locations at each seat) each day. The data from the two tests are not pooled. Table 3-7 summarizes field levels in the front half of the bus. Data for the rear is given in Table 3-8.

In both the front and rear of the bus, sub-power frequency fields were the major contributor to the total ELF field in the bus. However, there was a significant gradient in the intensity of those fields from the rear of the bus to the front. The average intensity of those low frequency fields was 27.1 mG in the rear half of the bus and only 5.7 mG in the front half. These low-frequency field components did not fluctuate significantly with road type and were not related strongly to vehicle speed as in the personal vehicles. It appears as though much of this field is produced by sources at the rear of the bus and do not arise primarily from the rotating tires. (It is unlikely that this vehicle had steel belted radial tires.)

The higher-frequency field in the kilohertz range and related to engine speed is the major contributor to field levels in the high ELF frequency band. This field averaged 2 mG in the front half of the bus and 3 mG in the back.

3.3.6 Magnetic Field Level Summary

Table 3-9 summarizes the magnetic field levels measured in the conventional motor vehicles. While there is large variability in level within each vehicle depending upon location, driving condition, and road type, the average levels in the four personal vehicles are not that dissimilar. Furthermore, the distribution of field level across frequency bands are also consistent. Those similarities result from the findings that the same field sources are dominant in all four vehicles. Conditions in the mass transit bus are materially different than those in the personal vehicles, apparently due to strong field sources which are not present in personal vehicles.

Table 3-7
Minimum, Maximum, and Average Magnetic Field Levels by Road Type and Frequency Band for the Front Half of the Bus (Test #1)

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
0 Hz	Pretest	40	142	877	419	155	37.1
Static	Rural	112	132	880	448	148	33.0
	Suburban	98	138	816	459	154	33.7
	Suburban Residential	99	155	815	450	166	37.0
	Highway	50	166	880	444	131	29.5
	Urban	150	60	964	392	158	40.4
	Interstate	84	52	1124	408	183	44.9
	Commercial	113	131	1010	440	158	35.9
	Turnpike	114	172	1003	446	151	34.0
	All Roads	820	52	1124	434	159	36.8
5 - 55 Hz	Pretest	40	0.0	38.4	3.1	5.6	184.0
Sub-Power	Rural	112	0.5	29.9	5.1	5.0	98.1
Frequencies	Suburban	98	0.5	30.5	4.8	5.2	108.0
	Suburban Residential	99	0.5	28.9	4.6	5.1	110.7
	Highway	50	0.5	37.4	5.6	5.1	91.3
	Urban	150	0.4	35.4	5.7	6.6	116.6
	Interstate	84	1.0	104.9	8.3	8.7	104.1
	Commercial	113	0.4	41.2	5.6	6.5	116.0
	Turnpike	114	0.6	68.9	6.4	5.7	88.9
	All Roads	820	0.4	104.9	5.7	6.2	108.3
60 Hz	Pretest	40	0.0	4.4	0.2	0.5	205.5
Power	Rural	112	0.0	2.5	0.4	0.3	80.0
Frequency	Suburban	98	0.0	3.7	0.5	0.4	90.8
	Suburban Residential	99	0.0	4.3	0.4	0.4	99.2
	Highway	50	0.0	6.5	0.4	0.6	150.6
	Urban	150	0.0	14.2	1.3	1.4	109.8
	Interstate	84	0.0	3.8	0.4	0.4	114.9
	Commercial	113	0.0	8.1	0.8	0.8	99.1
	Turnpike	114	0.0	3.8	0.4	0.5	137.7
	All Roads	820	0.0	14.2	0.6	0.8	132.7
65 - 300 Hz	Pretest	40	0.0	7.9	0.6	1.1	172.5
Power	Rural	112	0.0	5.5	0.7	0.9	134.3
Frequency	Suburban	98	0.1	8.6	0.7	1.0	142.0
Harmonics	Suburban Residential	99	0.0	6.1	0.7	1.0	138.5
	Highway	50	0.1	7.9	0.8	1.1	132.4
	Urban	150	0.0	9.3	0.9	1.3	139.7
	Interstate	84	0.1	8.0	1.0	1.2	118.0
	Commercial	113	0.1	7.6	0.8	1.3	149.1
	Turnpike	114	0.1	6.5	0.9	1.1	124.3
	All Roads	820	0.0	9.3	0.8	1.1	136.6
305 - 3000 Hz	Pretest	40	0.0	8.7	0.7	1.5	207.5
High ELF	Rural	112	0.1	8.5	1.0	1.5	145.5
Frequencies	Suburban	98	0.1	8.4	1.0	1.5	156.9

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
	Suburban Residential	99	0.0	11.6	0.9	1.5	164.9
	Highway	50	0.1	13.6	0.6	1.1	182.8
	Urban	150	0.1	15.9	1.6	3.0	190.8
	Interstate	84	0.1	10.9	0.7	1.0	142.8
	Commercial	113	0.1	15.9	1.4	2.8	197.2
	Turnpike	114	0.1	15.0	0.6	1.0	160.4
	All Roads	820	0.0	15.9	1.1	2.0	192.6
5 - 3000 Hz All ELF Frequencies	Pretest	40	0.1	40.1	3.3	5.9	176.1
	Rural	112	0.5	31.4	5.3	5.2	97.7
	Suburban	98	0.5	31.9	5.1	5.4	106.7
	Suburban Residential	99	0.6	31.5	4.9	5.4	109.8
	Highway	50	0.5	37.8	5.8	5.3	92.4
	Urban	150	0.5	39.5	6.4	7.2	111.7
	Interstate	84	1.0	105.2	8.5	8.8	103.9
	Commercial	113	0.5	41.6	6.1	7.0	115.1
	Turnpike	114	0.7	69.0	6.6	5.9	89.3
	All Roads	820	0.5	105.2	6.1	6.5	107.1
5 - 3000 Hz (Excluding 60 Hz) Internal ELF Frequencies	Pretest	40	0.0	39.9	3.3	5.9	176.5
	Rural	112	0.5	31.4	5.3	5.2	98.4
	Suburban	98	0.5	31.7	5.0	5.4	107.8
	Suburban Residential	99	0.5	31.5	4.8	5.4	110.6
	Highway	50	0.5	37.7	5.7	5.3	92.6
	Urban	150	0.5	39.4	6.1	7.3	118.7
	Interstate	84	1.0	105.2	8.5	8.8	104.0
	Commercial	113	0.5	41.6	6.0	7.1	118.4
	Turnpike	114	0.7	69.0	6.6	5.9	89.6
	All Roads	820	0.5	105.2	6.0	6.5	109.2

Table 3-8
Minimum, Maximum, and Average Magnetic Field Levels by Road Type and Frequency Band for the Rear Half of the Bus (Test #2)

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
0 Hz	Pretest	40	133	476	323	96	29.7
Static	Rural	102	98	660	373	104	27.9
	Suburban	105	143	624	386	118	30.7
	Suburban Residential	93	108	624	363	116	31.9
	Highway	115	112	728	392	117	29.9
	Urban	145	41	670	332	110	33.2
	Interstate	83	44	796	331	116	34.9
	Commercial	114	128	690	379	117	30.8
	Turnpike	118	136	618	383	104	27.0
	All Roads	875	41	796	367	115	31.2
5 - 55 Hz	Pretest	40	0.0	112.3	13.8	22.9	166.7
Sub-Power	Rural	102	2.5	92.4	27.0	25.6	94.6
Frequencies	Suburban	105	2.3	108.4	26.1	25.2	96.9
	Suburban Residential	93	2.1	107.2	26.7	25.7	96.5
	Highway	115	2.2	108.6	26.5	25.4	96.0
	Urban	145	2.8	144.2	30.5	28.9	94.8
	Interstate	83	2.2	118.1	26.0	24.3	93.4
	Commercial	114	2.5	115.6	29.4	28.3	96.4
	Turnpike	118	2.2	122.9	23.5	23.3	98.9
	All Roads	875	2.1	144.2	27.1	26.2	96.5
60 Hz	Pretest	40	0.0	5.3	0.5	0.8	159.1
Power	Rural	102	0.1	5.1	1.1	0.9	83.6
Frequency	Suburban	105	0.1	5.8	1.1	0.9	85.0
	Suburban Residential	93	0.1	6.0	1.0	1.0	93.7
	Highway	115	0.1	7.2	1.1	1.0	94.2
	Urban	145	0.1	9.8	1.7	1.4	79.4
	Interstate	83	0.1	5.4	1.0	0.9	90.3
	Commercial	114	0.0	7.8	1.3	1.1	85.8
	Turnpike	118	0.1	7.5	1.0	0.9	94.6
	All Roads	875	0.0	9.8	1.2	1.1	90.6
65 - 300 Hz	Pretest	40	0.0	13.6	1.5	2.5	165.3
Power	Rural	102	0.3	13.7	2.8	2.8	99.8
Frequency	Suburban	105	0.2	16.9	2.8	2.9	103.7
Harmonics	Suburban Residential	93	0.2	17.2	2.8	2.9	104.9
	Highway	115	0.2	18.0	2.9	3.0	103.5
	Urban	145	0.4	21.3	3.3	3.5	106.4
	Interstate	83	0.3	13.7	2.8	2.8	99.8
	Commercial	114	0.3	20.2	3.1	3.2	104.1
	Turnpike	118	0.2	12.5	2.5	2.6	103.1
	All Roads	875	0.2	21.3	2.9	3.0	104.3
305 - 3000 Hz	Pretest	40	0.0	20.0	2.0	4.4	217.7
High ELF	Rural	102	0.2	20.7	3.4	5.1	147.3
Frequencies	Suburban	105	0.1	24.1	3.2	4.8	151.4

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
	Suburban Residential	93	0.2	22.6	3.1	4.7	150.4
	Highway	115	0.2	23.2	2.4	3.5	146.1
	Urban	145	0.2	23.7	3.9	5.5	140.3
	Interstate	83	0.2	21.6	2.0	2.6	129.8
	Commercial	114	0.2	23.5	3.6	5.2	144.7
	Turnpike	118	0.2	24.8	1.8	2.4	135.5
	All Roads	875	0.1	24.8	3.0	4.5	151.0
5 - 3000 Hz	Pretest	40	0.1	113.7	14.1	23.4	165.8
All ELF	Rural	102	2.7	92.6	27.5	26.1	94.8
Frequencies	Suburban	105	2.4	109.7	26.5	25.7	97.0
	Suburban Residential	93	2.2	107.7	27.1	26.2	96.6
	Highway	115	2.2	110.2	26.8	25.8	95.9
	Urban	145	2.9	145.7	31.2	29.5	94.7
	Interstate	83	2.3	119.1	26.3	24.6	93.3
	Commercial	114	2.9	116.5	29.9	28.8	96.4
	Turnpike	118	2.3	123.0	23.8	23.5	98.7
	All Roads	875	2.2	145.7	27.6	26.6	96.5
5 - 3000 Hz	Pretest	40	0.0	113.6	14.1	23.4	166.1
(Excluding	Rural	102	2.6	92.6	27.5	26.1	94.9
60 Hz)	Suburban	105	2.4	109.6	26.5	25.7	97.2
Internal ELF	Suburban Residential	93	2.2	107.7	27.1	26.2	96.7
Frequencies	Highway	115	2.2	110.1	26.8	25.8	96.1
	Urban	145	2.9	145.6	31.1	29.6	95.1
	Interstate	83	2.2	119.0	26.3	24.6	93.4
	Commercial	114	2.5	116.4	29.9	28.8	96.6
	Turnpike	118	2.3	123.0	23.8	23.5	98.9
	All Roads	875	2.2	145.6	27.5	26.6	96.7

Table 3-9
Summary of Minimum, Maximum, and Average Magnetic Field Levels by Vehicle and Frequency Band

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
0 Hz	Car #1	930	37	816	357	109	30.4
Static	Car #2	865	9	637	276	111	40.4
	Minivan Test #1	872	23	964	297	144	48.7
	Minivan Test #2	926	17	819	286	121	42.2
	Pickup Truck	967	9	968	358	176	49.1
	Bus Test #1	820	52	1124	434	159	36.8
	Bus Test #2	875	41	796	367	115	31.2
5 - 55 Hz	Car #1	930	0.1	99.7	5.2	8.1	154.9
Sub-Power	Car #2	865	0.1	124.2	9.3	10.3	111.0
Frequencies	Minivan Test #1	872	0.1	111.6	3.6	6.3	176.4
	Minivan Test #2	926	0.1	104.7	3.6	5.9	166.3
	Pickup Truck	967	0.1	88.9	3.9	5.8	148.6
	Bus Test #1	820	0.4	104.9	5.7	6.2	108.3
	Bus Test #2	875	2.1	144.2	27.1	26.2	96.5
60 Hz	Car #1	930	0.0	19.4	1.0	1.5	143.3
Power	Car #2	865	0.0	17.1	0.9	1.2	138.9
Frequency	Minivan Test #1	872	0.0	11.9	0.7	1.0	141.2
	Minivan Test #2	926	0.0	10.0	0.6	0.9	141.6
	Pickup Truck	967	0.0	17.5	1.0	1.5	151.9
	Bus Test #1	820	0.0	14.2	0.6	0.8	132.7
	Bus Test #2	875	0.0	9.8	1.2	1.1	90.6
65 - 300 Hz	Car #1	930	0.1	13.6	0.9	1.2	130.5
Power	Car #2	865	0.0	12.3	0.9	1.0	106.3
Frequency	Minivan Test #1	872	0.1	13.3	1.1	1.5	142.5
Harmonics	Minivan Test #2	926	0.1	10.9	0.8	0.8	103.7
	Pickup Truck	967	0.1	9.7	0.6	0.6	96.9
	Bus Test #1	820	0.0	9.3	0.8	1.1	136.6
	Bus Test #2	875	0.2	21.3	2.9	3.0	104.3
305 - 3000 Hz	Car #1	930	0.0	6.2	0.5	0.8	144.5
High ELF	Car #2	865	0.0	5.8	0.4	0.4	109.3
Frequencies	Minivan Test #1	872	0.1	7.8	0.8	1.4	174.5
	Minivan Test #2	926	0.1	5.3	0.5	0.5	114.1
	Pickup Truck	967	0.1	4.7	0.2	0.3	106.5
	Bus Test #1	820	0.0	15.9	1.1	2.0	192.6
	Bus Test #2	875	0.1	24.8	3.0	4.5	151.0
5 - 3000 Hz	Car #1	930	0.1	100.0	5.9	8.0	135.6
All ELF	Car #2	865	0.3	124.5	9.6	10.3	107.0
Frequencies	Minivan Test #1	872	0.2	111.7	4.3	6.4	147.9
	Minivan Test #2	926	0.3	104.9	4.0	5.9	147.1
	Pickup Truck	967	0.2	89.0	4.5	5.8	129.6
	Bus Test #1	820	0.5	105.2	6.1	6.5	107.1
	Bus Test #2	875	2.2	145.7	27.6	26.6	96.5
5 - 3000 Hz	Car #1	930	0.1	99.9	5.5	8.1	147.2

Frequency Band	Vehicle Location	Total Samples Recorded	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
(Excluding	Car #2	865	0.1	124.5	9.4	10.4	110.5
60 Hz)	Minivan Test #1	872	0.2	111.7	4.1	6.5	158.3
Internal ELF	Minivan Test #2	926	0.2	104.9	3.8	5.9	157.1
Frequencies	Pickup Truck	967	0.1	89.0	4.0	5.8	145.6
	Bus Test #1	820	0.5	105.2	6.0	6.5	109.2
	Bus Test #2	875	2.2	145.6	27.5	26.6	96.7

Significant static magnetic field sources were not found in any of the vehicles. In fact, average static field levels were about one third less than the normal geomagnetic field level of the test area (about 500 mG). That overall attenuation appears to arise from shielding by steel vehicle body and chassis components. Significant spatial variations in static field level were observed depending on the degree of field perturbation by the vehicle at that location. Large temporal variations in static field level were also observed due to two factors. First, the vehicle traveled through areas where the geomagnetic field was highly perturbed by iron and steel objects in or near the roadway. Second, the static field perturbation of the vehicle chassis and body was dependant upon the orientation of the vehicle with respect to the geomagnetic field. As the vehicle turned, that orientation changed and the perturbed static field level in the vehicle changed.

The largest ELF fields in all of the vehicles appeared at frequencies below the normal power frequency of 60 Hz. In the personal vehicles, these sub-power frequency fields arose primarily from rotating parts of the drive train having residual magnetism. Magnetized steel belts in radial tires appeared to be the common dominant source. Significant low-frequency field components also occurred from transient changes in the geomagnetic field at the measurement location as a result of driving through a region of highly perturbed geomagnetic field. This effect was compounded by the orientation-dependant shielding of the vehicle body and chassis. Since these low-frequency field sources are dependant upon movement of the vehicle, their intensities have large temporal variability and are affected by driving conditions and road type. They are also spatially variable throughout the vehicle dependant primarily upon distance from the tires.

Sub-power frequency field levels in the bus were larger than those in personal vehicles, especially in the rear of the bus. These fields appeared to arise predominantly from sources on the bus which were not present in the other vehicles. These field levels had large spatial variability with a consistent gradient from the rear of the bus, but showed little dependance on driving condition or road type.

The conventional vehicle did not produce significant 60 Hz field levels on a routine basis. Nevertheless, those fields were present in all of the vehicles from sources along the road way, most notably electric power distribution lines. While average levels were less than 1 mG, 60 Hz fields averaged on the order of 3 mG in vehicles driving on urban streets where powerlines were larger and numerous. It is reassuring to note that the vehicles which tended to have the lowest average interior geomagnetic field levels also had the lowest interior 60 Hz field levels. The effects of ferromagnetic shielding by the vehicle body is confirmed with fields from two different external field sources.

Higher frequency ELF fields in the personal vehicles are generally small but reach a few milligauss at locations very near localized sources such as electronic headlight controls. The minivan also had an unknown source beneath the floor near the center of the vehicle which produced elevated fields at frequencies above 60 Hz. The mass transit bus was unique in that it produced considerably larger fields at frequencies above 60 Hz than did the personal vehicles. In the rear of the bus, fields in the 65-300 Hz range and 305-3000 Hz range averaged 2.9 and 3.0 mG, respectively.

Although mean field levels measured within the conventional vehicles were within reasonable agreement, values were highly variable within each vehicle. The standard deviation was typically larger than the mean value of field. To better understand the factors which most strongly affect field levels with the vehicles, a multi-factor analysis of variance (ANOVA) was conducted to quantify the extent to which vehicle type, road type, and measurement location within the vehicle contributed to the overall variance.

That analysis showed that each of the factors accounted for similar portions of the variability. That is, road type is as important of a factor in determining magnetic field levels in a conventional vehicle as is position in the vehicle or specific vehicle type. Another reassuring finding was that the residual variability (variability not systematically accounted for by vehicle type, measurement location, or road type) was typically four to ten times smaller than the variability accounted for by the three systematically controlled parameters. That finding implies that the road test protocol effectively controlled the major sources of variability in field levels in vehicles and the reported values are minimally affected by uncontrolled random variability.

3.4 Electric Field Characteristics

ELF electric fields were measured at one or more location in each vehicle using a fiber optic isolated free body sensor. The noise floor 1 m in the electric field instrumentation is in the range of two to three volts per meter for wideband ELF measurements and an order of magnitude better for specific frequency components. No electric fields attributable to the vehicle or exterior sources like powerlines were detected in any of the vehicles.

Occasional electric field readings exceeded the noise level of the sensor. Figure 3-9 shows an example of such readings at time 0 seconds, 560 seconds, 1040 seconds,

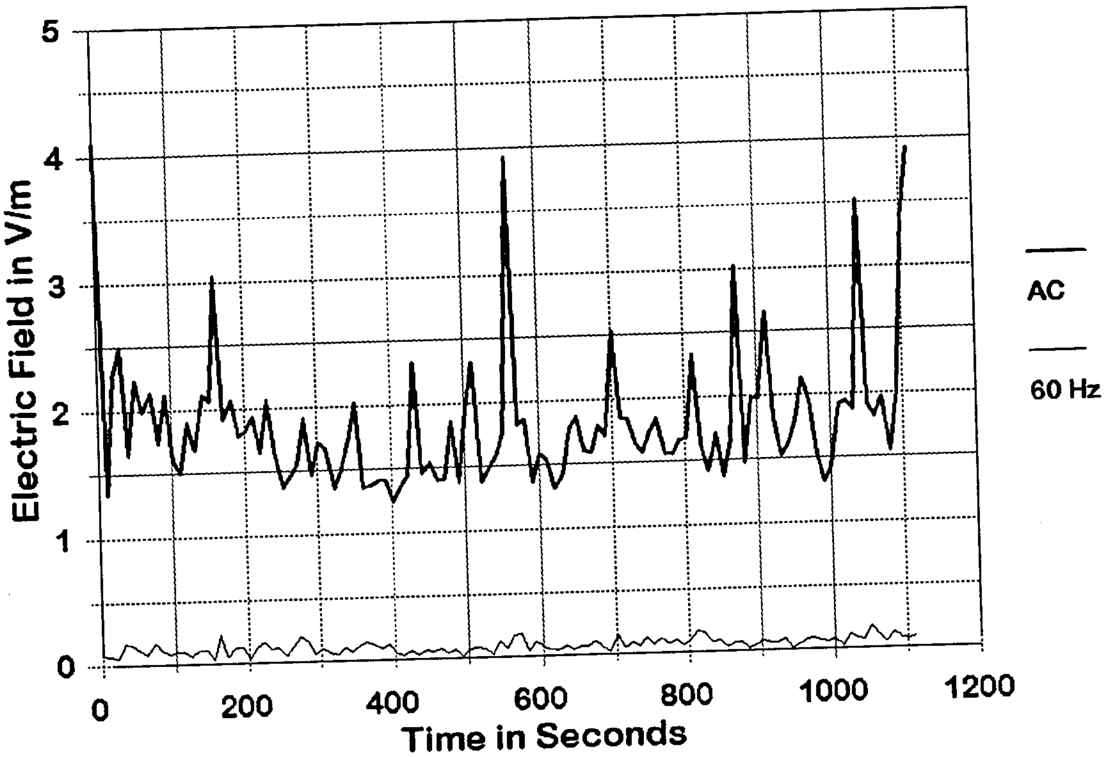


Figure 3-9 Example of Electric Field Data Recorded in Front Section of the Mass Transit Bus.

and at the end of the record at 1100 seconds. Spectral analysis of those field samples reveal only low frequency components with amplitudes decreasing exponentially at higher frequencies. The fields arise from transient changes in the static electric field environment. This test engineer had static electric charge on his clothing and as he moved near the measurement site, the electric field arising from the charge on his clothing changed. In this particular record, the engineer moved past the measurement sensor after starting the monitoring equipment, midway through the measurement to check its status, and again near the end of the record to stop the recording.

3.5 Steel Belted Radial Tires

The principal source of ELF magnetic fields in conventional personal motor vehicles was found to be the rotating tires. All of the personal vehicles tested were equipped with steel belted radial tires and all of those tires appeared to have some permanent magnetism. However, based on examination of the road test data, it appeared as though there was considerable variability between tires. To better understand the nature of the magnetism in steel belted radial tires, a brief study was undertaken in which tires were removed from various vehicles and their magnetic fields were examined in the laboratory. The effort to assess magnetism in steel belted radial tires has been previously reported in detail [6], but the principal findings are summarized here because of their relevance to magnetic field characteristics in both conventional and electric vehicles.

To examine the magnetic characteristics of the tires without the confounding influence of the steel drum, axle, chassis, and vehicle body, the wheels were removed from the vehicle and mounted on a mandrel which was connected to a distant electric motor by means of long fan belts. Although the spindle of the mandrel was steel most of the other parts were made of non-ferromagnetic material such as aluminum and wood. The entire apparatus was mounted on a large wooden bench well removed from other ferromagnetic material. Vehicle wheels with their tires were mounted on the mandrel and turned slowly by hand or rapidly at two different speeds with the electric motor. Three triaxial fluxgate magnetometers were mounted linearly on a fiberglass spar so that the sensors were located 10 cm, 70 cm and 160 cm from the surface of the tire. For most tests, the spar was fixed radially extending from the tire at the center of the tread. For some tires, the spar was also positioned axially and at various angles between axial and radial to better define the spatial distribution of fields around the rotating tire. Analog field waveform data from the magnetometers was recorded digitally using the *MultiWave®* System II recording equipment employed for many of the other field recordings described in this report.

Preliminary measurements were conducted with neither vehicle wheel nor tire on the mandrel to ensure that the test apparatus did not produce any magnetic fields of material value. None were found regardless of whether the device was turned slowly by hand or rotated at 240 or 360 rpm by the electric motor. These rotational speeds were chosen because it was expected that their integral number of revolutions per second (4 and 6) would result in magnetic fields with integral frequencies. Hence, any relationship between rotational speed and field frequency would be more apparent. Furthermore, those speeds are relevant because they represent the rotational rates of the average size tires on vehicles traveling 18.5 and 28 mph. Higher speeds were also of interest, but judged to be too risky if a wheel became unbalanced on the mandrel.

All four wheels from Car 1 and Car 2 in the road tests were removed from the vehicles and tested in the laboratory. Both vehicles had four matched tires which, based on their serial numbers, appeared to have been manufactured in the same plant at the same time. Hence, they were identical from all visible evidence. Additionally, three wheels were tested from two other vehicles. Two contained a matched pair of tires from the same car (designated Car 4) and the third was an old tire which had served as a spare without highway use for at least five years. It is designated as having come from Car 3.

Figure 3-10 shows the waveform of the tangential component of the magnetic field from the left rear tire of Car 1 measured at a point 10 cm radially from the center of the tread. The tire was spinning at 240 rpm (4 revolutions/second) which is equivalent to about 18.5 mph for this size tire. At that speed, it takes 0.25 seconds for the tire to make one revolution. Hence, as expected, each quarter second section of the field waveform is a perfect repeat of the previous quarter second of waveform. The waveform pattern repeats four times per second because the wheel rotates four times per second.

The magnetic field waveform is a recording of the tangential component of the magnetic field 10 cm from the tire as the tire rotates. The same waveform would be recorded if the sensor were to revolve around the tire because it is just a continuous record of static field strength at incremental positions around the tire. The magnetic field that is being measured is static magnetic fields generated by residual magnetism in the steel belts.

Small regions of tire belt have differing amounts of magnetism and different magnetic polarity. One portion produces a strong negative magnetic field of about 430 mG. Each time that patch of tire goes by the sensor, a strong negative field is detected. Since there is one such patch and the tire rotates four times per second, there are four negative pulses of magnetic field per second or a 4 Hz field. Two patches of tire belt produce positive magnetic fields of 150 mG or more. Since the tire rotates four

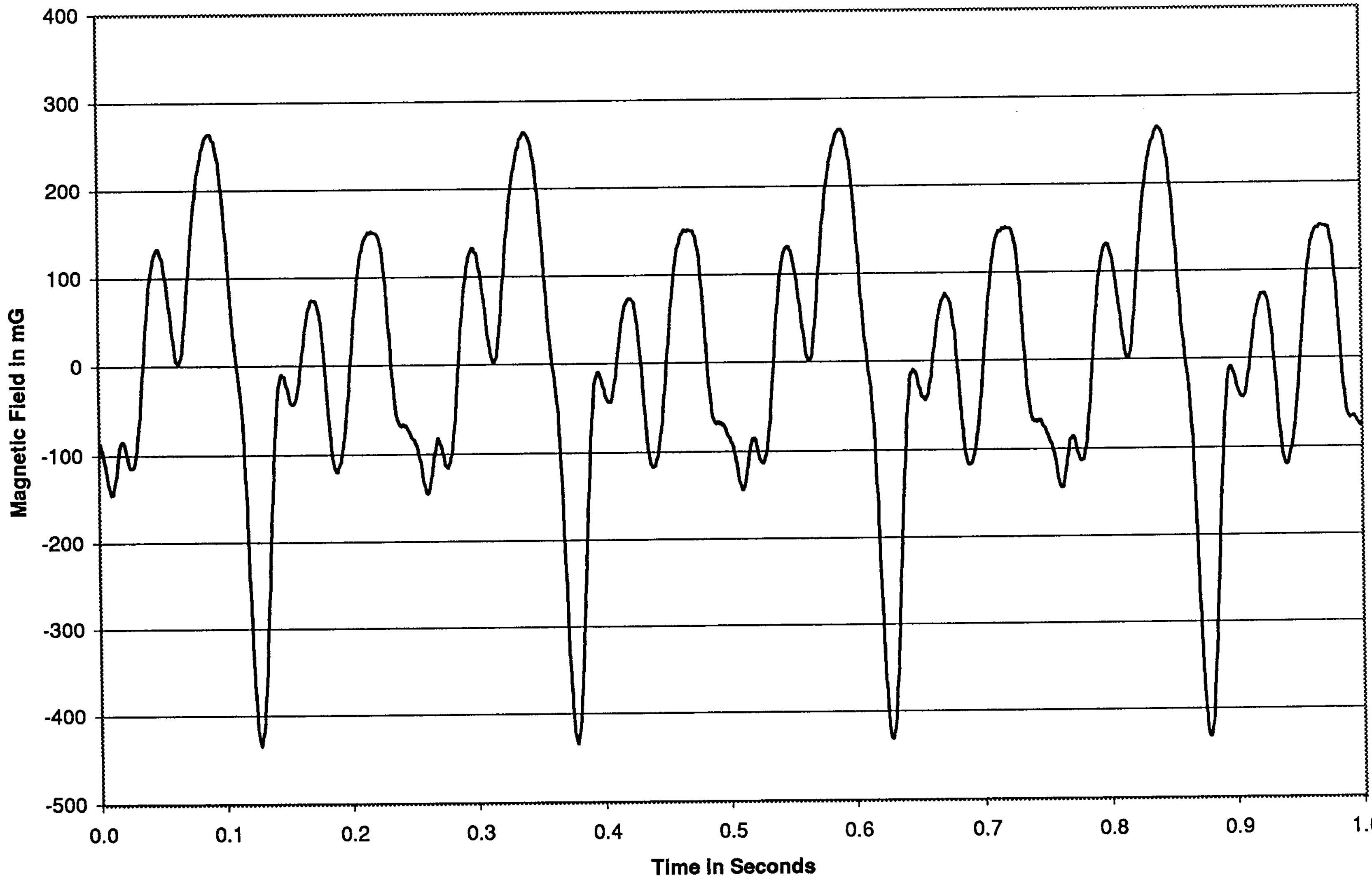


Figure 3-10 Waveform of the Tangential Magnetic Field 10 cm from the Tread of the Left Rear Tire from Car 1 when Spinning at Four Revolutions per Second.

times per second, those patches make positive pulses of 150 mG or more eight times per second or 8 Hz. Other patches of tire belt produce lower fields. A total of four patches produce positive fields giving rise to four positive pulses per revolution, or a 16 Hz field.

One could go on with higher numbers of smaller and smaller patches of field. But there are a few points already demonstrated. First, for each large negative field pulse, there is a corresponding positive field pulse. These dominant positive and negative portions are 2 poles of a magnet. These two largest poles are referred to as a dipole and produce a field at the frequency of tire rotation. The two positive pulses of 150 mG or more have negative regions between them. Since there are 2 such positive and 2 such negative poles, they represent a 4 pole or quadrapole source which produces fields at twice the rotational frequency of the tire. Similarly, the four positive regions have corresponding negative regions between them for a total of eight poles. That octapolar source produces fields at four times the rotational frequency of the tire. The second point to observe is that any waveform can be generated with a distribution of permanent magnetism on the tire belt but the fields will always be at frequencies which are an integral multiple of the tire rotational frequency.

The frequencies present in the field waveform can be determined accurately with a Fast Fourier Transform (FFT). Such an operation produces the frequency spectrum in the top frame of Figure 3-11. As expected, the principal frequency components are integral multiples of 4 Hz.

If the tire spins faster, the patches of steel belt with residual magnetism go past the sensor more times per second. The bottom frame of Figure 3-11 shows the frequency spectrum of the field 10 cm from the same tire when rotating approximately six revolutions per second. The principal frequency components are now integral multiples of the new rotational frequency, 6 revolutions per second. Although the frequency components have shifted in frequency, their magnitudes have not changed because the magnetic field produced by each patch of magnetism in the steel belt remains unchanged.

The spectra of the magnetic fields at three radial distances from the left rear tire of Car 1 are shown in Figure 3-12. Important to observe are the rapid rate at which the fields attenuate with distance and that higher frequency fields attenuate more rapidly than the lower frequency fields. As a result, at relevant distances from the tire, the fields from the dipole and quadrapole field patterns on the steel belt create fields of notable magnitude.

It can be shown theoretically that fields from the dipole source should attenuate at a rate inversely proportional to the distance cubed ($1/2^3$), fields from quadrapole

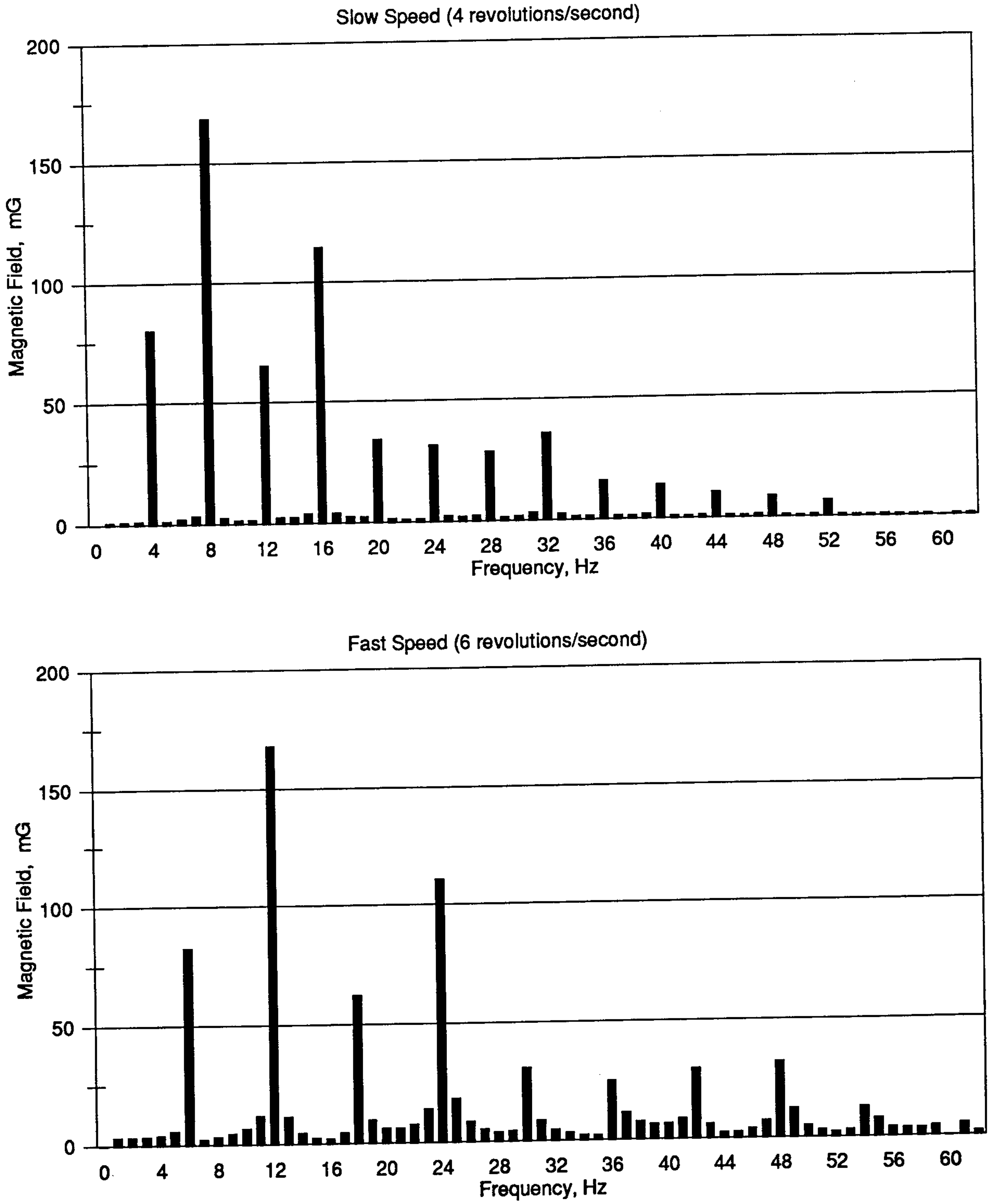


Figure 3-11 Frequency Spectrum of the Magnetic Field 10 cm from the Tread of the Left Rear Tire of Car 1 while Rotating at Four (Top Frame) and Six (Bottom Frame) Revolutions per Second.

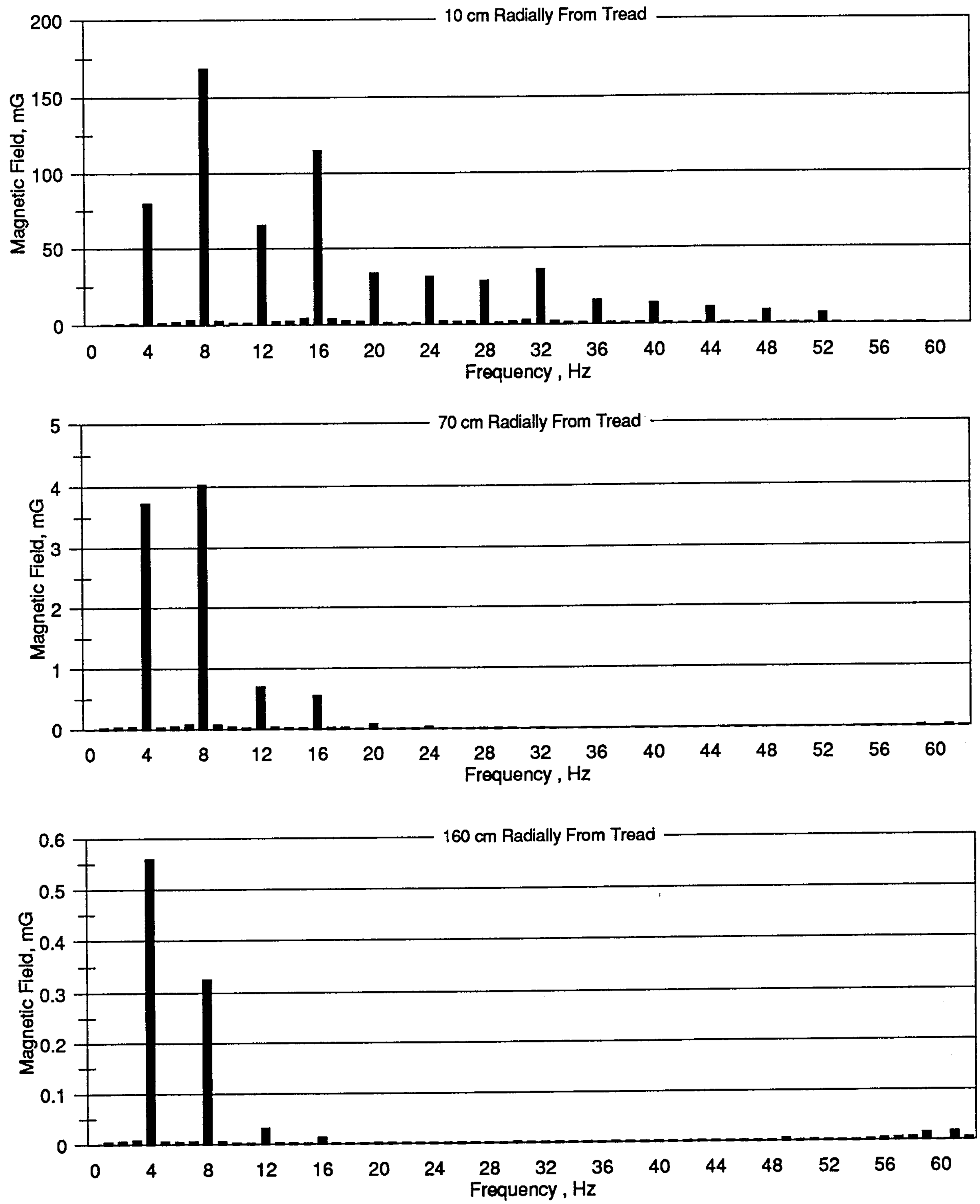


Figure 3-12 Frequency Spectrum of the Magnetic Field Measured Simultaneously at Three Radial Distances from the Tread of the Left Rear Tire of Car 1 while Rotating at Four Revolutions per Second.

source at a rate inversely proportional to the distance to the fourth power ($1/2^4$), octapolar fields at a rate inversely proportional to the distance to the fifth power ($1/2^5$) and so forth. Those theoretical rates were confirmed up to the 16 pole component (32 Hz).

ELF field levels measured at various distances radially and axially from the surface of the tires tested in this effort are provided in Table 3-10. Field levels measured close to the various tires differ by as much as 3 to 1. Differences of nearly 2 to 1 are seen among tires of a matched set from the same vehicle. The reason for the magnetism and the reason for the differences between vehicles is not known.

An effort was made to estimate the extent to which car bodies shield their occupants from the magnetic field produced by the tires.

Using the data in Table 3-10 for the left rear tire of Car 2 and the attenuation rate of the magnetic field described above, we calculated the expected magnetic field level at the location of the waist of the left rear passenger. The expected field level at this location is approximately 28.6 mG with no perturbation due to the vehicle body. Referring to measured field values for the waist of the left rear passenger in that vehicle during highway testing, we found the field from the tires to be approximately 27 mG. Therefore, we must conclude that the body of Car 2 provides no significant shielding of the magnetic field produced by the rotation of the left rear tire.

However, Car 1 did appear to provide some shielding of the magnetic field from the rotating tire. Again using data in Table 3-10 and the attenuation rates, we calculated the expected field level at the location of the waist of the left rear passenger to be approximately 22.5 mG with no vehicle body present. Referring to the measured field values for this location during highway testing, we found the field from the tires to be approximately 3.5 mG. This 85% attenuation may be a result of the shielding properties of the body of the vehicle. The materials and construction of the two vehicles appeared similar so we have no explanation for the widely differing amounts of shielding.

Table 3-10
Magnetic Field Levels in Milligauss (mG) Measured at Three Distances Radially and Axially From Eleven Rotating Tires

	High Speed						Low Speed					
	Radially			Axially			Radially			Axially		
Test	10 cm	70 cm	160cm	10 cm	70 cm	160cm	10 cm	70 cm	160cm	10 cm	70 cm	160cm
Background	0.14	0.07	0.06	0.47	0.13	0.12	0.10	0.06	0.06	0.40	0.08	0.10
Car 1 - LR (mG)	239.0	5.84	0.70	55.55	4.02	0.53	239.5	5.56	0.65	48.19	3.74	0.49
Car 1 - LF (mG)	228.4	4.89	0.57	26.11	3.15	0.43	229.4	4.68	0.53	24.51	2.96	0.40
Car 1 - RF (mG)	200.5	4.63	0.58	15.01	2.93	0.43	196.0	4.37	0.54	14.06	2.72	0.40
Car 1 - RR (mG)	151.9	3.13	0.39	16.92	1.17	0.28	153.4	2.99	0.38	15.98	1.09	0.28
Car 1 - Avg (mG)	204.9	4.62	0.56	28.40	2.82	0.42	204.6	4.40	0.53	25.69	2.63	0.39
Car 1 - COV %	19.00	24.32	22.27	65.99	42.43	24.88	18.99	24.24	21.52	61.02	42.41	21.69
Car 2 - LR (mG)	304.4	7.38	0.69	25.70	2.26	0.33	304.7	7.19	0.66	24.18	2.10	0.31
Car 2 - LF (mG	160.9	4.01	0.45	27.47	2.42	0.33	161.2	3.88	0.42	25.63	2.25	0.31
Car 2 - RR (mG)	277.2	6.18	0.50	10.14	0.80	0.13	277.3	6.05	0.49	9.80	0.75	0.13
Car 2 - RF (mG)	238.7	6.20	0.68	37.89	3.43	0.47	239.5	5.98	0.65	35.37	3.19	0.43
Car 2 - Avg (mG)	245.3	5.94	0.58	25.30	2.23	0.32	245.7	5.78	0.56	23.74	2.07	0.29
Car 2 - COV %	25.43	23.63	21.23	45.24	48.56	43.43	25.37	23.93	21.07	44.39	48.47	42.11
Car 3-Spare mG)	93.7	2.69	0.38	-	-	-	94.1	2.52	0.35	-	-	-
Car 4-Tire A(mG)	182.3	2.56	0.31	-	-	-	182.8	2.45	0.29	-	-	-
Car 4-Tire B (mG)	102.0	2.23	0.32	-	-	-	101.2	2.09	0.29	-	-	-
All Average (mG)	198.2	4.59	0.82	26.86	2.74	1.24	198.1	4.41	0.81	24.74	2.65	1.26
All COV %	34.08	37.42	12.93	53.84	35.10	6.96	34.17	38.13	10.33	50.12	32.36	7.09

4.0 ELECTRIC AUTOMOBILES AND TRUCKS

Significant advances in the design of electric-powered passenger vehicles have occurred in recent years as automobile manufacturers prepare to begin production of electric vehicles in large quantities. Electric passenger vehicles of current design differ markedly from conversion vehicles and early prototypes previously assessed for electric and magnetic field characteristics. Because of this rapidly evolving technology, participation of the auto makers was solicited and four agreed to participate by providing access to their electric vehicles within the scheduled time of this project. They are Chrysler, Ford, General Motors, and Honda.

Only a very limited number of prototype vehicles are available which faithfully represent vehicles in production or soon to be in large scale production. Those prototypes are heavily committed to other ongoing development tests by their manufacturers. Hence, the electric vehicles were not available for shipment to Pittsburgh and testing on the road course used to test conventional vehicles. However, the automobile manufacturers generously agreed to make their facilities available for magnetic field testing at their locations. Ultimately, electric and magnetic field measurements were made in two passenger automobiles, two pickup trucks, and one van.

4.1 Electric Vehicle Characteristics

The purpose of this effort is to characterize the electric and magnetic fields in electric cars and trucks as a class of transportation vehicles rather than focus on the characteristics of any particular vehicle. Consequently, the make and model of specific vehicles are not reported. Alternatively, they are identified as "EV1" through "EV5". All of the vehicles tested were of that manufacturer's most recent design and representative of production vehicles. Some additional information about individual vehicles is provided in later sections describing the measurement results.

4.2 Test Conditions

Magnetic field tests in conventional vehicles discussed in Section 3 above revealed that the principal sources of time-varying magnetic fields within those vehicles were electrical circuits in the vehicle, rotating mechanical parts (especially tires), powerlines and man made field sources along the roadway, vehicle perturbations in the geomagnetic field, and passing perturbations in the geomagnetic field caused by ferromagnetic structures like other cars and bridges in or near the roadway. Those tests found that important factors affecting field levels in conventional vehicles were the characteristics of each particular vehicle, the location in the vehicle where the measurements were made, and various characteristics of the road. All three factors accounted for roughly similar variability in magnetic field levels

Because the characteristics of the roadway were an important factor in determining magnetic field levels in cars and trucks, the most ideal comparative measurements in electric vehicles (EVs) would be conducted on the identical road course. That was not possible due to the limited availability of prototype vehicles representing the most current design. Hence, the decision was made to conduct tests which examined field characteristics in the vehicles and minimized the variability due to different road courses. This was done by conducting tests with the vehicles on a dynamometer and on a test track. Measurement locations within the vehicles and measurement equipment and procedures were the same as those discussed above for conventional vehicles. Where possible, electric and magnetic field measurements were made inside the EVs while performing the Federal Urban Driving Schedule (FUDS) on a dynamometer. The FUDS is a standardized schedule of speed, acceleration, and braking which ensures that the electric vehicles were tested under similar driving conditions. To help relate the results of these dynamometer tests to the results of the highway measurements of conventional vehicles discussed in the preceding section, one of the conventional vehicles (identified as Car #1 in Section 3) was also tested on the various dynamometers used for the EV tests.

Although dynamometer tests using the FUDS have the significant advantage of permitting comparable tests at different facilities, they have two distinct disadvantages. The first is that while the drive train of the vehicle is in motion, the vehicle itself and its non-drive wheels are stationary. That eliminates the production of time-varying fields from three important sources: rotation of the non-drive wheels and tires, differential geomagnetic field shielding by changes in car orientation, and movement past ferromagnetic structures in or near the roadway. The second disadvantage is that the dynamometer facility creates magnetic fields which contribute to the measured fields within the vehicle. Fields from sources other than the dynamometer can be characterized by ambient measurements before the test but fields from the rotating mechanical and electrical components of the dynamometer can not be reliably assessed.

In many cases, electric and magnetic field measurements were made in the electric vehicles while operating on a test track. This test was intended to augment the dynamometer tests because it avoids the limitations of the dynamometer tests; the vehicle and all of its parts are in motion in an environment of low ambient magnetic fields. The disadvantage of the test track approach is that it does not ensure identical operating conditions for all vehicles. This limitation is further exasperated by differences in the test tracks at the automakers facilities. Some were large with long, straight sections while others were small. Some were hilly requiring more fluctuations in motive power, while others were flat. Most of the tracks had operating policies which constrained times or places where vehicles could accelerate and decelerate, constrained vehicle speeds, or constrained the use of accessories such as head lights.

Because of the differences of ambient field levels in the dynamometer facilities, differences in test track design, and differences in test track driving schedules, the electric and magnetic field data from the five EVs may not be perfectly comparable. Nevertheless, the data from the five vehicles, most of which were tested both on a dynamometer and a test track, should provide a reliable indication of the range of field conditions within state-of-the-art electric vehicles.

To help understand the sources of electric and magnetic fields present in the electric vehicles, a set of 'pretest' measurements were conducted analogous to those described for the conventional vehicles in Section 3 above. Identical pretest conditions for the EVs were not possible because some conditions like the 'engine idling' do not apply to the electric vehicles.

Magnetic field measurements were also made around charging equipment when possible. When possible, three-axis field measurements were made at incremental distances along radials extending away from the four sides and the top of the charging equipment. One vehicle had an internal charger so the measurements were made around and within the vehicle.

4.3 Vehicle Magnetic Field Characteristics

The magnetic field characteristics observed during the pretest, dynamometer tests, and track tests are discussed for each individual vehicle and then compared and summarized for all five vehicles. To blind the identity of individual vehicles, they are referred to as "Electric Vehicle #1" through "Electric Vehicle #5" or "EV1" through "EV5". Those identifiers have no relation to actual vehicle model names.

4.3.1 Electric Vehicle #1

Electric Vehicle #1 (EV1) is a vehicle with front and rear seats suitable for four or more passengers. (One American automaker builds an electric vehicle model named "EV1". This is not that vehicle.) The magnetic field measurements were made in the drivers seat, the front right passenger seat and at the two locations in the rear seat behind the driver and front seat passenger. Pretest, dynamometer FUDS, and track tests were conducted on this vehicle.

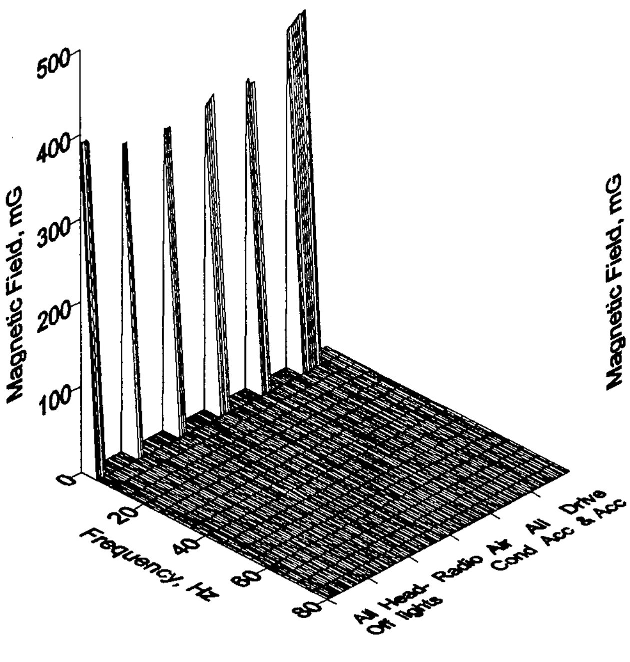
The pretest was conducted just prior to the track tests in an outdoor location having low ambient fields. Sensors in rear-seat measurement locations were secured in stationary plastic holders at positions representing the head, waist, and ankles of a seated passenger. Front-seat sensors were strapped at appropriate locations to the driver and test engineer who rode in the front seat. Electric and magnetic field data were collected at all of the sensor locations with the vehicle in the following states:

- Everything off - ambient fields;
- Headlights on;
- Radio on;
- Air conditioning on, blower full speed;
- Lights, radio, and air conditioning on; and
- On, in "drive", and all accessories on.

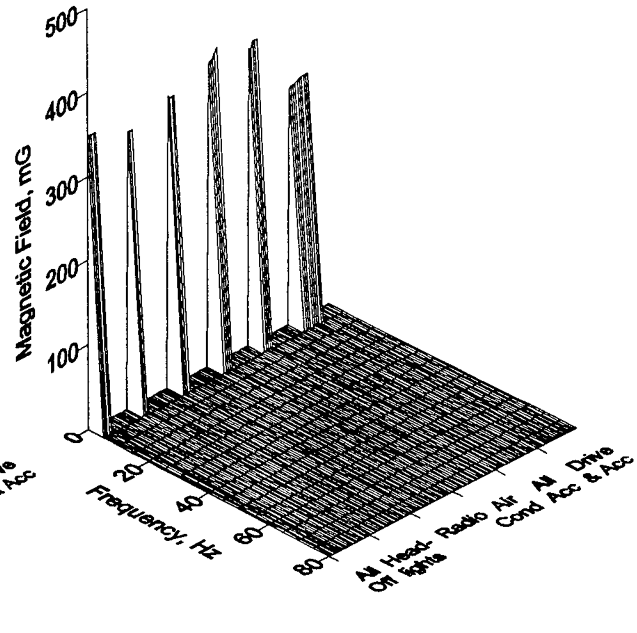
In this vehicle, like most of the EVs, the ignition switch had to be in the "accessory" position to turn on the accessories. In the last condition, the vehicle was in the "on" position and in drive with the brake on, as it would be just before accelerating.

Figure 4-1 shows the magnetic field levels measured at the ankle height sensors as a function of frequency for several sequential samples measured at 10-second intervals for each of the above stated vehicle states. The static (0 Hz) field component is the only component clearly visible in this figure. Static field levels are suppressed below the normal 500 mG geomagnetic field level by the shielding provided by the vehicle frame, body, and seat components. They do not change appreciably with vehicle status except when the vehicle is in drive with the brake applied. Similar characteristics of the static field are visible at the head and waist sensor positions but with a smaller change when the vehicle is placed in drive.

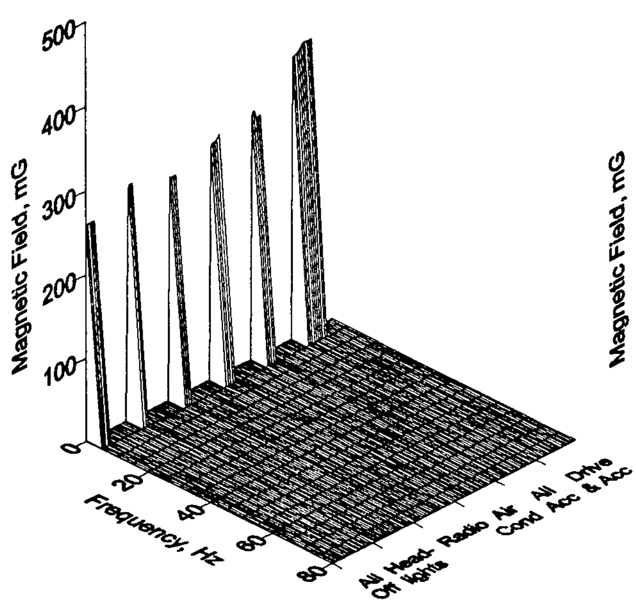
Figure 4-1 also shows the presence of a time-varying field of about 62 Hz at the right rear passenger's ankles for all of the vehicle states except when everything is off. To better show the characteristics of the time-varying fields, concurrent measurements were made with the static field suppressed to allow greater sensitivity. Figure 4-2 shows that data. Ambient time-varying fields are very small when the vehicle is off. When the vehicle is turned on to the accessory position for the test, harmonic-rich fields appear most predominantly in the right-rear ankle position, smaller in the front seat ankle positions, and smallest in the left rear ankle position. Figure 4-2 also shows that while the 62 Hz field and its harmonics are present in roughly constant magnitude in all vehicle states, other frequency components are present only in certain states. For example, a field of about 0.4 mG at about 750 Hz appears at both front seat positions only when the air conditioner and fan are on. These time-varying magnetic fields apparently arise from sources beneath the floor



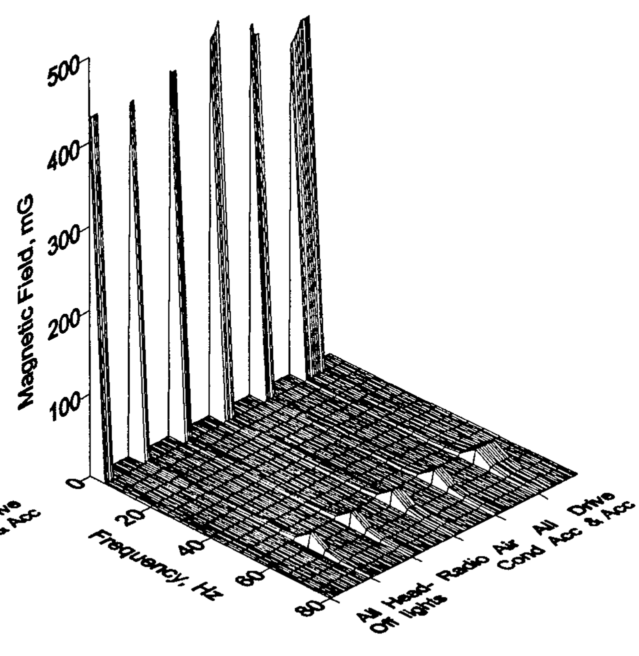
Driver's Ankle



Right Front Passenger's Ankle

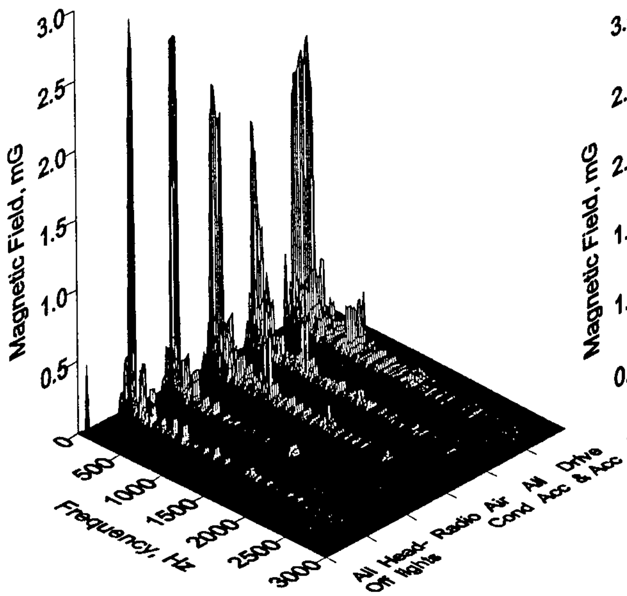


Left Rear Passenger's Ankle

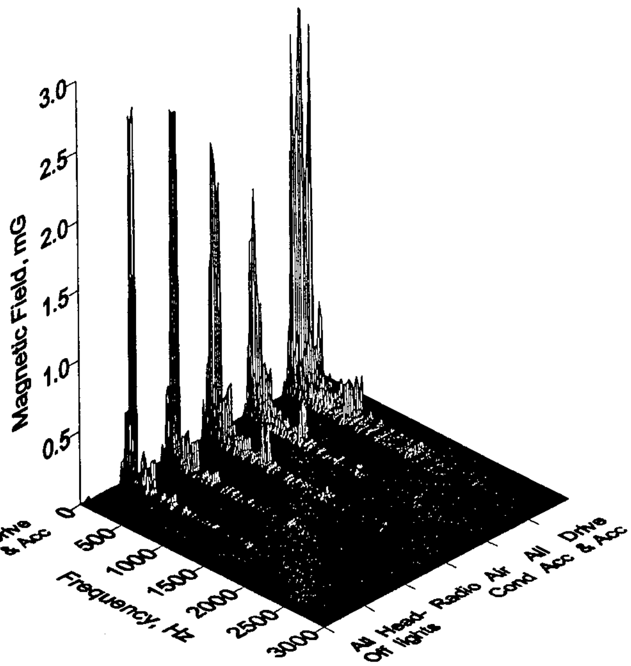


Right Rear Passenger's Ankle

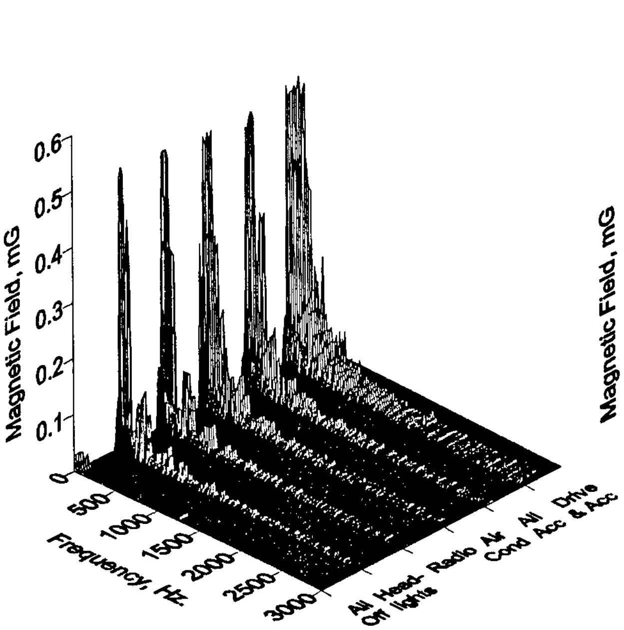
Figure 4-1 Magnetic Field Levels as a Function of Frequency at Ankle Level in Electric Vehicle 1 during Three or More Successive Samples with the Vehicle in the Indicated State during the Pretest.



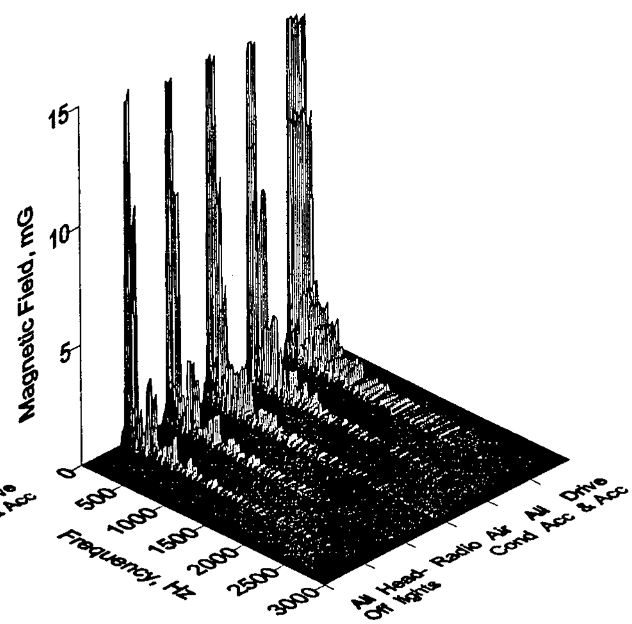
Driver's Ankle



Right Front Passenger's Ankle



Left Rear Passenger's Ankle



Right Rear Passenger's Ankle

Figure 4-2 Time-Varying Magnetic Field Levels as a Function of Frequency at Ankle Level in Electric Vehicle 1 during Three or More Successive Samples with the Vehicle in the Indicated State during the Pretest. Static Fields are Suppressed to Better Show the Time-Varying Components.

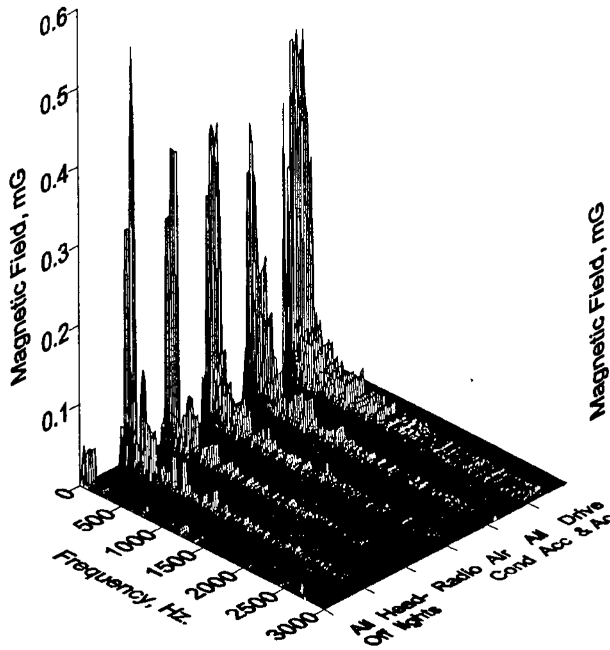
because their magnitudes are appreciably smaller at waist level (Figure 4-3) and smaller yet at head level. Although the fields are smaller at the waist and head position, most of the same frequency components remain present.

Because the frequency of the principal ELF field component was so near the power frequency, extensive data checking was undertaken to determine the likelihood that this field arose from the measurement instrumentation or some other unexpected source unrelated to the vehicle. An extensive audit of on-site records, data comparisons, interviews with the test engineers, and reanalysis of the data indicate that the field originates from a highly-localized source just below the floor behind the front passenger seat. However, the authors remain unconvinced. Magnetic field data measured at the right rear ankle position in this vehicle should be used with caution, as should 62 Hz and harmonic field components recorded elsewhere in this vehicle.

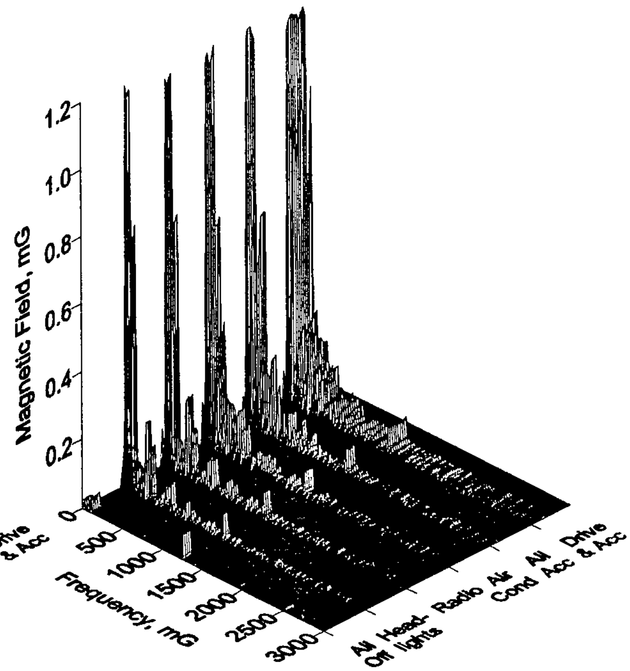
Table 4-1 summarizes the average field levels in EV1 during the pretest by measurement position, vehicle state, and frequency band. As those data indicate, the average ELF field level in the stationary vehicle is approximately 3 mG and essentially independent of accessory status once the vehicle is switched on. The field is highest at the ankle position in the right rear seat and is predominantly at a frequency just over 60 Hz. Aside from the ankle-height locations, the magnetic field is less than 2 mG in all seats.

Magnetic field levels in EV1 were also measured while the vehicle was mounted on a chassis dynamometer running the speed and acceleration profile of the (FUDS). All of the accessories were off. Waveform measurements were made at the head, waist, and ankle positions of the driver and three passengers. Figure 4-4 shows the time-varying field levels at waist level as a function of frequency and time. The frequency scale is expanded to show just the portion below 1000 Hz where most of the significant frequency components exist. The principal frequency components near 60 Hz and above seen in the pretest (Figure 4-3) are present at essentially constant values regardless of the vehicle speed, acceleration, or braking. However, low frequency components, principally below 60 Hz, are present and fluctuate in frequency and intensity. The characteristics of these low-frequency fields are much like those seen in the conventional vehicles arising from rotating tires and other mechanical parts. While the same sources are likely involved in producing these fields in the electric vehicle, contributions from moving mechanical parts or electrical parts of the dynamometer can not be ruled out.

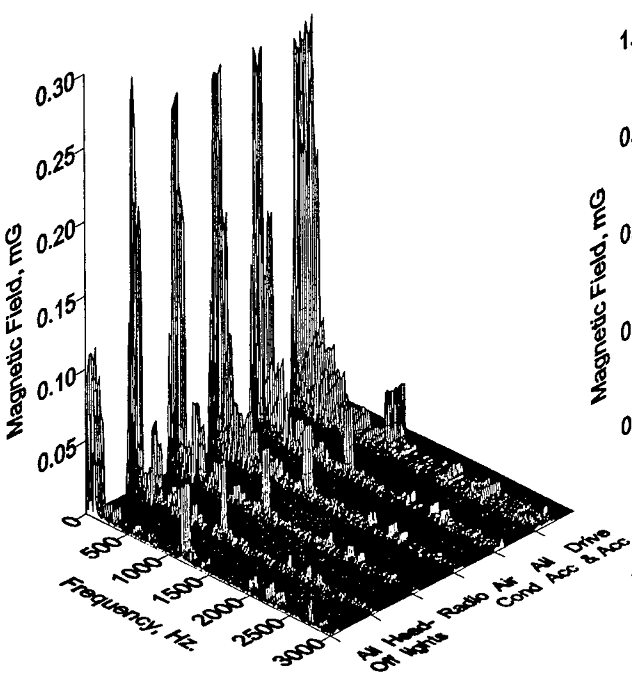
Magnetic fields at head and ankle levels shared similar frequency characteristics as those shown in Figure 4-4 for waist level but the constant higher-frequency field components showed a larger relationship with height



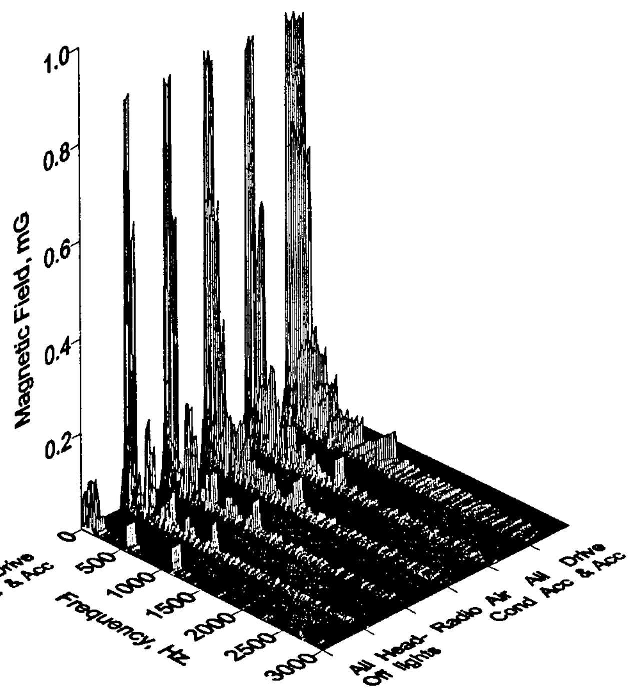
Driver's Waist



Right Front Passenger's Waist



Left Rear Passenger's Waist



Right Rear Passenger's Waist

Figure 4-3 Time-Varying Magnetic Field Levels as a Function of Frequency at Waist Level in Electric Vehicle 1 during Three or More Successive Samples with the Vehicle in the Indicated State during the Pretest. Static Fields are Suppressed to Better Show the Time-Varying Components.

Table 4-1
Summary of Average Magnetic Field Levels in Electric Vehicle #1
During the Stationary Pretest Measurements (Means of 3 or More Measurements)

Frequency Band	Sensor Location	Everything Off Field (mG)	Headlights On Field (mG)	Radio On Field (mG)	Air Cond. and Fan On Field (mG)	All Acc. On Field (mG)	In Drive, Acc On Field (mG)
Static	Driver's Head	199	192	175	193	176	214
	Right Front Pass. Head	241	239	242	248	252	238
	Left Rear Pass. Head	271	273	271	275	272	274
	Right Rear Pass. Head	343	344	345	348	346	340
	Driver's Waist	123	134	124	132	139	162
	Right Front Pass. Waist	362	352	351	360	354	336
	Left Rear Pass. Waist	223	229	224	231	231	242
	Right Rear Pass. Waist	254	255	257	264	256	250
	Driver's Ankle	390	364	357	363	361	408
	Right Front Pass. Ankle	349	329	345	366	356	285
	Left Rear Pass. Ankle	259	282	266	283	289	341
	Right Rear Pass. Ankle	429	422	432	453	430	405
	All Positions	287	285	282	293	289	291
5 - 55 Hz Low Frequencies	Driver's Head	0.1	0.1	0.4	0.3	0.3	0.5
	Right Front Pass. Head	0.2	0.4	0.3	0.8	0.4	0.6
	Left Rear Pass. Head	0.2	0.2	0.2	0.2	0.2	0.2
	Right Rear Pass. Head	0.1	0.1	0.1	0.1	0.1	0.1
	Driver's Waist	0.1	0.1	0.1	0.1	0.1	0.2
	Right Front Pass. Waist	0.1	0.5	0.5	0.5	0.5	0.5
	Left Rear Pass. Waist	0.1	0.2	0.2	0.2	0.2	0.2
	Right Rear Pass. Waist	0.1	0.3	0.3	0.4	0.3	0.4
	Driver's Ankle	0.1	0.3	0.2	0.3	0.2	0.3
	Right Front Pass. Ankle	0.0	0.3	0.3	0.4	0.3	0.3
	Left Rear Pass. Ankle	0.0	0.2	0.2	0.4	0.2	0.4
	Right Rear Pass. Ankle	0.0	5.6	5.4	5.6	5.5	5.9
	All Positions	0.1	0.7	0.7	0.8	0.7	0.8
60 Hz Power Frequency	Driver's Head	0.0	0.3	0.3	0.3	0.3	0.3
	Right Front Pass. Head	0.0	0.5	0.5	0.5	0.6	0.5
	Left Rear Pass. Head	0.0	0.2	0.2	0.2	0.2	0.2
	Right Rear Pass. Head	0.0	0.3	0.3	0.3	0.3	0.3
	Driver's Waist	0.0	0.3	0.3	0.3	0.3	0.3
	Right Front Pass. Waist	0.0	1.2	1.1	1.1	1.2	1.1
	Left Rear Pass. Waist	0.0	0.3	0.3	0.3	0.3	0.3
	Right Rear Pass. Waist	0.0	0.9	0.8	0.8	0.8	0.8
	Driver's Ankle	0.0	0.4	0.3	0.3	0.4	0.3
	Right Front Pass. Ankle	0.0	0.5	0.5	0.5	0.5	0.5
	Left Rear Pass. Ankle	0.0	0.5	0.5	0.5	0.5	0.5
	Right Rear Pass. Ankle	0.0	14.5	14.3	14.4	14.0	14.2
	All Positions	0.0	1.7	1.6	1.6	1.6	1.6

Table 4-1 (Continued)

Frequency Band	Sensor Location	Everything Off Field (mG)	Headlights On Field (mG)	Radio On Field (mG)	Air Cond. and Fan On Field (mG)	All Acc. On Field (mG)	In Drive, Acc On Field (mG)
65 - 300 Hz Power Harmonics	Driver's Head	0.0	0.6	0.6	0.6	0.5	0.6
	Right Front Pass. Head	0.1	0.8	0.7	0.7	0.7	0.8
	Left Rear Pass. Head	0.0	0.2	0.3	0.3	0.3	0.3
	Right Rear Pass. Head	0.0	0.3	0.3	0.3	0.3	0.3
	Driver's Waist	0.1	0.6	0.5	0.6	0.5	0.6
	Right Front Pass. Waist	0.1	1.2	1.2	1.3	1.3	1.3
	Left Rear Pass. Waist	0.2	0.3	0.3	0.3	0.3	0.4
	Right Rear Pass. Waist	0.2	0.9	0.9	0.9	1.0	0.9
	Driver's Ankle	0.0	2.9	2.7	3.0	1.8	2.6
	Right Front Pass. Ankle	0.0	2.8	2.7	2.7	1.8	2.9
	Left Rear Pass. Ankle	0.0	0.5	0.5	0.6	0.6	0.7
	Right Rear Pass. Ankle	0.0	15.0	15.7	15.4	15.7	16.0
	All Positions	0.1	2.2	2.2	2.2	2.1	2.3
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.2	0.2	0.1	0.1	0.2
	Right Front Pass. Head	0.1	0.2	0.2	0.2	0.2	0.3
	Left Rear Pass. Head	0.1	0.1	0.1	0.1	0.1	0.1
	Right Rear Pass. Head	0.1	0.1	0.1	0.1	0.1	0.1
	Driver's Waist	0.0	0.2	0.1	0.1	0.1	0.2
	Right Front Pass. Waist	0.1	0.4	0.4	0.3	0.3	0.4
	Left Rear Pass. Waist	0.1	0.1	0.1	0.1	0.1	0.1
	Right Rear Pass. Waist	0.1	0.3	0.3	0.3	0.3	0.3
	Driver's Ankle	0.0	0.5	0.4	0.7	0.6	0.6
	Right Front Pass. Ankle	0.0	0.4	0.4	0.5	0.4	0.6
	Left Rear Pass. Ankle	0.0	0.2	0.2	0.2	0.2	0.2
	Right Rear Pass. Ankle	0.0	5.0	5.0	4.3	3.9	4.8
	All Positions	0.1	0.6	0.6	0.6	0.5	0.7
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.1	0.7	0.8	0.8	0.7	0.9
	Right Front Pass. Head	0.2	1.1	1.0	1.3	1.0	1.2
	Left Rear Pass. Head	0.2	0.4	0.4	0.4	0.4	0.4
	Right Rear Pass. Head	0.1	0.5	0.5	0.5	0.5	0.5
	Driver's Waist	0.1	0.7	0.6	0.7	0.6	0.7
	Right Front Pass. Waist	0.1	1.8	1.8	1.8	1.8	1.8
	Left Rear Pass. Waist	0.2	0.5	0.5	0.5	0.4	0.5
	Right Rear Pass. Waist	0.2	1.3	1.3	1.3	1.4	1.4
	Driver's Ankle	0.1	3.0	2.8	3.1	1.9	2.7
	Right Front Pass. Ankle	0.0	2.9	2.8	2.8	1.9	3.0
	Left Rear Pass. Ankle	0.1	0.8	0.8	0.9	0.8	1.0
	Right Rear Pass. Ankle	0.0	22.2	22.5	22.2	22.1	22.7
	All Positions	0.1	3.0	3.0	3.0	2.8	3.1
	Number of Samples	5	3	4	5	5	10

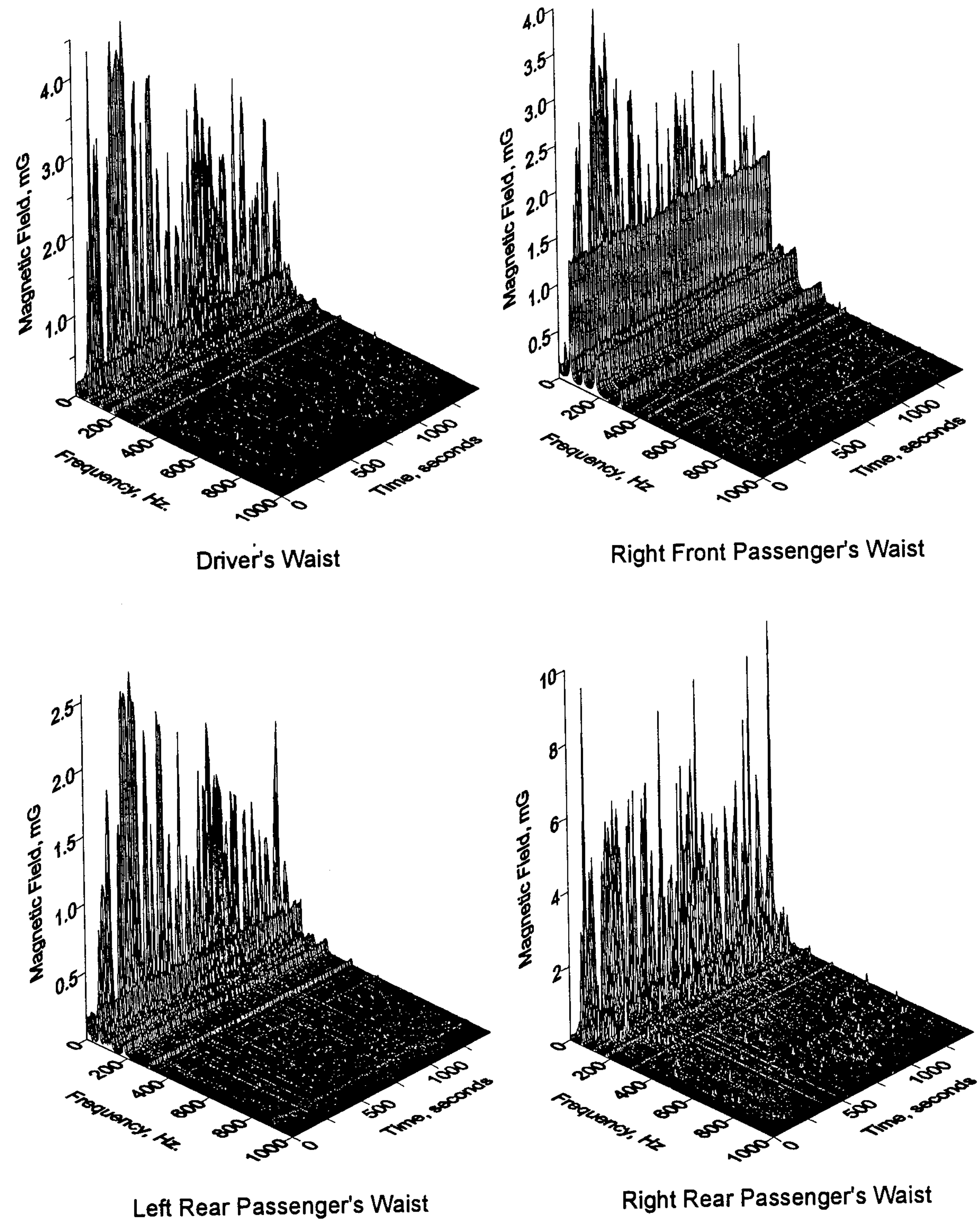


Figure 4-4 **Time-Varying Magnetic Field Levels as a Function of Frequency and Time at Waist Level in Electric Vehicle 1 while Running the FUDS on a Dynamometer.**

above the floor than did the lower frequency components. The field levels measured during the FUDS at all three heights are summarized in Table 4-2. Comparing the field data collected during the FUDS test on the dynamometer to those in Table 4-1 for the pretest data, one sees general agreement in field distributions across frequency and location except for the appearance of lower frequency fields in the FUDS test.

Magnetic fields were also measured at the head, waist, and ankle position of the driver and three passengers in EV1 while operating on an oval test track. Due to the small size of the track, most of the driving was at approximately 30 mph with acceleration and braking at the beginning and end of the record, respectively. The spectral characteristics of the field were similar to those observed in the pretest and FUDS test.

Table 4-3 shows summary statistics for the test track measurements. Temporal variability of the 60 Hz and higher field components remained small as in the FUDS test and pretest data. The intensities of those field components are similar and have similar spatial variability within the vehicle.

Low frequency components are larger in the track tests presumably because all four tires are rotating and time-varying field components are being generated due to differential shielding of the geomagnetic field as the vehicle changes directions on the oval track. Hence, it appears as though the low-frequency fields seen in the FUDS test arise primarily from the vehicle, not the dynamometer. The temporal variability of the low frequency fields as reflected in their coefficients of variation is larger in the FUDS test data than in the track test data. That difference probably arises from the wider range of driving speeds, including some stops, in the FUDS test compared to the relatively constant-speed during the track tests.

The static field levels observed in EV1 during the track tests showed a very well-defined, sinusoidal-like variation in intensity as the vehicle circumnavigated the oval track. This variability is undoubtedly due to differential shielding by the vehicle body, chassis, and seats depending on orientation in the geomagnetic field. This variation gives rise to coefficients of variation in the static field which are much larger at most locations than those seen in the stationary vehicle on the dynamometer. That indicates that temporal variations in the static field from movement of the vehicle considerably exceed variations due to changes in dc current in the vehicle's electrical system.

Table 4-2
Summary of Magnetic Field Levels in Electric Vehicle #1
During the FUDS Test on a Dynamometer

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	304	387	337	19	6
	Right Front Pass. Head	243	319	269	16	6
	Left Rear Pass. Head	310	364	342	13	4
	Right Rear Pass. Head	201	289	217	14	6
	Driver's Waist	197	286	253	17	7
	Right Front Pass. Waist	203	338	238	25	10
	Left Rear Pass. Waist	190	227	207	10	5
	Right Rear Pass. Waist	301	420	328	21	7
	Driver's Ankle	335	664	456	57	13
	Right Front Pass. Ankle	314	527	361	36	10
	Left Rear Pass. Ankle	106	257	167	37	22
	Right Rear Pass. Ankle	315	873	497	112	23
	All Positions	106	873	306	105	34
5 - 55 Hz Low Frequencies	Driver's Head	0.1	4.3	1.3	0.8	62
	Right Front Pass. Head	0.2	2.7	1.0	0.6	56
	Left Rear Pass. Head	0.2	1.7	0.7	0.4	62
	Right Rear Pass. Head	0.1	2.4	0.7	0.4	65
	Driver's Waist	0.1	5.2	1.9	1.4	72
	Right Front Pass. Waist	0.2	4.1	1.6	1.0	64
	Left Rear Pass. Waist	0.1	2.7	1.1	0.7	71
	Right Rear Pass. Waist	0.2	3.3	1.0	0.6	63
	Driver's Ankle	0.1	11.6	3.6	2.4	66
	Right Front Pass. Ankle	0.1	17.4	5.2	3.6	69
	Left Rear Pass. Ankle	0.1	7.4	2.4	1.8	76
	Right Rear Pass. Ankle	1.8	9.0	3.2	1.1	33
	All Positions	0.1	17.4	2.0	2.0	103
60 Hz Power Frequency	Driver's Head	0.3	0.6	0.4	0.0	8
	Right Front Pass. Head	0.5	0.9	0.7	0.0	6
	Left Rear Pass. Head	0.2	0.3	0.2	0.0	8
	Right Rear Pass. Head	0.3	0.4	0.4	0.0	3
	Driver's Waist	0.2	0.5	0.4	0.0	11
	Right Front Pass. Waist	1.2	1.6	1.3	0.0	3
	Left Rear Pass. Waist	0.2	0.4	0.3	0.0	10
	Right Rear Pass. Waist	0.9	1.0	0.9	0.0	3
	Driver's Ankle	0.3	1.7	0.5	0.2	37
	Right Front Pass. Ankle	0.3	9.4	0.7	0.8	111
	Left Rear Pass. Ankle	0.5	0.9	0.6	0.1	9
	Right Rear Pass. Ankle	11.1	12.5	11.8	0.2	2
	All Positions	0.2	12.5	1.5	3.1	206

Table 4-2 (Continued)

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
65 - 300 Hz Power Harmonics	Driver's Head	0.3	0.7	0.4	0.1	18
	Right Front Pass. Head	0.4	0.6	0.5	0.0	6
	Left Rear Pass. Head	0.2	0.3	0.2	0.0	10
	Right Rear Pass. Head	0.2	0.3	0.3	0.0	6
	Driver's Waist	0.2	1.3	0.4	0.1	37
	Right Front Pass. Waist	0.8	1.4	0.9	0.1	8
	Left Rear Pass. Waist	0.2	0.5	0.3	0.0	14
	Right Rear Pass. Waist	0.7	0.8	0.7	0.0	3
	Driver's Ankle	0.2	8.4	1.1	1.0	94
	Right Front Pass. Ankle	0.4	12.1	1.7	1.7	100
	Left Rear Pass. Ankle	0.4	1.6	0.9	0.3	35
	Right Rear Pass. Ankle	9.1	10.0	9.5	0.2	2
	All Positions	0.2	12.1	1.4	2.5	181
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.3	0.1	0.0	20
	Right Front Pass. Head	0.2	0.3	0.2	0.0	8
	Left Rear Pass. Head	0.1	0.1	0.1	0.0	13
	Right Rear Pass. Head	0.1	0.2	0.1	0.0	10
	Driver's Waist	0.1	0.2	0.1	0.1	36
	Right Front Pass. Waist	0.2	0.4	0.3	0.0	10
	Left Rear Pass. Waist	0.1	0.2	0.1	0.0	19
	Right Rear Pass. Waist	0.2	0.3	0.2	0.0	8
	Driver's Ankle	0.1	0.7	0.3	0.2	49
	Right Front Pass. Ankle	0.1	1.2	0.5	0.3	58
	Left Rear Pass. Ankle	0.1	1.4	0.6	0.4	65
	Right Rear Pass. Ankle	2.1	3.3	2.6	0.3	11
	All Positions	0.1	3.3	0.4	0.7	154
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.5	4.3	1.5	0.8	50
	Right Front Pass. Head	0.8	2.9	1.4	0.4	32
	Left Rear Pass. Head	0.4	1.8	0.8	0.4	49
	Right Rear Pass. Head	0.5	2.4	0.8	0.3	41
	Driver's Waist	0.4	5.2	2.0	1.3	63
	Right Front Pass. Waist	1.5	4.4	2.4	0.7	30
	Left Rear Pass. Waist	0.4	2.7	1.2	0.7	57
	Right Rear Pass. Waist	1.2	3.5	1.6	0.4	25
	Driver's Ankle	0.5	11.6	4.0	2.4	60
	Right Front Pass. Ankle	0.7	17.6	5.8	3.6	62
	Left Rear Pass. Ankle	0.7	7.5	2.8	1.7	60
	Right Rear Pass. Ankle	14.7	17.6	15.7	0.4	2
	All Positions	0.4	17.6	3.3	4.2	127
	Number of Samples	145				

Table 4-3
Summary of Magnetic Field Levels in Electric Vehicle #1
During the Test Track Measurements

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	152	467	325	105	32
	Right Front Pass. Head	220	323	272	33	12
	Left Rear Pass. Head	146	380	267	82	31
	Right Rear Pass. Head	300	377	343	25	7
	Driver's Waist	91	279	199	62	31
	Right Front Pass. Waist	188	400	302	72	24
	Left Rear Pass. Waist	118	355	240	79	33
	Right Rear Pass. Waist	111	358	274	71	26
	Driver's Ankle	143	453	310	102	33
	Right Front Pass. Ankle	303	437	360	34	9
	Left Rear Pass. Ankle	24	375	214	94	44
	Right Rear Pass. Ankle	409	597	486	43	9
	All Positions	24	597	299	102	34
5 - 55 Hz Low Frequencies	Driver's Head	0.5	10.4	1.5	1.6	106
	Right Front Pass. Head	0.7	2.5	1.3	0.4	31
	Left Rear Pass. Head	0.4	1.3	0.8	0.2	21
	Right Rear Pass. Head	1.4	2.2	1.8	0.2	11
	Driver's Waist	0.6	2.4	1.3	0.5	36
	Right Front Pass. Waist	1.0	4.2	1.6	0.6	37
	Left Rear Pass. Waist	0.6	2.2	1.2	0.4	31
	Right Rear Pass. Waist	2.3	3.8	3.0	0.4	14
	Driver's Ankle	1.3	4.3	2.5	0.7	29
	Right Front Pass. Ankle	2.2	8.5	3.4	1.2	36
	Left Rear Pass. Ankle	1.3	8.2	3.1	1.5	47
	Right Rear Pass. Ankle	6.0	9.9	7.2	1.0	13
	All Positions	0.4	10.4	2.4	1.9	78
60 Hz Power Frequency	Driver's Head	0.3	0.7	0.4	0.1	15
	Right Front Pass. Head	0.4	0.6	0.6	0.0	6
	Left Rear Pass. Head	0.2	0.2	0.2	0.0	6
	Right Rear Pass. Head	0.2	0.4	0.3	0.0	12
	Driver's Waist	0.2	0.3	0.3	0.0	6
	Right Front Pass. Waist	1.1	1.3	1.2	0.0	3
	Left Rear Pass. Waist	0.2	0.3	0.3	0.0	7
	Right Rear Pass. Waist	0.7	1.0	0.9	0.1	6
	Driver's Ankle	0.2	0.5	0.3	0.1	22
	Right Front Pass. Ankle	0.4	1.6	0.6	0.2	33
	Left Rear Pass. Ankle	0.4	0.6	0.5	0.1	10
	Right Rear Pass. Ankle	13.8	15.3	14.6	0.4	3
	All Positions	0.2	15.3	1.7	3.9	235

Table 4-3 (Continued)

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
65 - 300 Hz Power Harmonics	Driver's Head	0.5	1.6	0.6	0.2	27
	Right Front Pass. Head	0.7	0.9	0.8	0.0	6
	Left Rear Pass. Head	0.3	0.3	0.3	0.0	6
	Right Rear Pass. Head	0.3	0.5	0.4	0.1	15
	Driver's Waist	0.5	0.7	0.6	0.0	6
	Right Front Pass. Waist	1.3	1.5	1.4	0.1	4
	Left Rear Pass. Waist	0.3	0.5	0.4	0.0	8
	Right Rear Pass. Waist	0.9	1.3	1.0	0.1	8
	Driver's Ankle	2.4	3.0	2.6	0.1	4
	Right Front Pass. Ankle	2.7	5.0	3.0	0.3	11
	Left Rear Pass. Ankle	0.7	1.7	1.4	0.2	13
	Right Rear Pass. Ankle	16.1	18.5	17.3	0.6	3
	All Positions	0.3	18.5	2.5	4.6	184
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.8	0.2	0.1	47
	Right Front Pass. Head	0.2	0.3	0.3	0.0	6
	Left Rear Pass. Head	0.1	0.1	0.1	0.0	6
	Right Rear Pass. Head	0.1	0.2	0.2	0.0	13
	Driver's Waist	0.1	0.2	0.2	0.0	6
	Right Front Pass. Waist	0.4	0.5	0.4	0.0	5
	Left Rear Pass. Waist	0.1	0.2	0.1	0.0	7
	Right Rear Pass. Waist	0.3	0.5	0.4	0.0	7
	Driver's Ankle	0.4	0.6	0.5	0.0	8
	Right Front Pass. Ankle	0.5	1.1	0.6	0.1	15
	Left Rear Pass. Ankle	0.5	0.8	0.6	0.1	12
	Right Rear Pass. Ankle	4.7	5.7	5.4	0.2	4
	All Positions	0.1	5.7	0.7	1.4	191
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.8	10.6	1.7	1.5	91
	Right Front Pass. Head	1.2	2.7	1.6	0.3	20
	Left Rear Pass. Head	0.5	1.3	0.9	0.2	17
	Right Rear Pass. Head	1.5	2.3	1.9	0.2	10
	Driver's Waist	0.9	2.5	1.5	0.4	29
	Right Front Pass. Waist	2.1	4.6	2.4	0.5	19
	Left Rear Pass. Waist	0.7	2.2	1.3	0.4	27
	Right Rear Pass. Waist	2.7	4.1	3.3	0.4	12
	Driver's Ankle	2.9	5.1	3.7	0.5	14
	Right Front Pass. Ankle	3.7	10.0	4.6	1.1	24
	Left Rear Pass. Ankle	1.7	8.4	3.6	1.4	38
	Right Rear Pass. Ankle	22.9	25.7	24.4	0.7	3
	All Positions	0.5	25.7	4.2	6.2	147
	Number of Samples	43				

4.3.2 Electric Vehicle #2

Electric Vehicle #2 (EV2) is another vehicle with front and rear seats suitable for four or more passengers. Like EV1, field measurements were made at the head, waist, and ankle positions of passengers in the driver's seat, the front right passenger seat, and the rear seats behind the driver and front passenger. Only pretest and track measurements were made on this vehicle as a dynamometer equipped for running the FUDS was not available.

The pretest measurements were conducted at an outdoor location with low ambient ELF magnetic fields. The procedure was nearly the same as that described above for EV1. The air conditioner on this vehicle would not operate with the ignition switch in the "accessory" position, so no data were collected for the air conditioning only or all accessory states. The air conditioning did function when the ignition switch was in the "on" position so the last pretest state included the vehicle on, in drive, brake set, and lights, radio, air conditioning and fan operating. Figure 4-5 and Table 4-4 show the results of the pretest measurements. ELF field levels were very small throughout the vehicle rising only slightly near the ankles of the driver and front seat passenger when the headlights were on (0.6 and 1.0 mG, respectively) and somewhat more appreciably at the same locations when the vehicle and all of its accessories were on (2.1 and 7.4 mG, respectively). The principal frequency components of this field were approximately 155 Hz and harmonics thereof. When the lights were on in the last condition with the vehicle on, in drive, and all accessories on, another set of frequencies, 670 Hz and harmonics thereof, appeared in the field spectrum. ELF field levels at other locations in the stationary car did not exceed 0.5 mG for any condition.

Two sets of track tests were run with EV2. Both tests included acceleration from zero to 60, sustained operation at about 50, 30, and 15 mph, various accelerations and decelerations, and three long periods of deceleration. During the first track test, vehicle was placed in neutral and allowed to coast while in the long deceleration tests. But in the second set of tests, the ignition switch was also turned off while coasting during the long decelerations. Headlights and emergency flashers were on during both track tests. Figure 4-6 shows time-varying field levels at the ankle positions prior to and during the first track test. Field components at frequencies above 1 kHz were small so the figure only displays frequency components up to 1 kHz. Data collected during the first portion of the record plotted in Figure 4-5 were recorded with the vehicle off and represent ambient conditions. The next portion of the record (from approximately 100 s. to 300 s.) shows field conditions in the stationary vehicle with the vehicle on and in drive, but with no accessories on. The field component in the 600 Hz range appears at this time. At approximately 300

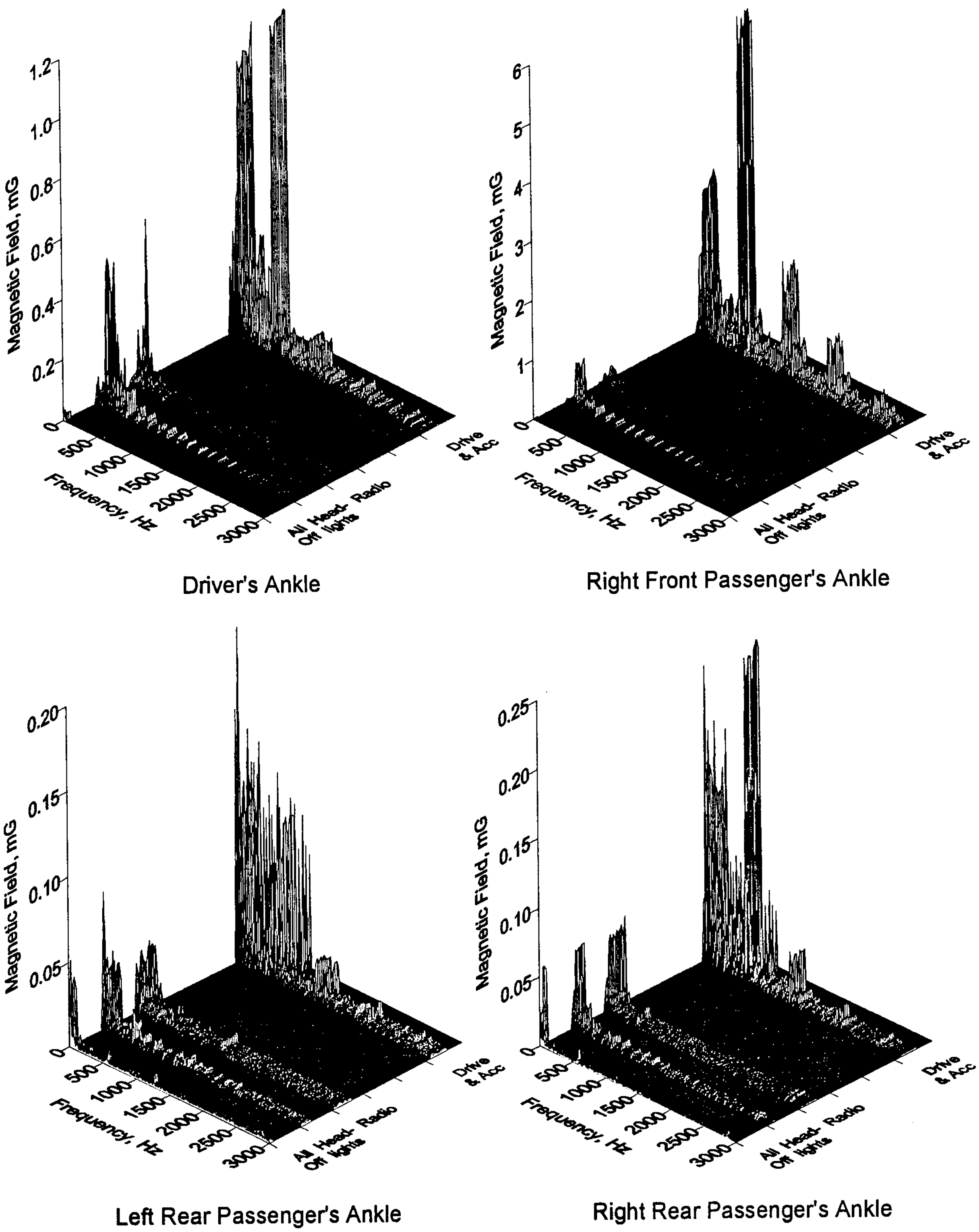


Figure 4-5 Time-Varying Magnetic Field Levels as a Function of Frequency at Ankle Level in Electric Vehicle 2 for Successive Samples with the Vehicle in the Indicated State during the Pretest.

Table 4-4
Summary of Average Magnetic Field Levels in Electric Vehicle #2
During the Stationary Pretest Measurements (Means of 3 or More Measurements)

Frequency Band	Sensor Location	Everything Off Field (mG)	Headlights On Field (mG)	Radio On Field (mG)	Air Cond. and Fan On Field (mG)	All Acc. On Field (mG)	In Drive, Acc On Field (mG)
Static	Driver's Head	338	347	345			359
	Right Front Pass. Head	354	361	357			343
	Left Rear Pass. Head	361	359	362			357
	Right Rear Pass. Head	337	335	337			335
	Driver's Waist	246	241	247			229
	Right Front Pass. Waist	277	277	278			289
	Left Rear Pass. Waist	294	290	294			283
	Right Rear Pass. Waist	189	184	188			194
	Driver's Ankle	277	304	277			280
	Right Front Pass. Ankle	309	283	299			437
	Left Rear Pass. Ankle	234	219	233			187
	Right Rear Pass. Ankle	692	685	692			698
	All Positions	326	324	326			333
5 - 55 Hz Low Frequencies	Driver's Head	0.1	0.1	0.1			0.1
	Right Front Pass. Head	0.2	0.1	0.1			0.2
	Left Rear Pass. Head	0.0	0.0	0.0			0.0
	Right Rear Pass. Head	0.1	0.1	0.1			0.1
	Driver's Waist	0.1	0.1	0.1			0.1
	Right Front Pass. Waist	0.0	0.0	0.0			0.2
	Left Rear Pass. Waist	0.1	0.1	0.1			0.1
	Right Rear Pass. Waist	0.1	0.1	0.1			0.1
	Driver's Ankle	0.0	0.1	0.2			0.6
	Right Front Pass. Ankle	0.0	0.1	0.2			1.4
	Left Rear Pass. Ankle	0.1	0.1	0.0			0.2
	Right Rear Pass. Ankle	0.0	0.0	0.0			0.2
	All Positions	0.1	0.1	0.1			0.3
60 Hz Power Frequency	Driver's Head	0.0	0.0	0.0			0.0
	Right Front Pass. Head	0.0	0.0	0.0			0.0
	Left Rear Pass. Head	0.0	0.0	0.0			0.0
	Right Rear Pass. Head	0.1	0.1	0.0			0.1
	Driver's Waist	0.0	0.0	0.0			0.0
	Right Front Pass. Waist	0.0	0.0	0.0			0.0
	Left Rear Pass. Waist	0.1	0.0	0.0			0.0
	Right Rear Pass. Waist	0.1	0.1	0.1			0.1
	Driver's Ankle	0.0	0.0	0.0			0.1
	Right Front Pass. Ankle	0.0	0.0	0.0			0.3
	Left Rear Pass. Ankle	0.0	0.0	0.0			0.1
	Right Rear Pass. Ankle	0.1	0.1	0.1			0.1
	All Positions	0.0	0.0	0.0			0.1

Table 4-4 (Continued)

Frequency Band	Sensor Location	Everything Off Field (mG)	Headlights On Field (mG)	Radio On Field (mG)	Air Cond. and Fan On Field (mG)	All Acc. On Field (mG)	In Drive, Acc On Field (mG)
65 - 300 Hz Power Harmonics	Driver's Head	0.1	0.1	0.1			0.1
	Right Front Pass. Head	0.1	0.1	0.1			0.1
	Left Rear Pass. Head	0.1	0.1	0.1			0.1
	Right Rear Pass. Head	0.1	0.1	0.1			0.1
	Driver's Waist	0.1	0.1	0.1			0.2
	Right Front Pass. Waist	0.1	0.1	0.1			0.3
	Left Rear Pass. Waist	0.1	0.1	0.1			0.1
	Right Rear Pass. Waist	0.1	0.1	0.1			0.1
	Driver's Ankle	0.0	0.6	0.1			1.6
	Right Front Pass. Ankle	0.0	0.9	0.2			3.4
	Left Rear Pass. Ankle	0.0	0.1	0.0			0.2
	Right Rear Pass. Ankle	0.0	0.0	0.0			0.2
	All Positions	0.1	0.2	0.1			0.5
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.1	0.1			0.1
	Right Front Pass. Head	0.1	0.1	0.1			0.1
	Left Rear Pass. Head	0.2	0.2	0.2			0.2
	Right Rear Pass. Head	0.1	0.1	0.1			0.1
	Driver's Waist	0.0	0.1	0.0			0.1
	Right Front Pass. Waist	0.1	0.1	0.1			0.4
	Left Rear Pass. Waist	0.1	0.1	0.1			0.1
	Right Rear Pass. Waist	0.1	0.1	0.1			0.1
	Driver's Ankle	0.0	0.2	0.0			1.3
	Right Front Pass. Ankle	0.0	0.5	0.0			6.5
	Left Rear Pass. Ankle	0.0	0.1	0.0			0.2
	Right Rear Pass. Ankle	0.0	0.0	0.0			0.3
	All Positions	0.1	0.1	0.1			0.8
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.1	0.2	0.2			0.2
	Right Front Pass. Head	0.2	0.2	0.2			0.3
	Left Rear Pass. Head	0.2	0.2	0.2			0.2
	Right Rear Pass. Head	0.2	0.2	0.2			0.2
	Driver's Waist	0.1	0.1	0.1			0.3
	Right Front Pass. Waist	0.1	0.1	0.1			0.5
	Left Rear Pass. Waist	0.2	0.2	0.2			0.2
	Right Rear Pass. Waist	0.2	0.2	0.2			0.2
	Driver's Ankle	0.1	0.6	0.2			2.1
	Right Front Pass. Ankle	0.1	1.0	0.2			7.4
	Left Rear Pass. Ankle	0.1	0.1	0.1			0.4
	Right Rear Pass. Ankle	0.1	0.1	0.1			0.4
	All Positions	0.1	0.3	0.2			1.0
	Number of Samples	3	6	11			10

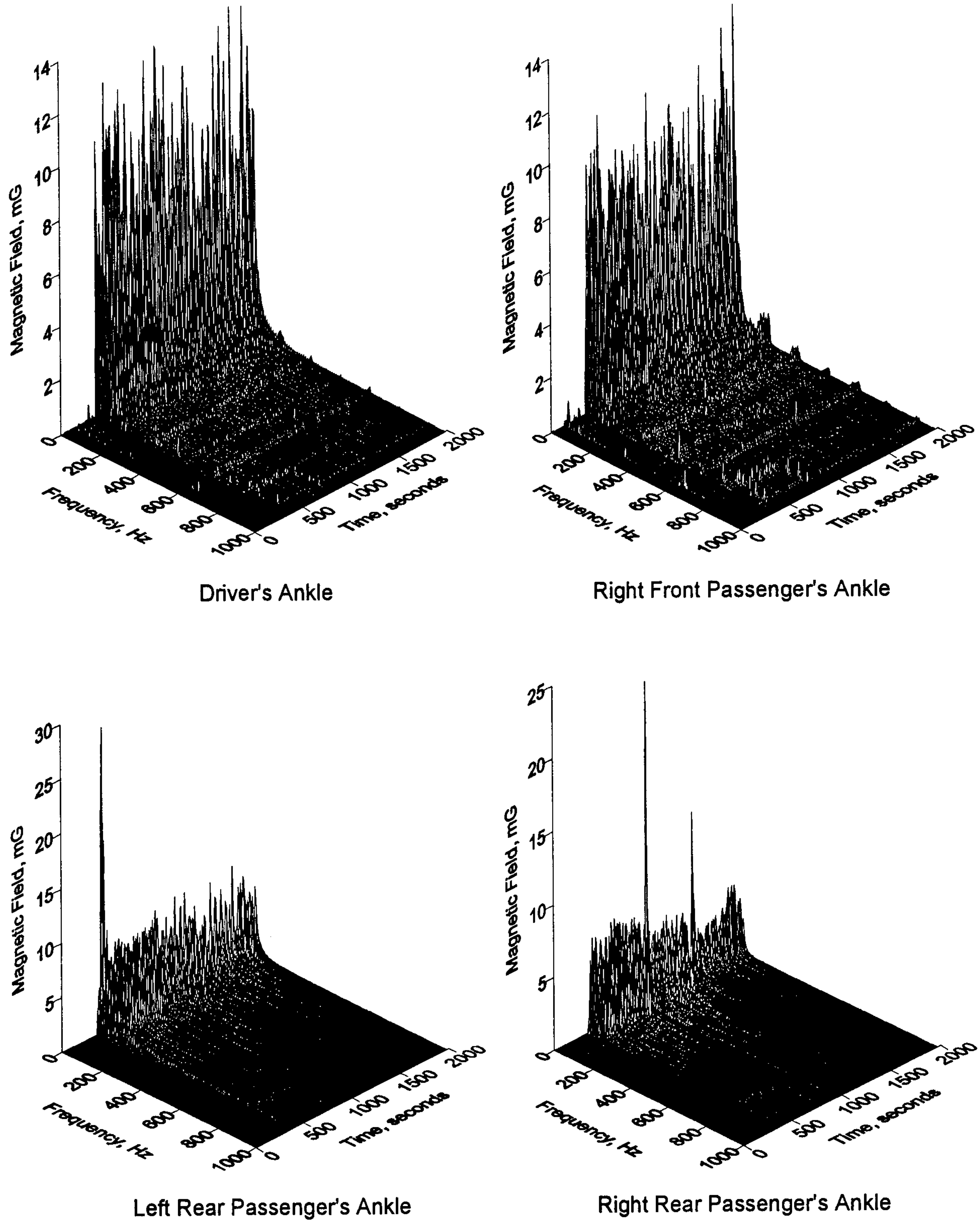


Figure 4-6 Time-Varying Magnetic Field Levels as a Function of Frequency and Time at Ankle Level in Electric Vehicle 2 while Stationary (Zero to 350 s) and while Driving the First Test Sequence on the Track (300 s and Beyond).

s., the headlights and emergency flashers were turned on and driving commenced. (Headlights and flashers were a safety requirement on this track.) The field components at 155 Hz and harmonics thereof become more apparent at the front seat ankle positions (as reported during the pretest) and low frequency components from rotating tires and other movement-related sources become dominant. At locations in the vehicle other than the front seat ankle positions, low frequency field components dominate with very little evidence of the 155 Hz and harmonic fields. Table 4-5 summarizes field levels in the vehicle by frequency band for the actual driving portion of this first track test.

Figure 4-7 shows the ankle level magnetic fields in EV2 during the second set of test track measurements. Field characteristics are similar to those shown in Figure 4-6 for the first track test. Significant changes in magnetic field conditions are not observable during the intervals when the vehicle was shut off and coasting. That seems to indicate that the low frequency field components arise from rotating tires and other mechanical parts and from movement-related sources, not from low frequency current in the vehicle's electrical system. Field levels measured at all magnetic sensor locations during the second track test are tabulated on Table 4-6. The similarity of the values to those on Table 4-5 for the first track test demonstrates the repeatability of the field measurements and suggests that modest differences in speed and acceleration schedules do not materially affect the results. That observation implies that these measurements on a test track can be generalized to other driving conditions provided one accounts for field contributions from sources along the route which were not present on the test track.

4.3.3 Electric Vehicle #3

Electric Vehicle #3 (EV3) is a two passenger vehicle for which stationary pretest and track data were obtained. A dynamometer equipped for running the FUDS was not available. Magnetic field conditions were measured at the ankle, waist and head of the driver, and the test engineer who rode in the front passenger seat.

The stationary pretest measurements were conducted at an outdoor location with low ambient magnetic fields. Figure 4-8 shows the field components which appeared at ankle level when the various accessories were turned on as well as when the vehicle was turned on, then put in "drive" with all of the accessories on. The frequency spectrum is complex with different components appearing for specific accessories. Fields at the head and waist measurement locations have similar frequency spectra but much lower amplitude as indicated in Table 4-7. Total ELF fields average 0.5 mG or less at every measurement location except the ankles for all of the vehicle states tested. Some variation

Table 4-5
Summary of Magnetic Field Levels in Electric Vehicle #2
During the First Test Track Measurements

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	279	434	343	42	12
	Right Front Pass. Head	141	419	278	67	24
	Left Rear Pass. Head	329	465	396	48	12
	Right Rear Pass. Head	303	441	365	45	12
	Driver's Waist	222	335	276	27	10
	Right Front Pass. Waist	198	418	249	41	16
	Left Rear Pass. Waist	204	416	336	65	19
	Right Rear Pass. Waist	130	401	240	70	29
	Driver's Ankle	125	506	315	88	28
	Right Front Pass. Ankle	243	535	388	73	19
	Left Rear Pass. Ankle	160	551	316	87	28
	Right Rear Pass. Ankle	448	992	589	99	17
	All Positions	125	992	344	115	33
5 - 55 Hz Low Frequencies	Driver's Head	0.5	4.2	2.2	0.7	34
	Right Front Pass. Head	0.5	4.6	2.1	0.7	34
	Left Rear Pass. Head	0.5	5.2	3.2	0.9	27
	Right Rear Pass. Head	0.4	5.9	3.0	0.9	30
	Driver's Waist	0.7	7.1	3.8	1.4	37
	Right Front Pass. Waist	0.7	5.3	3.1	0.9	31
	Left Rear Pass. Waist	1.4	17.2	11.5	3.0	26
	Right Rear Pass. Waist	0.8	14.7	7.5	2.1	28
	Driver's Ankle	1.8	18.4	10.2	4.0	39
	Right Front Pass. Ankle	2.3	16.3	9.4	3.4	36
	Left Rear Pass. Ankle	0.8	42.7	7.6	3.7	49
	Right Rear Pass. Ankle	0.6	24.4	5.1	2.3	46
	All Positions	0.4	42.7	5.7	4.0	70
60 Hz Power Frequency	Driver's Head	0.0	2.8	0.1	0.2	199
	Right Front Pass. Head	0.0	1.0	0.1	0.1	93
	Left Rear Pass. Head	0.0	1.7	0.1	0.1	96
	Right Rear Pass. Head	0.0	0.5	0.1	0.1	56
	Driver's Waist	0.0	2.6	0.2	0.2	107
	Right Front Pass. Waist	0.0	0.9	0.1	0.1	68
	Left Rear Pass. Waist	0.0	1.6	0.5	0.2	44
	Right Rear Pass. Waist	0.0	0.6	0.2	0.1	47
	Driver's Ankle	0.1	3.9	0.7	0.4	66
	Right Front Pass. Ankle	0.0	3.8	0.6	0.4	69
	Left Rear Pass. Ankle	0.0	5.6	0.5	0.5	104
	Right Rear Pass. Ankle	0.0	1.5	0.3	0.2	86
	All Positions	0.0	5.6	0.3	0.3	114

Table 4-5 (Continued)

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
65 - 300 Hz Power Harmonics	Driver's Head	0.1	1.1	0.3	0.1	41
	Right Front Pass. Head	0.1	0.7	0.3	0.1	37
	Left Rear Pass. Head	0.1	0.9	0.4	0.2	40
	Right Rear Pass. Head	0.1	0.8	0.3	0.1	45
	Driver's Waist	0.2	1.4	0.6	0.3	46
	Right Front Pass. Waist	0.2	1.7	0.7	0.5	76
	Left Rear Pass. Waist	0.1	2.6	1.4	0.5	39
	Right Rear Pass. Waist	0.2	1.8	0.9	0.5	54
	Driver's Ankle	1.0	6.2	3.0	1.4	46
	Right Front Pass. Ankle	1.2	5.8	3.0	1.3	43
	Left Rear Pass. Ankle	0.2	12.8	3.2	3.3	104
	Right Rear Pass. Ankle	0.2	8.2	2.5	3.0	118
	All Positions	0.1	12.8	1.4	1.8	133
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.3	0.1	0.0	29
	Right Front Pass. Head	0.1	0.3	0.2	0.0	25
	Left Rear Pass. Head	0.2	0.4	0.2	0.0	19
	Right Rear Pass. Head	0.1	0.3	0.2	0.1	33
	Driver's Waist	0.1	0.5	0.2	0.1	37
	Right Front Pass. Waist	0.1	0.4	0.2	0.1	26
	Left Rear Pass. Waist	0.1	1.1	0.6	0.2	38
	Right Rear Pass. Waist	0.1	0.7	0.3	0.1	46
	Driver's Ankle	0.4	1.9	0.9	0.3	28
	Right Front Pass. Ankle	0.8	3.4	1.3	0.4	31
	Left Rear Pass. Ankle	0.1	4.4	0.5	0.4	89
	Right Rear Pass. Ankle	0.1	1.4	0.3	0.2	64
	All Positions	0.1	4.4	0.4	0.4	98
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.5	4.3	2.2	0.7	34
	Right Front Pass. Head	0.6	4.6	2.1	0.7	34
	Left Rear Pass. Head	0.5	5.3	3.2	0.9	27
	Right Rear Pass. Head	0.5	5.9	3.0	0.9	30
	Driver's Waist	0.7	7.2	3.9	1.4	37
	Right Front Pass. Waist	0.7	5.5	3.2	1.0	31
	Left Rear Pass. Waist	1.5	17.3	11.7	3.0	25
	Right Rear Pass. Waist	0.8	14.7	7.5	2.1	28
	Driver's Ankle	2.6	19.2	10.8	4.0	37
	Right Front Pass. Ankle	3.1	17.1	10.0	3.4	34
	Left Rear Pass. Ankle	0.9	45.1	8.7	4.3	50
	Right Rear Pass. Ankle	0.7	24.7	6.1	3.1	51
	All Positions	0.5	45.1	6.0	4.2	70
	Number of Samples	163				

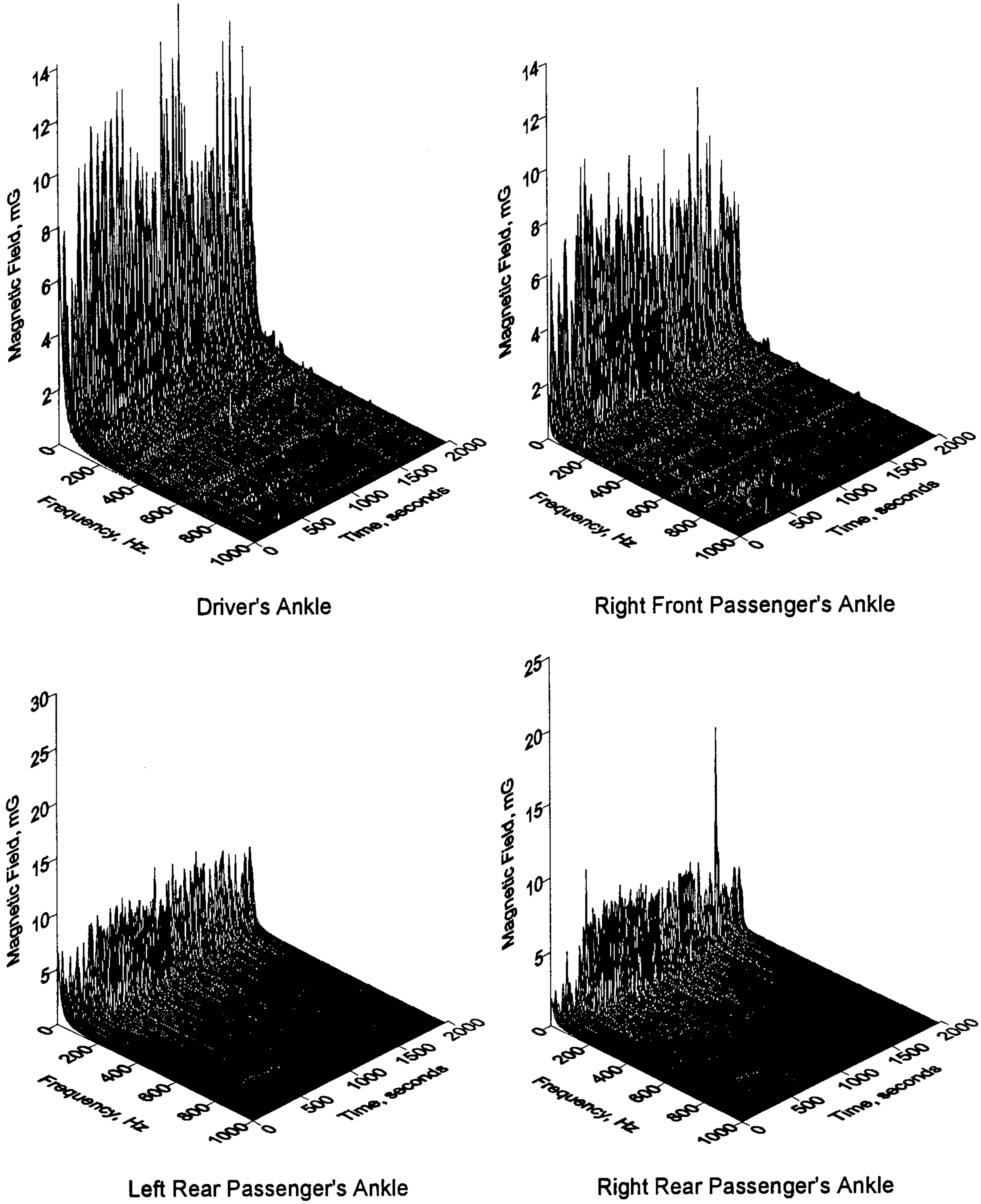


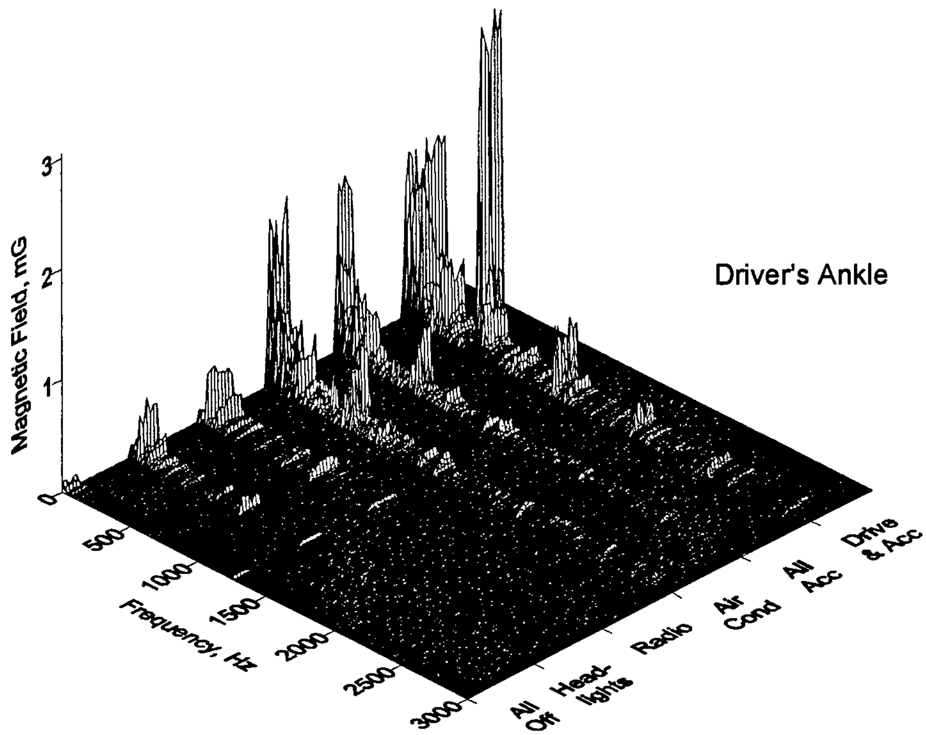
Figure 4-7 Time-Varying Magnetic Field Levels as a Function of Frequency and Time at Ankle Level in Electric Vehicle 2 while Driving the Second Test Sequence on the Track.

Table 4-6
Summary of Magnetic Field Levels in Electric Vehicle #2
During the Second Test Track Measurements

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	282	439	353	42	12
	Right Front Pass. Head	170	384	278	55	20
	Left Rear Pass. Head	326	454	407	42	10
	Right Rear Pass. Head	308	440	383	41	11
	Driver's Waist	215	339	283	22	8
	Right Front Pass. Waist	201	368	261	27	10
	Left Rear Pass. Waist	241	423	363	44	12
	Right Rear Pass. Waist	135	359	242	64	26
	Driver's Ankle	152	489	344	73	21
	Right Front Pass. Ankle	184	793	385	149	39
	Left Rear Pass. Ankle	136	534	289	88	30
	Right Rear Pass. Ankle	451	846	553	84	15
	All Positions	135	846	353	110	31
5 - 55 Hz Low Frequencies	Driver's Head	0.1	4.4	2.2	0.9	39
	Right Front Pass. Head	0.1	3.8	2.0	0.8	37
	Left Rear Pass. Head	0.0	5.1	3.1	1.2	40
	Right Rear Pass. Head	0.1	4.9	2.8	1.2	42
	Driver's Waist	0.2	7.6	3.8	1.5	40
	Right Front Pass. Waist	0.1	8.4	3.1	1.3	41
	Left Rear Pass. Waist	0.1	17.3	11.0	4.4	40
	Right Rear Pass. Waist	0.1	10.5	6.8	3.0	43
	Driver's Ankle	0.5	18.4	9.4	4.1	43
	Right Front Pass. Ankle	0.2	13.6	6.8	2.7	39
	Left Rear Pass. Ankle	0.1	15.5	7.3	2.8	39
	Right Rear Pass. Ankle	0.2	19.0	4.7	2.2	47
	All Positions	0.0	19.0	5.3	3.8	72
60 Hz Power Frequency	Driver's Head	0.0	0.2	0.1	0.0	46
	Right Front Pass. Head	0.0	1.6	0.1	0.1	125
	Left Rear Pass. Head	0.0	0.3	0.1	0.1	48
	Right Rear Pass. Head	0.0	0.4	0.1	0.1	50
	Driver's Waist	0.0	0.5	0.2	0.1	51
	Right Front Pass. Waist	0.0	1.3	0.1	0.1	78
	Left Rear Pass. Waist	0.0	1.2	0.4	0.2	48
	Right Rear Pass. Waist	0.0	0.6	0.2	0.1	48
	Driver's Ankle	0.0	1.9	0.6	0.3	56
	Right Front Pass. Ankle	0.0	1.9	0.4	0.2	61
	Left Rear Pass. Ankle	0.0	2.9	0.5	0.4	74
	Right Rear Pass. Ankle	0.0	1.7	0.3	0.3	84
	All Positions	0.0	2.9	0.3	0.3	98

Table 4-6 (Continued)

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
65 - 300 Hz Power Harmonics	Driver's Head	0.1	0.6	0.3	0.1	35
	Right Front Pass. Head	0.1	0.8	0.3	0.1	36
	Left Rear Pass. Head	0.1	0.9	0.4	0.2	43
	Right Rear Pass. Head	0.1	0.6	0.3	0.1	44
	Driver's Waist	0.1	1.2	0.7	0.3	42
	Right Front Pass. Waist	0.1	1.7	0.7	0.5	66
	Left Rear Pass. Waist	0.1	2.9	1.3	0.6	43
	Right Rear Pass. Waist	0.1	1.8	0.8	0.4	53
	Driver's Ankle	0.2	6.1	3.0	1.3	45
	Right Front Pass. Ankle	0.1	8.0	2.1	1.3	62
	Left Rear Pass. Ankle	0.1	9.7	3.6	3.2	90
	Right Rear Pass. Ankle	0.1	8.0	2.9	2.9	101
	All Positions	0.1	9.7	1.4	1.8	132
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.3	0.1	0.0	27
	Right Front Pass. Head	0.1	0.5	0.2	0.0	25
	Left Rear Pass. Head	0.2	0.4	0.2	0.0	20
	Right Rear Pass. Head	0.1	0.3	0.1	0.1	35
	Driver's Waist	0.1	0.5	0.2	0.1	39
	Right Front Pass. Waist	0.1	1.1	0.2	0.1	41
	Left Rear Pass. Waist	0.1	1.1	0.5	0.2	41
	Right Rear Pass. Waist	0.1	0.6	0.3	0.1	48
	Driver's Ankle	0.2	3.0	0.9	0.4	43
	Right Front Pass. Ankle	0.0	3.9	0.7	0.4	51
	Left Rear Pass. Ankle	0.1	1.1	0.4	0.2	54
	Right Rear Pass. Ankle	0.0	0.7	0.3	0.2	59
	All Positions	0.0	3.9	0.3	0.3	88
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.2	4.4	2.2	0.9	38
	Right Front Pass. Head	0.2	3.8	2.1	0.7	36
	Left Rear Pass. Head	0.2	5.1	3.1	1.2	39
	Right Rear Pass. Head	0.1	5.0	2.9	1.2	42
	Driver's Waist	0.3	7.7	3.8	1.5	40
	Right Front Pass. Waist	0.1	8.4	3.2	1.3	40
	Left Rear Pass. Waist	0.2	17.4	11.1	4.4	40
	Right Rear Pass. Waist	0.2	10.7	6.9	3.0	43
	Driver's Ankle	0.9	19.0	10.0	4.1	41
	Right Front Pass. Ankle	0.2	14.4	7.3	2.8	38
	Left Rear Pass. Ankle	0.2	15.8	8.5	3.5	41
	Right Rear Pass. Ankle	0.3	19.1	5.9	3.1	53
	All Positions	0.1	19.1	5.6	4.0	72
	Number of Samples	198				



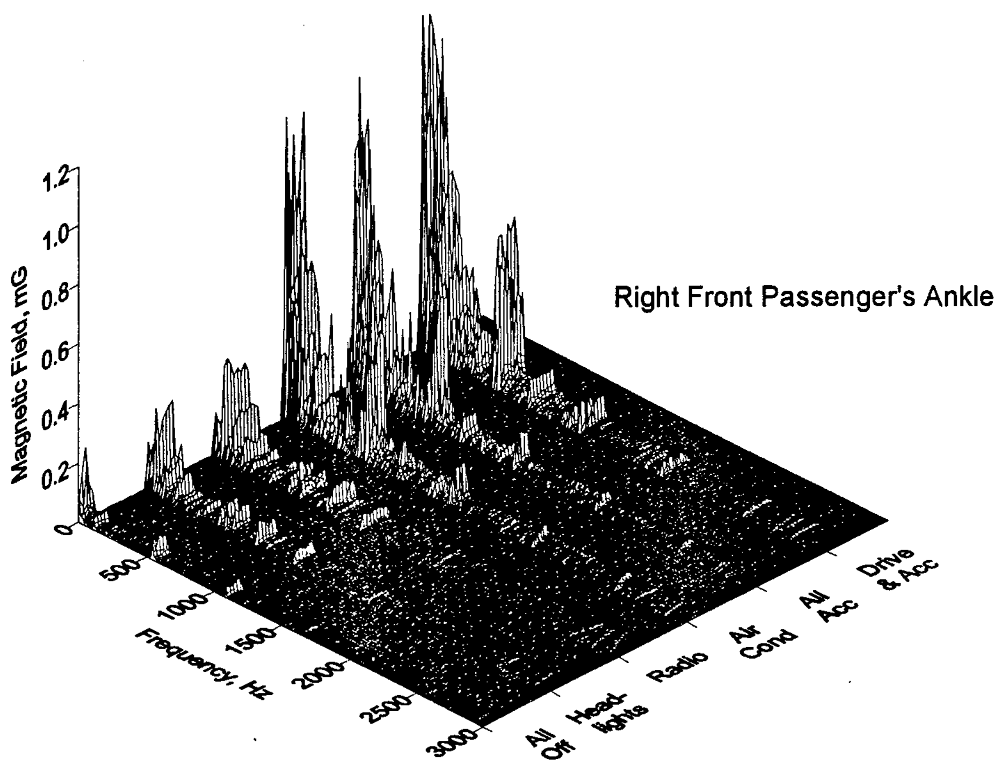


Figure 4-8 Time-Varying Magnetic Field Levels as a Function of Frequency at Ankle Level in Electric Vehicle 3 for Successive Samples with the Vehicle in the Indicated State during the Pretest.

Table 4-7
Summary of Average Magnetic Field Levels in Electric Vehicle #3
During the Stationary Pretest Measurements (Means of 5 or More Measurements)

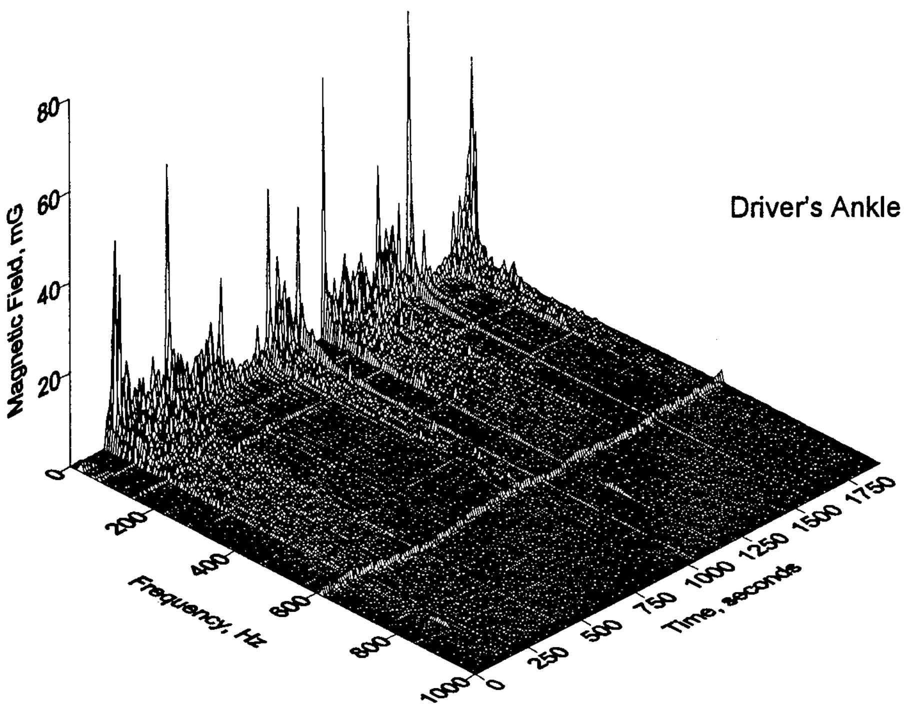
Frequency Band	Sensor Location	Everything Off Field (mG)	Headlights On Field (mG)	Radio On Field (mG)	Air Cond. and Fan On Field (mG)	All Acc. On Field (mG)	In Drive, Acc On Field (mG)
Static	Driver's Head	319	279	256	285	290	306
	Passenger's Head	631	609	593	546	528	636
	Driver's Waist	591	597	595	611	611	587
	Passenger's Waist	365	370	369	385	388	379
	Driver's Ankle	429	437	429	479	481	423
	Passenger's Ankle	662	678	666	731	736	722
	All Positions	500	495	485	506	506	509
5 - 55 Hz Low Frequencies	Driver's Head	0.0	0.0	0.0	0.0	0.0	0.0
	Passenger's Head	0.1	0.1	0.1	0.1	0.1	0.1
	Driver's Waist	0.2	0.2	0.2	0.2	0.2	0.3
	Passenger's Waist	0.1	0.2	0.1	0.2	0.2	0.2
	Driver's Ankle	0.1	0.2	0.2	2.0	2.1	2.1
	Passenger's Ankle	0.2	0.2	0.2	1.3	1.4	1.6
	All Positions	0.1	0.2	0.1	0.6	0.7	0.7
60 Hz Power Frequency	Driver's Head	0.0	0.0	0.0	0.0	0.0	0.0
	Passenger's Head	0.0	0.0	0.0	0.0	0.0	0.0
	Driver's Waist	0.0	0.0	0.0	0.0	0.0	0.0
	Passenger's Waist	0.0	0.0	0.0	0.0	0.0	0.1
	Driver's Ankle	0.0	0.1	0.0	0.5	0.4	0.5
	Passenger's Ankle	0.0	0.0	0.0	0.3	0.3	0.4
	All Positions	0.0	0.0	0.0	0.1	0.1	0.2
65 - 300 Hz Power Harmonics	Driver's Head	0.0	0.0	0.0	0.0	0.0	0.0
	Passenger's Head	0.0	0.0	0.0	0.0	0.0	0.0
	Driver's Waist	0.1	0.1	0.1	0.1	0.1	0.2
	Passenger's Waist	0.4	0.4	0.4	0.4	0.4	0.4
	Driver's Ankle	0.1	0.6	0.5	1.3	1.1	2.6
	Passenger's Ankle	0.1	0.4	0.4	1.0	1.0	1.1
	All Positions	0.1	0.2	0.2	0.5	0.4	0.7
305 - 3000 Hz High Frequencies	Driver's Head	0.0	0.0	0.1	0.1	0.1	0.1
	Passenger's Head	0.0	0.0	0.0	0.0	0.0	0.0
	Driver's Waist	0.2	0.2	0.2	0.2	0.2	0.3
	Passenger's Waist	0.2	0.2	0.2	0.2	0.2	0.2
	Driver's Ankle	0.1	0.2	0.2	1.0	0.9	3.3
	Passenger's Ankle	0.1	0.2	0.2	0.7	0.7	0.7
	All Positions	0.1	0.2	0.2	0.4	0.3	0.8
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.1	0.1	0.1	0.1	0.1	0.1
	Passenger's Head	0.1	0.1	0.1	0.1	0.1	0.1
	Driver's Waist	0.3	0.3	0.3	0.3	0.3	0.5
	Passenger's Waist	0.5	0.5	0.5	0.5	0.5	0.5
	Driver's Ankle	0.2	0.7	0.6	2.6	2.6	4.7
	Passenger's Ankle	0.2	0.5	0.5	1.8	1.9	2.1
	All Positions	0.2	0.3	0.3	0.9	0.9	1.3
	Number of Samples	5	6	8	6	5	8

in static field levels was observed between test conditions. That is believed to result from small changes in sensor position over the time of the tests. As in the other pretests, sensors for front seat measurements were strapped to the driver and test engineer who could not avoid small movements of their heads and feet as they conducted the test sequence.

Three sets of test track measurements were made in this vehicle. The first two were run with a nickel metal-hydride battery pack, the same pack used during the pretest measurements. During the third series of test track measurements, the vehicle used a lead-acid battery pack. This vehicle also has an option of a "normal" mode without regenerative braking and an "economy" mode in which some of the kinetic energy absorbed during braking is "regenerated" to return electrical energy back to the battery. The second series of track tests were conducted with the vehicle in the regenerative mode.

The time-varying magnetic fields below 1 kHz at the ankle positions in EV3 are plotted as functions of frequency and time in Figures 4-9 through 4-11 for the three sets of test track measurements. The driving schedule included periods of sustained driving at 50, 30, and 15 mph with acceleration and deceleration between. The driving schedule was repeated twice in both the first and second series of track tests, but only once in the third. Comparison of Figures 4-9 and 4-10 shows no consistent differences in ankle-level field conditions attributable to the use of regenerative braking in the second series of track tests. That may not be surprising because the driving schedule employed for the test had very little braking. Field conditions at the waist and head levels are influenced to a lesser degree by the drive system and reveal no characteristics not better visualized in the ankle-level data. Summary statistics for the fields at all measurement positions for the first and second set of track test data are given in Tables 4-8 and 4-9, respectively. Like the graphical data, the statistical summaries do not reveal consistent differences between the test data which are attributable to the use of regenerative braking.

Figure 4-11 shows ankle-level magnetic field conditions in EV3 during the third set of track tests when it was equipped with a lead-acid battery pack. Clear differences exist between these data and the data obtained in the first track test using the nickel metal-hydride battery (Figure 4-9). Magnetic field components are clearly present with frequencies proportional to vehicle speed (about 280 Hz at 50 mph) in Figure 4-11. Those components appear in summary Table 4-10 as elevated field levels at the ankles in the 65-300 Hz frequency range. They have minimal effect on the total ELF field at any measurement height.



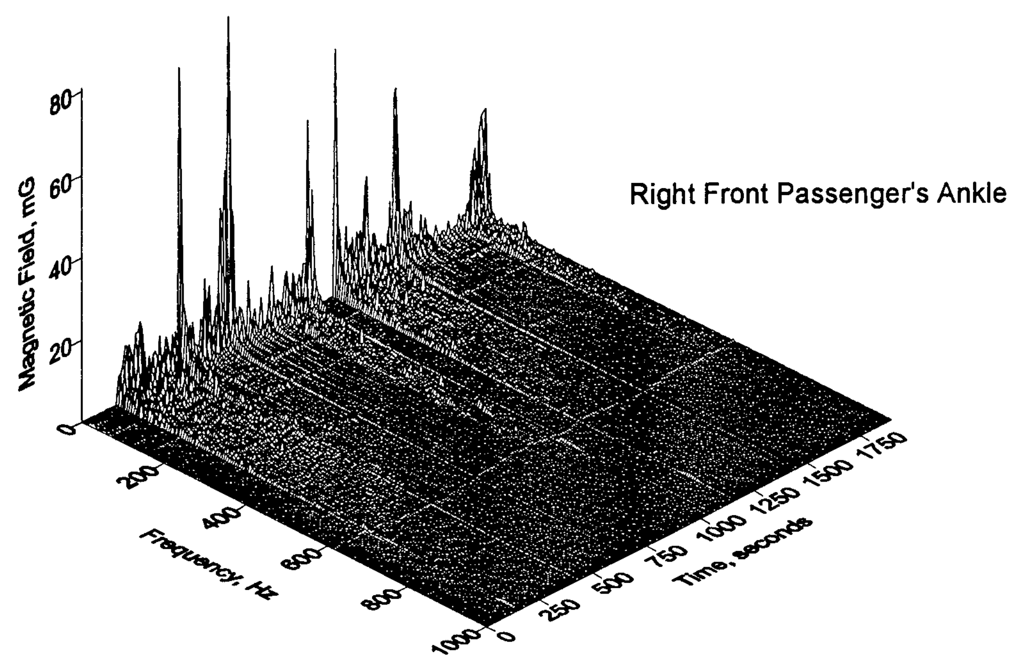


Figure 4-9 Time-Varying Magnetic Field Levels as a Function of Frequency and Time at Ankle Level in Electric Vehicle 3 during the First Series of Test Track Measurements (Normal Mode).

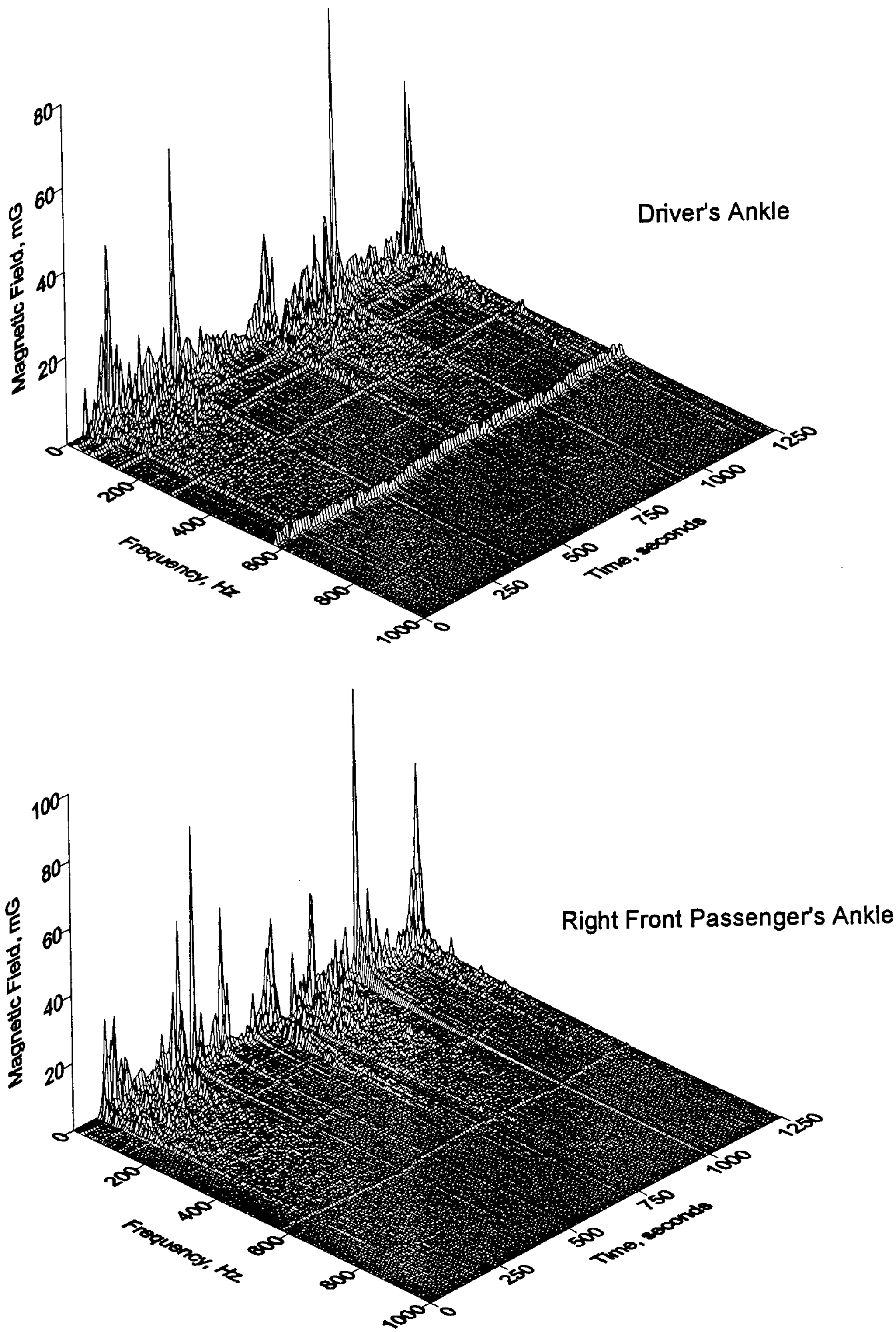
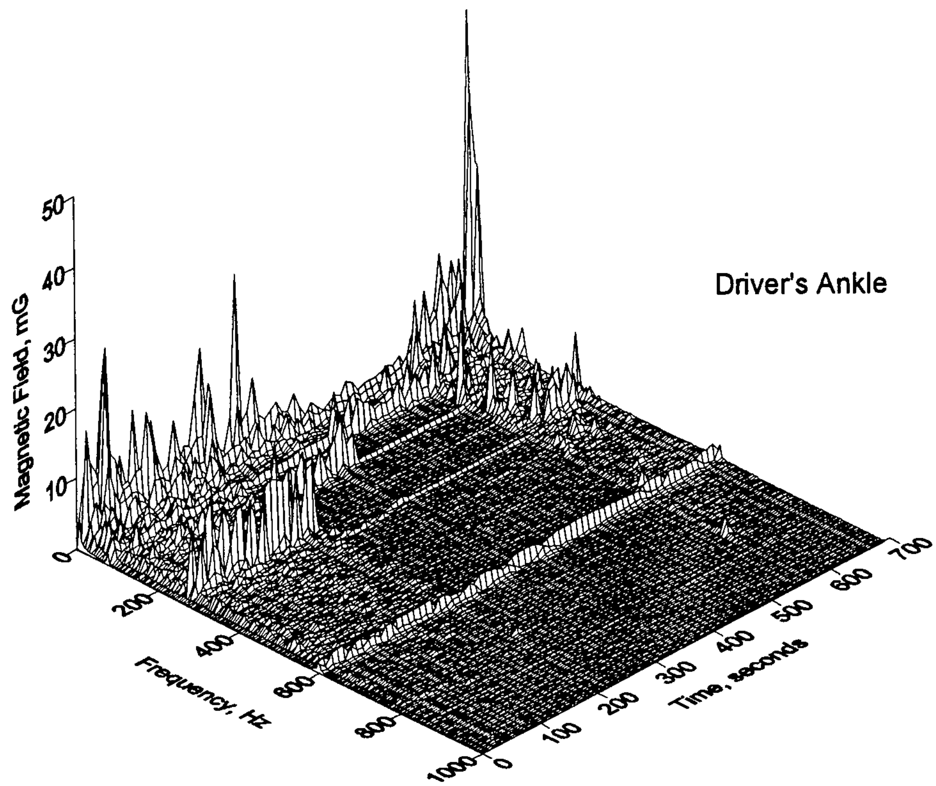


Figure 4-10 Time-Varying Magnetic Field Levels as a Function of Frequency and Time at Ankle Level in Electric Vehicle 3 during the Second Series of Test Track Measurements (Regenerative Mode).



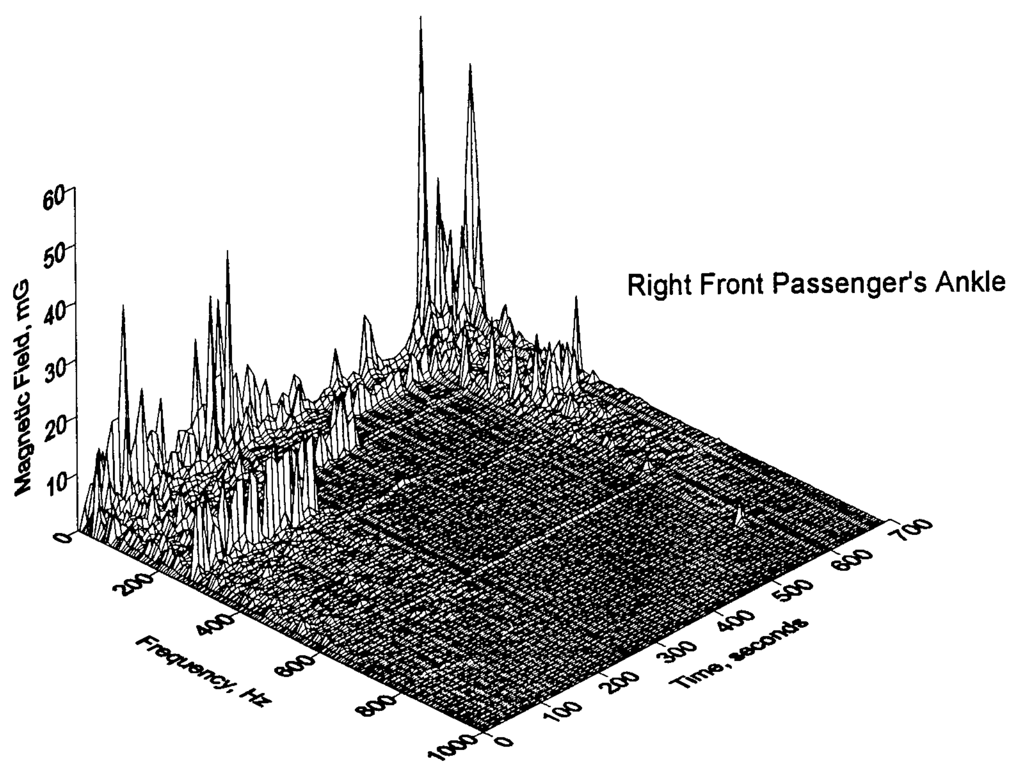


Figure 4-11 Time-Varying Magnetic Field Levels as a Function of Frequency and Time at Ankle Level in Electric Vehicle 3 during the Third Series of Test Track Measurements (Lead-Acid Battery).

Table 4-8
Summary of Magnetic Field Levels in Electric Vehicle #3
During the First Test Track Measurements (Normal Condition)

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	275	401	329	27	8
	Passenger's Head	485	855	680	81	12
	Driver's Waist	413	809	545	64	12
	Passenger's Waist	273	602	421	79	19
	Driver's Ankle	259	836	406	62	15
	Passenger's Ankle	573	1041	751	100	13
	All Positions	259	1041	522	169	32
5 - 55 Hz Low Frequencies	Driver's Head	0.1	4.7	0.4	0.5	120
	Passenger's Head	0.1	3.1	0.6	0.4	68
	Driver's Waist	0.3	25.8	2.3	2.8	119
	Passenger's Waist	0.1	19.5	2.4	2.3	97
	Driver's Ankle	0.7	83.0	16.4	12.7	78
	Passenger's Ankle	0.6	92.7	15.8	13.5	85
	All Positions	0.1	92.7	6.3	10.4	164
60 Hz Power Frequency	Driver's Head	0.0	0.2	0.0	0.0	93
	Passenger's Head	0.0	0.2	0.0	0.0	79
	Driver's Waist	0.0	1.1	0.1	0.1	115
	Passenger's Waist	0.0	1.0	0.1	0.1	92
	Driver's Ankle	0.1	5.4	1.2	1.2	98
	Passenger's Ankle	0.0	6.0	1.0	1.0	100
	All Positions	0.0	6.0	0.4	0.8	194
65 - 300 Hz Power Harmonics	Driver's Head	0.0	0.6	0.1	0.1	99
	Passenger's Head	0.0	0.5	0.1	0.1	77
	Driver's Waist	0.1	3.4	0.4	0.3	87
	Passenger's Waist	0.4	3.2	0.6	0.3	47
	Driver's Ankle	1.2	15.5	5.3	3.3	62
	Passenger's Ankle	0.7	14.8	4.4	2.9	67
	All Positions	0.0	15.5	1.8	2.8	157
305 - 3000 Hz High Frequencies	Driver's Head	0.0	0.3	0.1	0.0	43
	Passenger's Head	0.0	0.3	0.1	0.0	42
	Driver's Waist	0.3	1.4	0.3	0.1	35
	Passenger's Waist	0.2	1.5	0.3	0.1	41
	Driver's Ankle	1.8	6.2	2.8	0.8	30
	Passenger's Ankle	0.4	4.9	1.6	1.0	63
	All Positions	0.0	6.2	0.9	1.1	134
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.1	4.7	0.4	0.5	117
	Passenger's Head	0.1	3.2	0.6	0.4	68
	Driver's Waist	0.4	26.1	2.4	2.8	115
	Passenger's Waist	0.5	19.9	2.5	2.3	92
	Driver's Ankle	3.7	84.2	17.8	12.8	72
	Passenger's Ankle	2.4	93.5	16.7	13.5	81
	All Positions	0.1	93.5	6.7	10.8	160
	Number of Samples	165				

Table 4-9
Summary of Magnetic Field Levels in Electric Vehicle #3
During the Second Test Track Measurements (Regenerative Mode)

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	269	394	328	24	7
	Passenger's Head	472	795	669	65	10
	Driver's Waist	461	798	597	59	10
	Passenger's Waist	301	718	499	101	20
	Driver's Ankle	286	649	394	40	10
	Passenger's Ankle	492	1024	688	111	16
	All Positions	269	1024	529	154	29
5 - 55 Hz Low Frequencies	Driver's Head	0.0	2.3	0.4	0.3	92
	Passenger's Head	0.0	4.9	0.6	0.5	86
	Driver's Waist	0.2	15.2	2.2	2.1	96
	Passenger's Waist	0.1	29.5	2.6	3.2	121
	Driver's Ankle	0.4	83.8	14.9	12.6	85
	Passenger's Ankle	0.2	97.7	16.9	14.6	86
	All Positions	0.0	97.7	6.3	10.6	168
60 Hz Power Frequency	Driver's Head	0.0	0.1	0.0	0.0	77
	Passenger's Head	0.0	0.2	0.0	0.0	88
	Driver's Waist	0.0	0.7	0.1	0.1	100
	Passenger's Waist	0.0	1.2	0.1	0.1	93
	Driver's Ankle	0.1	7.8	1.1	1.1	107
	Passenger's Ankle	0.1	7.9	1.2	1.2	103
	All Positions	0.0	7.9	0.4	0.8	199
65 - 300 Hz Power Harmonics	Driver's Head	0.0	0.4	0.1	0.0	80
	Passenger's Head	0.0	0.7	0.1	0.1	82
	Driver's Waist	0.2	2.3	0.4	0.3	69
	Passenger's Waist	0.5	3.7	0.7	0.3	46
	Driver's Ankle	1.6	11.7	4.9	2.8	57
	Passenger's Ankle	0.7	18.5	5.3	3.8	72
	All Positions	0.0	18.5	1.9	3.0	156
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.2	0.1	0.0	28
	Passenger's Head	0.0	0.3	0.1	0.0	50
	Driver's Waist	0.3	1.2	0.4	0.1	26
	Passenger's Waist	0.2	1.8	0.3	0.1	54
	Driver's Ankle	2.9	6.6	3.8	0.6	17
	Passenger's Ankle	0.6	6.7	1.9	1.0	51
	All Positions	0.0	6.7	1.1	1.4	134
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.1	2.3	0.4	0.3	89
	Passenger's Head	0.1	4.9	0.6	0.5	85
	Driver's Waist	0.4	15.4	2.3	2.1	92
	Passenger's Waist	0.6	29.8	2.8	3.2	114
	Driver's Ankle	3.8	84.8	16.6	12.5	76
	Passenger's Ankle	1.0	99.0	18.3	14.7	80
	All Positions	0.1	99.0	6.8	11.0	161
	Number of Samples	117				

Table 4-10
Summary of Magnetic Field Levels in Electric Vehicle #3
During the Third Test Track Measurements (Lead-Acid Battery)

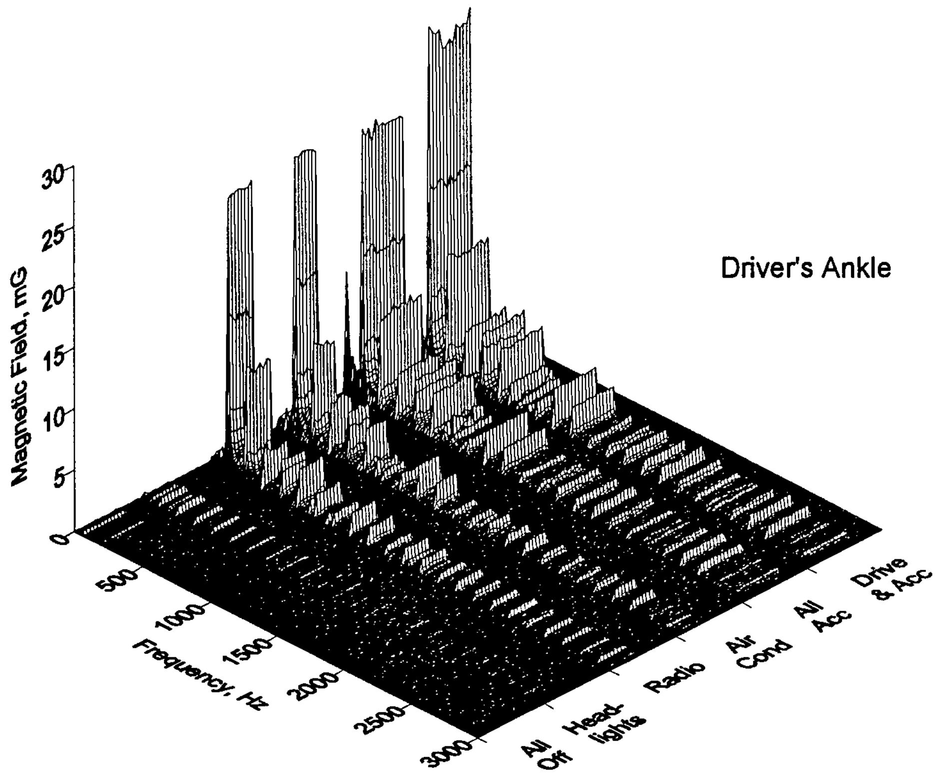
Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	278	389	332	31	9
	Passenger's Head	505	1019	704	66	9
	Driver's Waist	331	710	513	59	11
	Passenger's Waist	196	471	324	59	18
	Driver's Ankle	291	743	413	73	18
	Passenger's Ankle	441	1055	661	97	15
	All Positions	196	1055	491	164	33
5 - 55 Hz Low Frequencies	Driver's Head	0.1	1.5	0.3	0.2	76
	Passenger's Head	0.1	1.8	0.5	0.3	64
	Driver's Waist	0.4	8.8	1.9	1.4	74
	Passenger's Waist	0.1	13.5	2.5	2.2	88
	Driver's Ankle	2.8	60.9	12.6	10.2	81
	Passenger's Ankle	0.3	67.2	16.2	13.1	81
	All Positions	0.1	67.2	5.7	9.3	163
60 Hz Power Frequency	Driver's Head	0.0	0.1	0.0	0.0	57
	Passenger's Head	0.0	0.1	0.0	0.0	60
	Driver's Waist	0.0	0.4	0.1	0.1	92
	Passenger's Waist	0.0	0.6	0.1	0.1	80
	Driver's Ankle	0.1	3.6	0.9	0.7	87
	Passenger's Ankle	0.1	5.6	1.1	1.0	94
	All Positions	0.0	5.6	0.4	0.7	185
65 - 300 Hz Power Harmonics	Driver's Head	0.0	0.2	0.1	0.0	58
	Passenger's Head	0.0	0.2	0.1	0.0	54
	Driver's Waist	0.2	1.3	0.4	0.2	43
	Passenger's Waist	0.5	1.7	0.8	0.3	33
	Driver's Ankle	2.2	15.3	8.5	3.8	45
	Passenger's Ankle	0.8	21.6	10.7	5.4	51
	All Positions	0.0	21.6	3.4	5.2	151
305 - 3000 Hz High Frequencies	Driver's Head	0.0	0.1	0.0	0.0	28
	Passenger's Head	0.0	0.1	0.0	0.0	27
	Driver's Waist	0.2	0.7	0.2	0.1	32
	Passenger's Waist	0.2	0.8	0.3	0.1	43
	Driver's Ankle	2.2	7.5	3.2	1.1	33
	Passenger's Ankle	0.4	8.3	2.7	2.0	75
	All Positions	0.0	8.3	1.1	1.6	150
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.1	1.6	0.3	0.2	73
	Passenger's Head	0.1	1.8	0.5	0.3	63
	Driver's Waist	0.5	9.0	2.0	1.4	71
	Passenger's Waist	0.5	13.6	2.7	2.2	80
	Driver's Ankle	5.5	61.4	16.1	10.2	63
	Passenger's Ankle	0.9	70.1	20.3	13.3	66
	All Positions	0.1	70.1	7.0	10.6	152
	Number of Samples	70				

4.3.4 Electric Vehicle #4

The fourth electric vehicle (EV4) is another two-passenger vehicle in which magnetic fields were measured at the head, waist, and ankles of the driver and passenger. The fluxgate magnetometers were strapped to the driver and test engineer who rode in the passenger seat during the track tests. During the pretest and during the FUDS tests on the dynamometer, the passenger seat sensors were secured in the plastic sensor holder.

The pretest on this vehicle was conducted in the dynamometer laboratory. Although the vehicle was on the dynamometer, it was turned off and not operating. Ankle-level magnetic fields are shown in Figure 4-12 because they are the largest and least unobscured by the ambient fields shown in the first section of the graph when the vehicle is turned off. When the vehicle is turned on in either the accessory or the normal position, a set of frequencies at 132 Hz and harmonics thereof appear in the magnetic field spectrum. The principal source appears to be highly localized near the driver's right ankle with another source associated with the fan and air conditioner near the passenger's ankles. Those frequencies are also present at other measurement locations in the vehicle but at much lower magnitudes. For example, at waist height, the magnetic fields from the vehicle are more similar in magnitude to the ambient fields as shown in Figure 4-13. Table 4-11 summarizes the field levels at all measurement locations in the vehicle for each pretest condition.

EV4 was next run through the FUDS on the dynamometer. Figure 4-14 shows the time-varying field characteristics measured at the waist position of the driver and passenger. The fixed frequency components observed in the pretest (Figure 4-13) are still present but low frequency fields from the rotating tires and other equipment are now clearly present in the magnetic field spectrum. The fixed frequencies observed in the pretest remain constant in frequency and amplitude regardless of the speed, acceleration or braking occurring in the FUDS. The low frequency components, however, vary significantly in amplitude and frequency. Head level fields have similar characteristics but lower amplitude. Ankle level fields have the same frequency components, are generally larger in intensity except at the driver's ankle where the constant frequency field components are much more intense. Field intensities at all measurement locations are summarized in Table 4-12 by frequency band. Observe that the maximum and average magnetic field level in the 65-300 Hz and 305-3000 Hz bands at the driver's ankle are lower in the FUDS test data (Table 4-12) than in the pretest (Table 4-11). That is because the magnetic sensor was moved to the inside of the driver's right leg rather than the outside to avoid the highly localized magnetic field source in the floor "hump" between the front seats. It was assumed that a measurement at the inside of the ankles



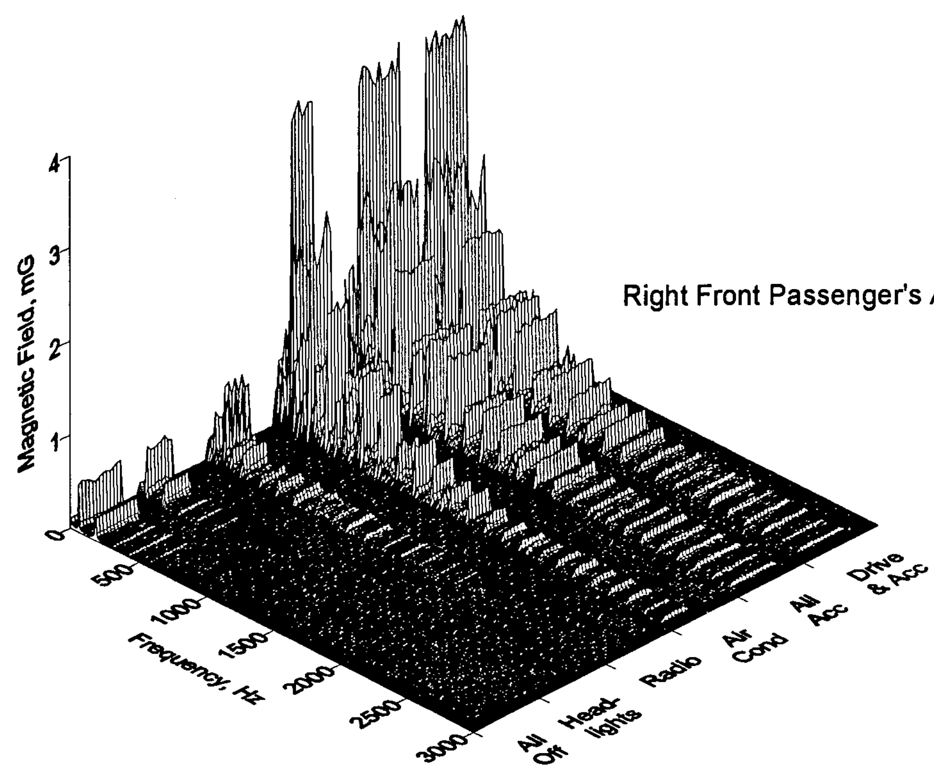


Figure 4-12 Time-Varying Magnetic Field Levels as a Function of Frequency at Ankle Level in Electric Vehicle 4 for Successive Samples with the Vehicle in the Indicated State during the Pretest.

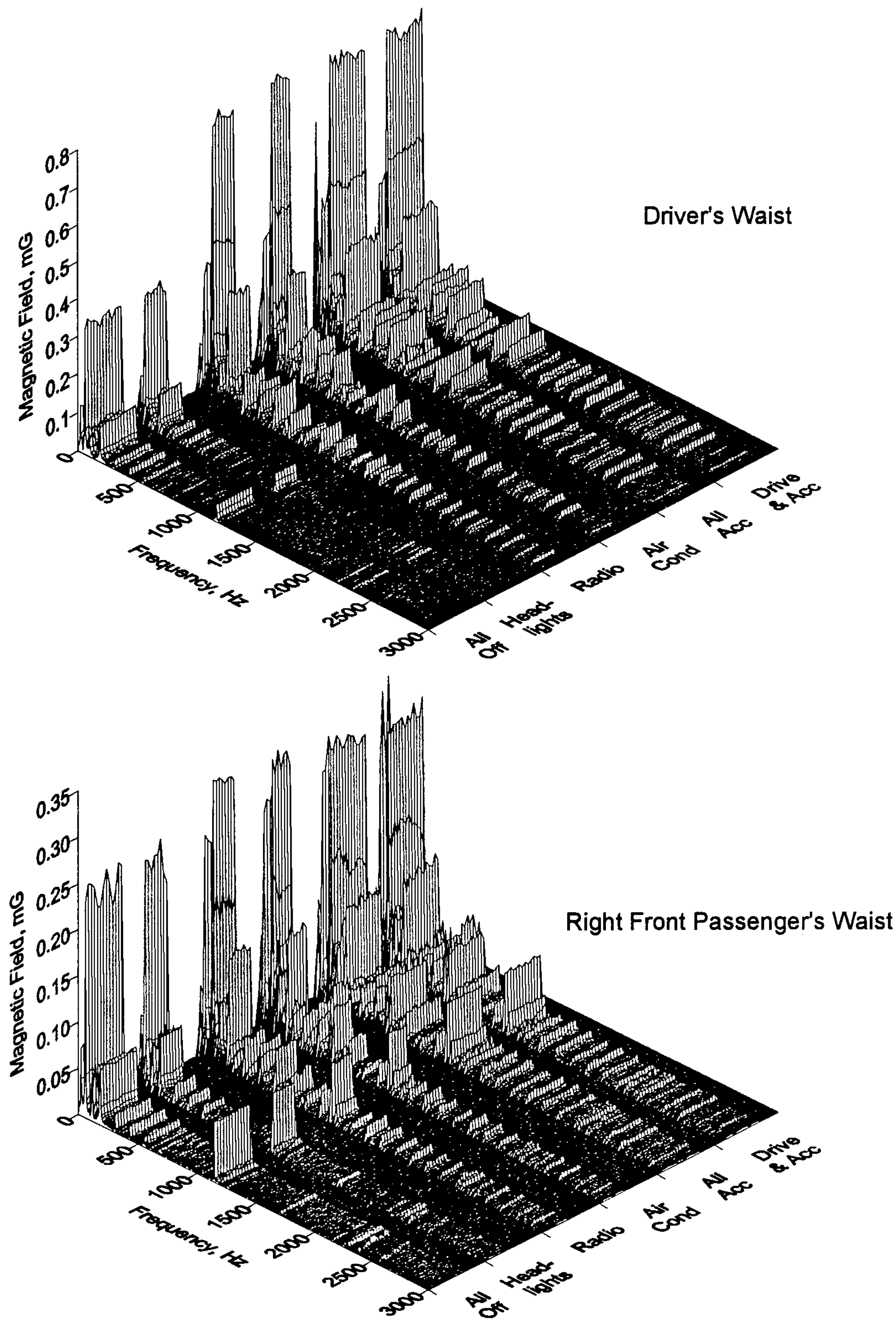
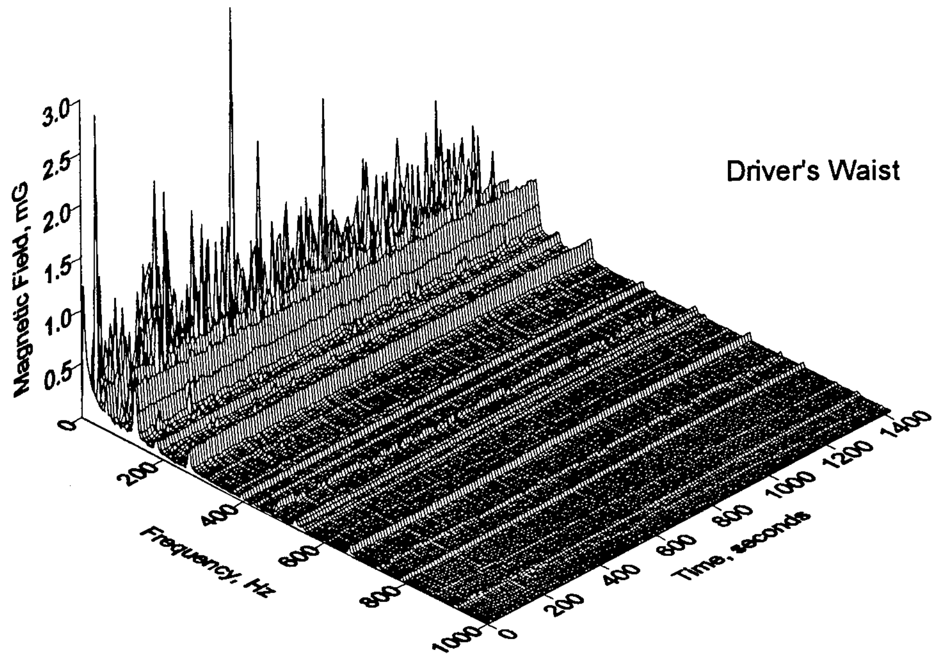


Figure 4-13 Time-Varying Magnetic Field Levels as a Function of Frequency at Waist Level in Electric Vehicle 4 for Successive Samples with the Vehicle in the Indicated State during the Pretest.

Table 4-11
Summary of Average Magnetic Field Levels in Electric Vehicle #4
During the Stationary Pretest Measurements (Means of 7 or More Measurements)

Frequency Band	Sensor Location	Everything Off Field (mG)	Headlights On Field (mG)	Radio On Field (mG)	Air Cond. and Fan On Field (mG)	All Acc. On Field (mG)	In Drive, Acc On Field (mG)
Static	Driver's Head	523	540	523	533	530	540
	Passenger's Head	484	486	483	489	493	509
	Driver's Waist	411	410	415	426	432	434
	Passenger's Waist	462	471	463	483	498	541
	Driver's Ankle	496	498	454	492	489	595
	Passenger's Ankle	714	718	718	767	785	836
	All Positions	515	520	509	532	538	576
5 - 55 Hz Low Frequencies	Driver's Head	0.0	0.0	0.1	0.1	0.1	0.1
	Passenger's Head	0.0	0.0	0.0	0.0	0.0	0.0
	Driver's Waist	0.2	0.2	0.2	0.3	0.3	0.3
	Passenger's Waist	0.1	0.1	0.1	0.2	0.2	0.2
	Driver's Ankle	0.2	0.2	1.7	2.0	3.1	3.4
	Passenger's Ankle	0.2	0.2	0.5	1.9	2.3	1.8
	All Positions	0.1	0.1	0.4	0.7	1.0	0.9
60 Hz Power Frequency	Driver's Head	0.1	0.1	0.1	0.1	0.1	0.1
	Passenger's Head	0.1	0.1	0.1	0.1	0.1	0.1
	Driver's Waist	0.3	0.3	0.3	0.3	0.3	0.3
	Passenger's Waist	0.2	0.2	0.2	0.2	0.2	0.2
	Driver's Ankle	0.4	0.4	0.9	1.0	0.9	1.1
	Passenger's Ankle	0.5	0.5	0.5	0.5	0.7	0.6
	All Positions	0.3	0.3	0.4	0.4	0.4	0.4
65 - 300 Hz Power Harmonics	Driver's Head	0.1	0.1	0.2	0.2	0.2	0.2
	Passenger's Head	0.1	0.1	0.1	0.1	0.1	0.1
	Driver's Waist	0.2	0.2	1.0	1.0	1.0	1.0
	Passenger's Waist	0.1	0.1	0.4	0.4	0.4	0.4
	Driver's Ankle	0.4	1.0	29.5	29.5	28.4	34.8
	Passenger's Ankle	0.4	0.4	1.2	5.1	5.0	5.1
	All Positions	0.2	0.3	5.4	6.1	5.8	6.9
305 - 3000 Hz High Frequencies	Driver's Head	0.0	0.0	0.1	0.1	0.1	0.1
	Passenger's Head	0.0	0.0	0.1	0.1	0.1	0.1
	Driver's Waist	0.1	0.1	0.3	0.3	0.3	0.3
	Passenger's Waist	0.1	0.1	0.1	0.2	0.2	0.2
	Driver's Ankle	0.1	1.0	7.9	9.9	9.5	11.5
	Passenger's Ankle	0.1	0.1	0.4	3.2	2.9	2.8
	All Positions	0.1	0.2	1.5	2.3	2.2	2.5
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.1	0.1	0.2	0.2	0.2	0.2
	Passenger's Head	0.1	0.1	0.2	0.2	0.2	0.2
	Driver's Waist	0.4	0.4	1.1	1.1	1.1	1.1
	Passenger's Waist	0.3	0.3	0.5	0.6	0.5	0.5
	Driver's Ankle	0.6	1.5	30.6	31.2	30.3	36.9
	Passenger's Ankle	0.7	0.7	1.5	6.3	6.3	6.1
	All Positions	0.4	0.5	5.7	6.6	6.4	7.5
	Number of Samples	13	8	8	7	13	13



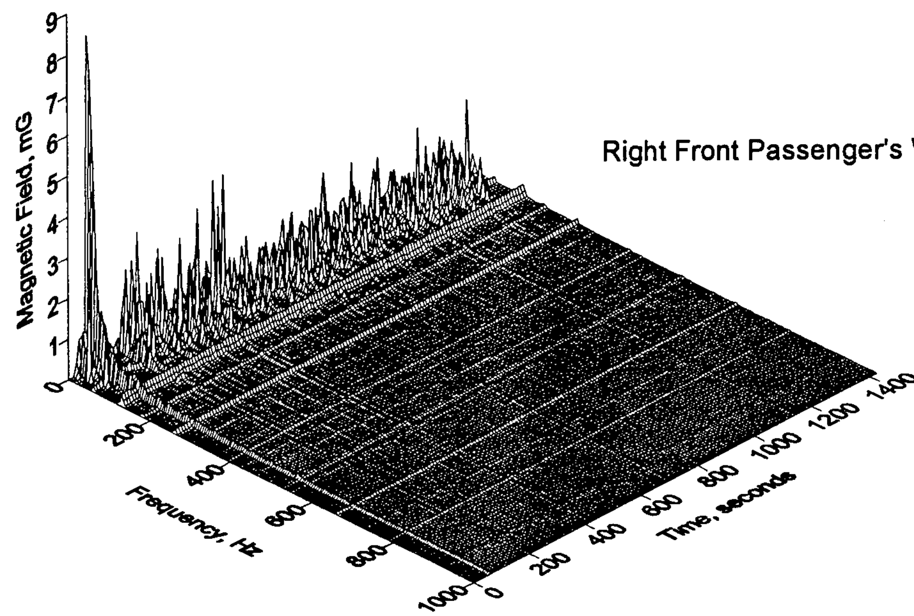


Figure 4-14 Time-Varying Magnetic Field as a Function of Frequency and Time at Waist Level in Electric Vehicle 4 during the FUDS on a Dynamometer.

Table 4-12
Summary of Magnetic Field Levels in Electric Vehicle #4
During the FUDS Test on a Dynamometer

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	471	515	491	10	2
	Passenger's Head	414	555	494	30	6
	Driver's Waist	324	548	400	39	10
	Passenger's Waist	415	590	460	27	6
	Driver's Ankle	401	1044	548	123	22
	Passenger's Ankle	436	885	702	75	11
	All Positions	324	1044	516	114	22
5 - 55 Hz Low Frequencies	Driver's Head	0.0	1.4	0.3	0.2	69
	Passenger's Head	0.0	1.8	0.2	0.2	103
	Driver's Waist	0.2	3.3	1.1	0.6	54
	Passenger's Waist	0.1	14.6	1.5	1.5	96
	Driver's Ankle	0.5	22.5	6.9	3.4	50
	Passenger's Ankle	0.5	57.2	7.6	6.9	90
	All Positions	0.0	57.2	2.9	4.4	151
60 Hz Power Frequency	Driver's Head	0.1	0.2	0.1	0.0	14
	Passenger's Head	0.0	0.1	0.1	0.0	20
	Driver's Waist	0.4	1.1	0.5	0.1	23
	Passenger's Waist	0.1	1.7	0.3	0.2	76
	Driver's Ankle	0.6	4.1	1.2	0.6	49
	Passenger's Ankle	0.3	9.1	1.1	1.1	103
	All Positions	0.0	9.1	0.5	0.7	127
65 - 300 Hz Power Harmonics	Driver's Head	0.2	0.4	0.3	0.0	7
	Passenger's Head	0.1	0.4	0.1	0.0	18
	Driver's Waist	0.7	2.2	0.8	0.1	17
	Passenger's Waist	0.4	2.4	0.6	0.3	40
	Driver's Ankle	10.4	24.5	11.7	2.6	22
	Passenger's Ankle	0.9	11.6	2.6	1.5	57
	All Positions	0.1	24.5	2.7	4.3	158
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.1	0.1	0.0	7
	Passenger's Head	0.1	0.1	0.1	0.0	14
	Driver's Waist	0.2	0.3	0.2	0.0	6
	Passenger's Waist	0.1	1.0	0.2	0.1	41
	Driver's Ankle	2.9	6.9	3.5	0.7	19
	Passenger's Ankle	0.4	5.2	0.8	0.6	68
	All Positions	0.1	6.9	0.8	1.3	157
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.3	1.4	0.4	0.2	34
	Passenger's Head	0.1	1.8	0.3	0.2	73
	Driver's Waist	0.9	3.4	1.6	0.5	33
	Passenger's Waist	0.5	14.8	1.7	1.4	83
	Driver's Ankle	11.2	26.8	14.5	3.0	21
	Passenger's Ankle	1.2	58.6	8.4	6.9	82
	All Positions	0.1	58.6	4.5	6.1	137
	Number of Samples	143				

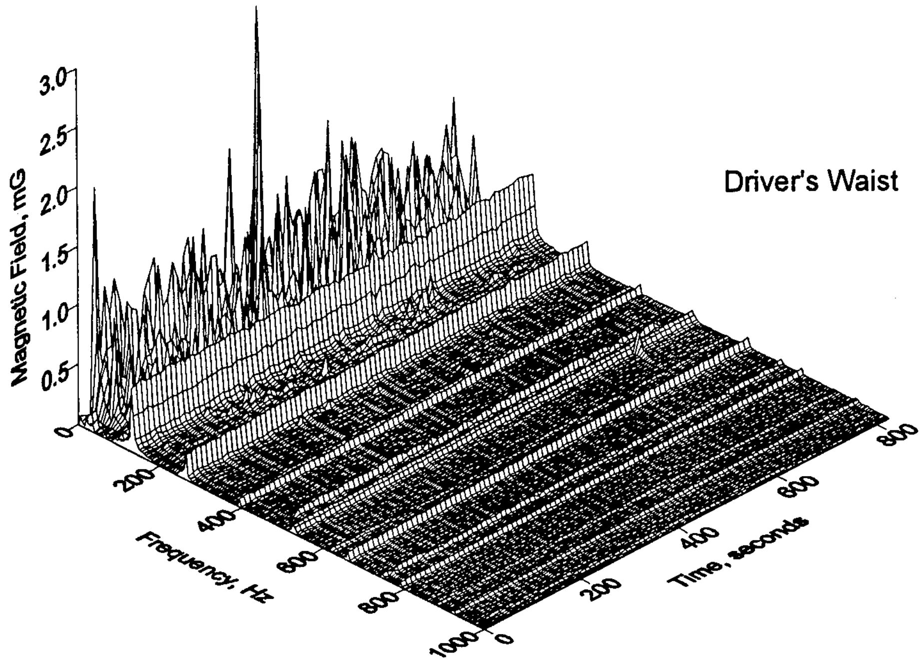
would be more representative of the field levels at both ankles. Furthermore, when the driver had his right foot on the pedals driving the vehicle, they were more distant from the field source than when it was resting on the floor as the end of the FUDS test (which gave rise to the maximum field levels tabulated) or during the pretest.

The final set of measurements in EV4 were conducted on the test track. The driving schedule was similar to that used in most of the other track tests, periods of fixed speed at 50, 30, and 15 mph with periods of acceleration and deceleration between. Figure 4-15 shows waist level magnetic fields as a function of frequency and time during that test. The first few samples were recorded before the driving began. As the vehicle began moving, the low frequency field components appeared to produce field conditions similar to those recorded during the FUDS tests on the dynamometer (Figure 4-14). The frequency and amplitude pattern of the low frequency field components differ because of the differences in speed and acceleration patterns in the two driving schedules. Field intensities recorded during the track tests in EV4 are reported in Table 4-13.

4.3.5 Electric Vehicle #5

Electric Vehicle #5 (EV5) is also a two-passenger vehicle. Magnetic fields were recorded at positions representing the head, waist, and ankle of the driver and front seat passengers. This vehicle was tested using the pretest, FUDS on the dynamometer, and test track protocols. Magnetic sensors were strapped to the driver at appropriate locations (the ankle sensor was on the inside of the right ankle) for all of the tests. Passenger-seat sensors were in the plastic sensor holder for the pretest and dynamometer tests and strapped to the test engineer who rode in the passenger seat during the track tests.

Pretest measurements were made with EV5 on the dynamometer but the dynamometer off. This particular vehicle has daytime running lights which are on any time the vehicle is turned on. Consequently, the lights were on along with the radio and the air conditioner and fan during those portions of the pretest. Figures 4-16 and 4-17 show magnetic field characteristics at waist and ankle levels, respectively. A very modest field at about 1000 Hz appears with only the headlights on. When the radio is turned on, magnetic fields appear at 132 Hz and harmonics thereof. Those fields become more intense when the air conditioner is turned on and remain at about the same intensity when the vehicle is switched on and placed in drive. Average field levels in each test state are given in Table 4-14. Fields are highly localized near the ankles (44 mG and 53 mG for the driver's and passenger's side, respectively)



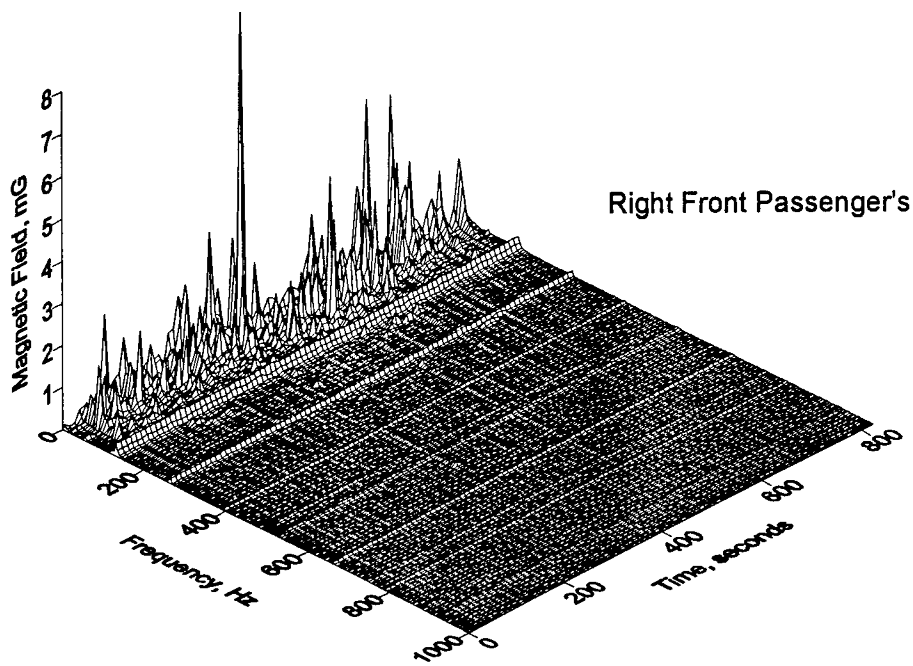


Figure 4-15 Time-Varying Magnetic Fields as a Function of Frequency and Time at Waste Level in Electric Vehicle 4 during the Test Track Measurements.

Table 4-13
Summary of Magnetic Field Levels in Electric Vehicle #4
During the Test Track Measurements

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	396	630	571	38	7
	Passenger's Head	445	641	592	31	5
	Driver's Waist	419	810	537	76	14
	Passenger's Waist	401	1286	546	114	21
	Driver's Ankle	643	1144	850	121	14
	Passenger's Ankle	792	1033	915	66	7
	All Positions	396	1286	669	174	26
5 - 55 Hz Low Frequencies	Driver's Head	0.0	0.9	0.2	0.1	49
	Passenger's Head	0.0	0.7	0.3	0.1	46
	Driver's Waist	0.1	4.8	1.4	0.6	47
	Passenger's Waist	0.1	9.0	1.7	1.4	80
	Driver's Ankle	0.6	14.4	5.0	2.1	43
	Passenger's Ankle	0.5	22.3	10.2	3.4	34
	All Positions	0.0	22.3	3.1	4.0	126
60 Hz Power Frequency	Driver's Head	0.0	0.1	0.0	0.0	55
	Passenger's Head	0.0	0.2	0.0	0.0	88
	Driver's Waist	0.0	1.2	0.1	0.2	127
	Passenger's Waist	0.0	3.3	0.2	0.4	193
	Driver's Ankle	0.1	3.4	0.6	0.5	89
	Passenger's Ankle	0.1	5.6	0.6	0.7	109
	All Positions	0.0	5.6	0.3	0.5	173
65 - 300 Hz Power Harmonics	Driver's Head	0.2	0.3	0.2	0.0	8
	Passenger's Head	0.1	0.2	0.1	0.0	9
	Driver's Waist	0.7	1.5	0.8	0.1	13
	Passenger's Waist	0.4	2.5	0.6	0.3	49
	Driver's Ankle	10.8	12.0	11.2	0.3	3
	Passenger's Ankle	0.9	5.2	1.9	0.7	35
	All Positions	0.1	12.0	2.5	4.0	161
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.1	0.1	0.0	11
	Passenger's Head	0.1	0.1	0.1	0.0	6
	Driver's Waist	0.2	0.4	0.2	0.0	9
	Passenger's Waist	0.1	0.3	0.2	0.0	19
	Driver's Ankle	3.1	6.8	3.5	0.4	11
	Passenger's Ankle	0.4	3.0	0.9	0.6	73
	All Positions	0.1	6.8	0.8	1.3	155
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.2	1.0	0.3	0.1	30
	Passenger's Head	0.1	0.7	0.3	0.1	37
	Driver's Waist	0.8	4.8	1.7	0.6	36
	Passenger's Waist	0.4	9.0	1.9	1.4	74
	Driver's Ankle	11.6	18.7	12.9	1.1	8
	Passenger's Ankle	1.1	22.6	10.5	3.4	33
	All Positions	0.1	22.6	4.6	5.4	116
	Number of Samples	83				

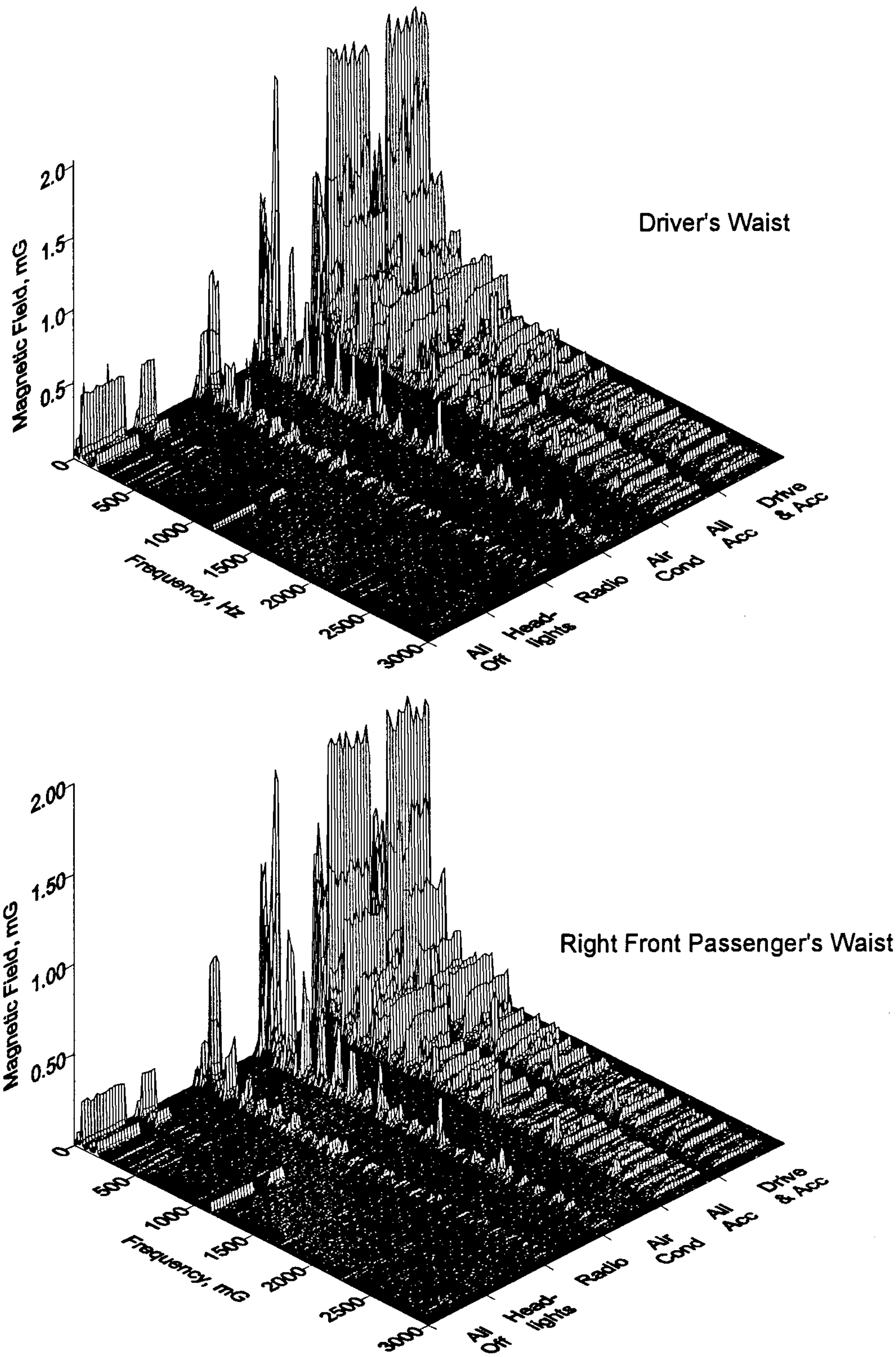


Figure 4-16 Time-Varying Magnetic Field Levels as a Function of Frequency at Waste Level in Electric Vehicle 5 for Successive Samples with the Vehicle in the Indicated State during the Pretest.

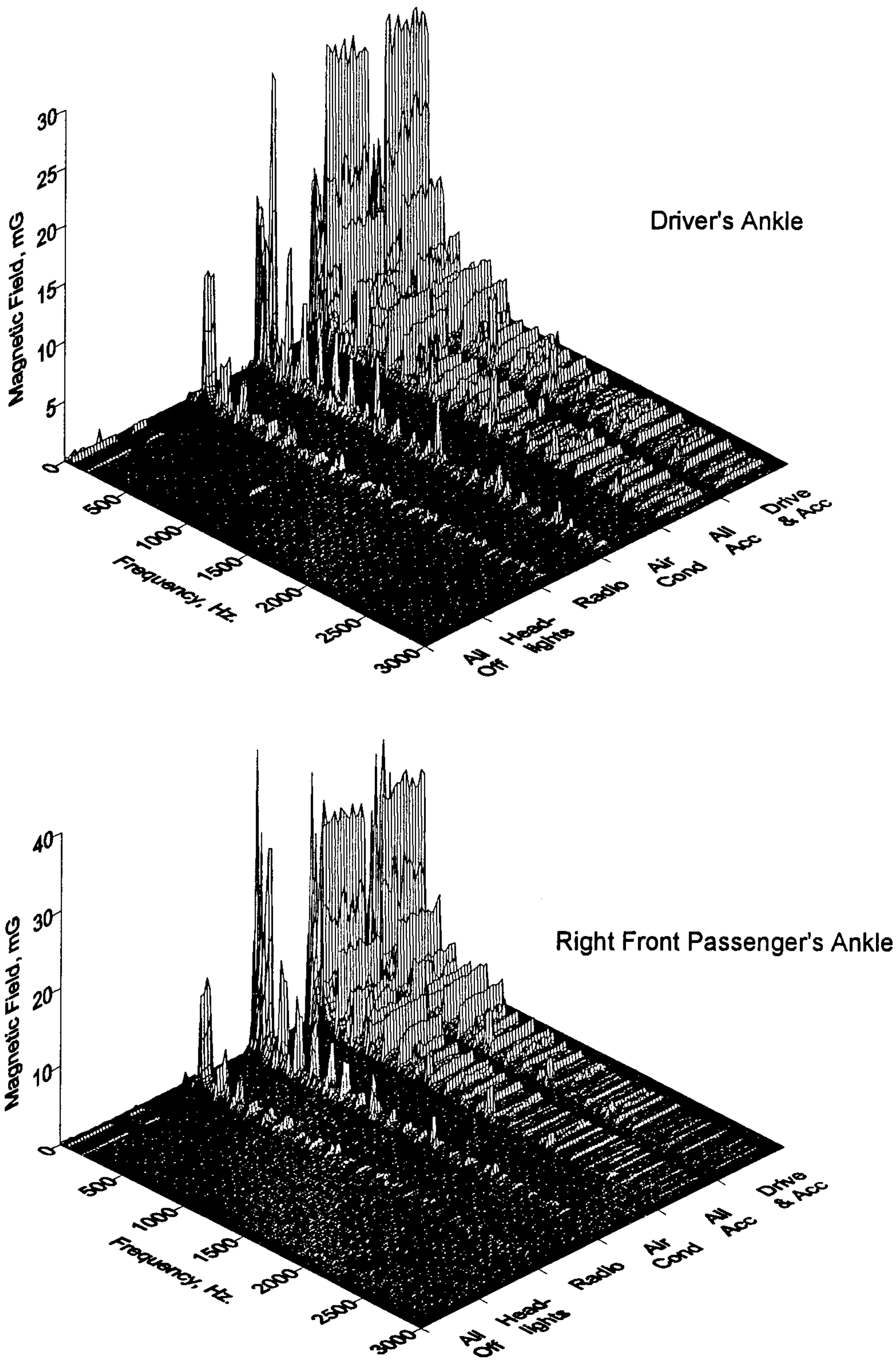


Figure 4-17 Time-Varying Magnetic Field Levels as a Function of Frequency at Ankle Level in Electric Vehicle 5 for Successive Samples with the Vehicle in the Indicated State during the Pretest.

Table 4-14
Summary of Average Magnetic Field Levels in Electric Vehicle #5
During the Stationary Pretest Measurements (Means of 4 or More Measurements)

Frequency Band	Sensor Location	Everything Off Field (mG)	Headlights On Field (mG)	Radio On Field (mG)	Air Cond. and Fan On Field (mG)	All Acc. On Field (mG)	In Drive, Acc On Field (mG)
Static	Driver's Head	440	448	445	448	447	445
	Passenger's Head	445	443	447	451	452	450
	Driver's Waist	324	323	334	347	352	353
	Passenger's Waist	275	272	279	287	291	287
	Driver's Ankle	390	381	387	396	401	420
	Passenger's Ankle	430	427	477	540	557	562
	All Positions	384	382	395	411	417	419
5 - 55 Hz Low Frequencies	Driver's Head	0.2	0.1	0.1	0.2	0.2	0.3
	Passenger's Head	0.0	0.0	0.0	0.2	0.2	0.2
	Driver's Waist	0.3	0.2	0.2	1.2	1.6	1.7
	Passenger's Waist	0.1	0.1	0.2	1.1	1.5	1.5
	Driver's Ankle	0.4	0.2	1.1	15.1	20.0	21.2
	Passenger's Ankle	0.3	0.2	1.8	24.3	24.9	24.4
	All Positions	0.2	0.1	0.6	7.0	8.1	8.2
60 Hz Power Frequency	Driver's Head	0.1	0.1	0.1	0.1	0.1	0.2
	Passenger's Head	0.1	0.1	0.1	0.1	0.1	0.1
	Driver's Waist	0.4	0.4	0.5	0.6	0.6	0.6
	Passenger's Waist	0.3	0.2	0.3	0.5	0.4	0.5
	Driver's Ankle	0.8	0.7	0.8	4.4	6.5	5.5
	Passenger's Ankle	0.6	0.6	0.8	5.3	11.4	10.5
	All Positions	0.4	0.4	0.4	1.8	3.2	2.9
65 - 300 Hz Power Harmonics	Driver's Head	0.1	0.0	0.2	0.3	0.4	0.4
	Passenger's Head	0.0	0.0	0.2	0.3	0.4	0.4
	Driver's Waist	0.2	0.2	1.1	2.0	2.7	2.8
	Passenger's Waist	0.2	0.2	0.9	1.8	2.2	2.2
	Driver's Ankle	0.5	0.5	14.9	25.3	34.6	34.5
	Passenger's Ankle	0.5	0.5	17.1	29.8	40.3	40.7
	All Positions	0.2	0.2	5.7	9.9	13.4	13.5
305 - 3000 Hz High Frequencies	Driver's Head	0.0	0.0	0.1	0.1	0.2	0.2
	Passenger's Head	0.0	0.0	0.1	0.2	0.2	0.2
	Driver's Waist	0.1	0.1	0.5	1.1	1.3	1.3
	Passenger's Waist	0.1	0.1	0.4	0.9	0.9	0.9
	Driver's Ankle	0.1	0.4	6.6	13.5	16.5	16.2
	Passenger's Ankle	0.1	0.1	6.5	15.4	16.6	16.4
	All Positions	0.1	0.1	2.4	5.2	5.9	5.9
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.3	0.1	0.2	0.4	0.6	0.6
	Passenger's Head	0.1	0.1	0.2	0.4	0.5	0.5
	Driver's Waist	0.6	0.5	1.4	2.7	3.5	3.6
	Passenger's Waist	0.3	0.3	1.1	2.4	2.9	2.9
	Driver's Ankle	1.1	1.0	16.4	33.7	44.2	44.3
	Passenger's Ankle	0.8	0.8	18.4	43.9	53.0	53.0
	All Positions	0.5	0.5	6.3	13.9	17.5	17.5
	Number of Samples	15	5	4	4	16	15

and attenuate rapidly to 3 to 4 mG at the waist and well less than 1 mG at the head.

Magnetic field measurements were conducted in EV5 while running the FUDS on a dynamometer. Unfortunately, the field sensor signals were recorded only intermittently during the test resulting in the loss of approximately half of the magnetic field samples. Table 4-15 provides a statistical summary of the valid measurement samples. The field spectrum during the FUDS tests consisted of the same series of fixed-frequency components seen in the pretest plus low-frequency components which result from the rotating tires and other mechanical parts. The fixed frequency components displayed amplitude levels comparable to those seen in the pretest when the vehicle was on with the radio and headlights. The fields were lower than those recorded in EV5 when the air conditioner was on. This finding suggests that electric power circuitry associated with the air conditioner materially adds to the magnetic field levels in the vehicle. Data from the FUDS test on the dynamometer were made without the air conditioner operating (as were the FUDS and track tests on the other electric vehicles).

4.3.6 Conventional Car #1

The limited availability of prototype electric vehicles of design representing production vehicles prevented the electric vehicles from being tested with the same protocol as that used for conventional vehicles. To better understand the extent to which the measurement protocol biases the results, the conventional vehicle identified as Car 1 in Section 3 was retested using the protocol employed for the electrics.

Conventional Car #1 was measured while running the FUDS on both dynamometers used to test the electric vehicles with inconsistent results. Table 4-16 gives the results measured on the dynamometer used to test EV1. Data obtained in Car 1 using the dynamometer used to test EV4 and EV5 are presented in Table 4-17. Table 4-16 contains data for all four seats to be comparable to EV1 in which four seats were tested. Table 4-17 shows only front seat data to provide better comparability with the two-passenger electric vehicles tested on the same dynamometer. The low frequency time-varying field components observed in the test reported in Table 4-17 are approximately three times larger at the head and ankle positions than those reported at the same positions in Table 4-16. That suggests that a substantial portion of those low frequency fields measured in Car 1 on the dynamometer used to test EV4 and EV5 arise from fields produced by the dynamometer.

Table 4-15
Summary of Magnetic Field Levels in Electric Vehicle #5
During the FUDS Test on a Dynamometer

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	442	513	479	18	4
	Passenger's Head	433	447	441	3	1
	Driver's Waist	314	342	326	18	5
	Passenger's Waist	267	285	276	6	2
	Driver's Ankle	390	455	411	4	1
	Passenger's Ankle	442	513	479	17	3
	All Positions	267	513	402	78	19
5 - 55 Hz Low Frequencies	Driver's Head	0.0	0.3	0.2	0.1	37
	Passenger's Head	0.0	0.4	0.1	0.1	58
	Driver's Waist	0.2	1.5	0.8	0.3	42
	Passenger's Waist	0.1	4.5	0.8	0.6	77
	Driver's Ankle	0.6	24.1	12.0	6.0	50
	Passenger's Ankle	0.6	56.1	17.3	10.5	61
	All Positions	0.0	56.1	5.2	8.5	163
60 Hz Power Frequency	Driver's Head	0.1	0.2	0.1	0.0	13
	Passenger's Head	0.1	0.1	0.1	0.0	9
	Driver's Waist	0.3	0.5	0.4	0.0	8
	Passenger's Waist	0.2	0.5	0.3	0.1	19
	Driver's Ankle	0.6	3.7	1.2	0.6	50
	Passenger's Ankle	0.3	10.2	1.4	1.7	124
	All Positions	0.1	10.2	0.6	0.9	155
65 - 300 Hz Power Harmonics	Driver's Head	0.2	0.4	0.2	0.0	19
	Passenger's Head	0.2	0.2	0.2	0.0	5
	Driver's Waist	1.0	2.5	1.2	0.2	19
	Passenger's Waist	0.9	1.6	1.0	0.1	12
	Driver's Ankle	12.9	79.9	18.8	11.1	59
	Passenger's Ankle	15.1	44.2	18.6	5.6	30
	All Positions	0.2	79.9	6.7	8.8	132
305 - 3000 Hz High Frequencies	Driver's Head	0.0	0.2	0.1	0.0	35
	Passenger's Head	0.0	0.1	0.1	0.0	20
	Driver's Waist	0.2	0.4	0.3	0.1	30
	Passenger's Waist	0.2	0.4	0.3	0.1	30
	Driver's Ankle	3.1	7.7	5.0	1.9	38
	Passenger's Ankle	3.2	8.6	5.2	2.0	39
	All Positions	0.0	8.6	1.8	2.6	142
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.3	0.5	0.3	0.0	12
	Passenger's Head	0.2	0.5	0.3	0.0	17
	Driver's Waist	1.2	2.6	1.6	0.2	15
	Passenger's Waist	1.0	4.7	1.4	0.5	35
	Driver's Ankle	13.5	80.8	24.0	10.6	44
	Passenger's Ankle	15.6	59.7	27.4	8.5	31
	All Positions	0.2	80.8	9.2	13.0	142
	Number of Samples	68				

Table 4-16
Summary of Magnetic Field Levels in Conventional Car #1
During the FUDS Test on the Dynamometer Used to Test EV1

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	314	344	324	5	2
	Right Front Pass. Head	362	456	400	14	4
	Left Rear Pass. Head	468	484	474	5	1
	Right Rear Pass. Head	347	361	356	5	1
	Driver's Waist	221	244	232	5	2
	Right Front Pass. Waist	219	265	242	10	4
	Left Rear Pass. Waist	159	218	176	19	11
	Right Rear Pass. Waist	285	309	299	8	3
	Driver's Ankle	207	256	238	13	6
	Right Front Pass. Ankle	165	226	204	14	7
	Left Rear Pass. Ankle	124	167	149	15	10
	Right Rear Pass. Ankle	174	194	185	6	3
	All Positions	124	484	273	96	35
5 - 55 Hz Low Frequencies	Driver's Head	0.2	8.7	1.7	1.2	71
	Right Front Pass. Head	0.2	5.9	1.4	0.9	68
	Left Rear Pass. Head	0.2	7.4	1.0	0.9	92
	Right Rear Pass. Head	0.1	6.7	0.8	0.7	83
	Driver's Waist	0.3	22.2	3.1	2.5	81
	Right Front Pass. Waist	0.4	11.3	2.4	1.8	74
	Left Rear Pass. Waist	0.2	30.0	1.9	3.4	181
	Right Rear Pass. Waist	0.2	9.6	1.4	1.1	78
	Driver's Ankle	0.8	23.6	6.0	3.6	61
	Right Front Pass. Ankle	0.7	18.2	7.1	4.7	66
	Left Rear Pass. Ankle	0.4	43.8	3.6	5.3	146
	Right Rear Pass. Ankle	0.6	9.4	2.6	1.7	65
	All Positions	0.1	43.8	2.7	3.3	122
60 Hz Power Frequency	Driver's Head	0.4	0.6	0.5	0.0	7
	Right Front Pass. Head	0.5	0.8	0.6	0.0	6
	Left Rear Pass. Head	0.3	0.7	0.4	0.0	10
	Right Rear Pass. Head	0.4	0.7	0.5	0.0	6
	Driver's Waist	0.7	1.6	0.9	0.1	10
	Right Front Pass. Waist	1.9	2.2	2.0	0.1	3
	Left Rear Pass. Waist	0.5	2.0	0.6	0.2	25
	Right Rear Pass. Waist	0.8	1.0	0.9	0.0	3
	Driver's Ankle	0.4	1.6	0.6	0.1	19
	Right Front Pass. Ankle	0.4	1.1	0.6	0.1	19
	Left Rear Pass. Ankle	2.1	4.2	2.3	0.2	11
	Right Rear Pass. Ankle	3.5	3.9	3.7	0.1	2
	All Positions	0.3	4.2	1.1	1.0	85

Table 4-16 (Continued)

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
65 - 300 Hz Power Harmonics	Driver's Head	0.3	1.4	0.4	0.1	24
	Right Front Pass. Head	0.3	0.7	0.4	0.1	13
	Left Rear Pass. Head	0.2	1.4	0.3	0.1	41
	Right Rear Pass. Head	0.3	1.1	0.3	0.1	25
	Driver's Waist	0.6	3.5	0.7	0.3	35
	Right Front Pass. Waist	1.2	1.7	1.4	0.1	5
	Left Rear Pass. Waist	0.4	4.9	0.5	0.5	95
	Right Rear Pass. Waist	0.8	1.5	0.9	0.1	8
	Driver's Ankle	0.7	3.6	1.0	0.3	32
	Right Front Pass. Ankle	0.5	2.1	0.9	0.4	42
	Left Rear Pass. Ankle	1.9	8.8	2.1	0.9	43
	Right Rear Pass. Ankle	2.3	2.8	2.5	0.1	3
	All Positions	0.2	8.8	0.9	0.8	80
305 - 3000 Hz High Frequencies	Driver's Head	0.1	0.3	0.1	0.0	20
	Right Front Pass. Head	0.1	0.3	0.2	0.0	11
	Left Rear Pass. Head	0.1	0.3	0.1	0.0	21
	Right Rear Pass. Head	0.1	0.4	0.1	0.0	19
	Driver's Waist	0.2	0.8	0.3	0.1	26
	Right Front Pass. Waist	0.3	0.5	0.4	0.0	9
	Left Rear Pass. Waist	0.1	1.3	0.2	0.1	79
	Right Rear Pass. Waist	0.3	0.6	0.3	0.0	9
	Driver's Ankle	0.6	1.2	0.8	0.1	12
	Right Front Pass. Ankle	0.4	1.0	0.5	0.1	24
	Left Rear Pass. Ankle	0.5	3.7	0.6	0.4	59
	Right Rear Pass. Ankle	0.7	1.0	0.8	0.1	7
	All Positions	0.1	3.7	0.4	0.3	73
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.7	8.8	1.9	1.1	58
	Right Front Pass. Head	0.7	6.0	1.6	0.8	51
	Left Rear Pass. Head	0.5	7.6	1.2	0.8	73
	Right Rear Pass. Head	0.5	6.8	1.1	0.6	57
	Driver's Waist	1.1	22.5	3.5	2.4	68
	Right Front Pass. Waist	2.3	11.7	3.7	1.3	36
	Left Rear Pass. Waist	0.7	30.5	2.2	3.4	155
	Right Rear Pass. Waist	1.2	9.8	2.0	0.8	43
	Driver's Ankle	1.5	24.0	6.2	3.5	56
	Right Front Pass. Ankle	1.1	18.3	7.3	4.6	64
	Left Rear Pass. Ankle	3.0	45.1	5.2	5.0	98
	Right Rear Pass. Ankle	4.4	10.4	5.4	0.9	18
	All Positions	0.5	45.1	3.4	3.3	97
	Number of Samples	142				

Table 4-17
Summary of Magnetic Field Levels in Conventional Car #1
During the FUDS Test on the Dynamometer Used to Test EV4 and EV5

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	297	315	305	3	1
	Passenger's Head	325	434	372	15	4
	Driver's Waist	184	219	200	5	3
	Passenger's Waist	174	293	206	34	17
	Driver's Ankle	160	215	196	15	7
	Passenger's Ankle	134	197	175	13	8
	All Positions	134	434	242	73	30
5 - 55 Hz Low Frequencies	Driver's Head	0.1	2.4	0.5	0.3	61
	Passenger's Head	0.1	0.8	0.4	0.2	53
	Driver's Waist	0.3	17.8	2.2	2.0	91
	Passenger's Waist	0.4	3.9	2.3	1.2	52
	Driver's Ankle	2.6	63.2	21.4	11.3	53
	Passenger's Ankle	2.0	42.1	23.7	13.3	56
	All Positions	0.1	63.2	8.4	12.3	147
60 Hz Power Frequency	Driver's Head	0.1	0.2	0.1	0.0	15
	Passenger's Head	0.2	0.3	0.2	0.0	7
	Driver's Waist	0.5	1.0	0.6	0.1	11
	Passenger's Waist	1.8	2.4	2.2	0.2	7
	Driver's Ankle	0.6	3.4	1.8	0.5	26
	Passenger's Ankle	1.5	4.7	2.4	0.4	16
	All Positions	0.1	4.7	1.2	1.0	80
65 - 300 Hz Power Harmonics	Driver's Head	0.0	0.4	0.1	0.0	60
	Passenger's Head	0.1	0.2	0.1	0.0	13
	Driver's Waist	0.2	3.0	0.4	0.3	81
	Passenger's Waist	0.8	1.2	1.0	0.1	7
	Driver's Ankle	1.9	10.1	3.3	1.2	37
	Passenger's Ankle	1.3	6.6	2.5	1.2	48
	All Positions	0.0	10.1	1.2	1.4	117
305 - 3000 Hz High Frequencies	Driver's Head	0.0	0.1	0.0	0.0	17
	Passenger's Head	0.0	0.1	0.1	0.0	9
	Driver's Waist	0.1	0.7	0.2	0.1	36
	Passenger's Waist	0.2	0.5	0.3	0.0	14
	Driver's Ankle	1.5	4.3	2.3	0.4	17
	Passenger's Ankle	0.6	2.9	1.2	0.5	44
	All Positions	0.0	4.3	0.7	0.9	128
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.1	2.4	0.5	0.3	56
	Passenger's Head	0.2	0.9	0.5	0.2	34
	Driver's Waist	0.7	18.1	2.4	2.0	83
	Passenger's Waist	2.1	4.4	3.5	0.7	21
	Driver's Ankle	4.2	64.2	22.1	11.0	50
	Passenger's Ankle	3.3	42.5	24.1	13.0	54
	All Positions	0.1	64.2	8.8	12.3	140
	Number of Samples	136				

Magnetic field data measured in Car 1 on a test track are presented in Table 4-18. This test was conducted on the same track using the same driver as EV3. The low frequency field levels observed in the track data for Conventional Car #1 are modestly larger than those reported in Table 4-16 from the dynamometer used to test EV1. This is similar to the observation reported in Section 4.3.1 above for EV1 and appears to confirm that the dynamometer used to test that vehicle (EV1) was not a significant source of low frequency fields. The low frequency fields measured in Car 1 on the track (Table 4-18) are much less than those measured on the dynamometer used to test EV4 and EV5 confirming the conclusion in the preceding paragraph regarding field production by that dynamometer.

4.3.7 Magnetic Field Level Summary

Magnetic field measurement procedures and results have been discussed above for five electric and one conventional vehicle. This section seeks to compare and contrast field characteristics measured in the various vehicles to better view the field characteristics of electric vehicles as a class.

Preceding tables and figures of this section have provided extensive magnetic field data which could be summarized in a host of ways. For the sake of illustration, the following discussion will compare time-average magnetic field levels for various frequency bands. That is not to imply that time average is the most important parameter of consideration. It was simply selected as a common indicator of central tendency. Similar analysis can be conducted for virtually any parameter based on summary data within this report or with the use of the full data set which is available from the EMF RAPID Database [5]. Because of the large spatial variability in field level within all of the vehicles examined, comparisons will be made between similar locations within the vehicles as well as spatial average values for all measurement points in the vehicle.

Table 4-19 compares average field levels measured in the electric vehicles traveling the FUDS on a dynamometer to field levels similarly measured in a conventional automobile. Because of substantial differences in the background field level produced by the two dynamometers used for these measurements, the most useful comparisons are between measurements made on the same dynamometer. The table is arranged to facilitate comparisons among vehicles tested on each dynamometer.

Static field levels in the electric vehicles tend to be higher than in their conventional counterparts but that difference appears more related to

Table 4-18
Summary of Magnetic Field Levels in Conventional Car #1
During Measurements on the Track Used to Test EV3

Frequency Band	Sensor Location	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)	Standard Deviation (mG)	Coefficient of Variation (%)
Static	Driver's Head	121	511	246	77	31
	Passenger's Head	80	359	236	70	30
	Driver's Waist	154	432	307	58	19
	Passenger's Waist	182	359	272	45	16
	Driver's Ankle	222	519	391	88	23
	Passenger's Ankle	220	630	452	113	25
	Avg. at All Positions	80	630	317	111	35
5 - 55 Hz Low Frequencies	Driver's Head	0.3	15.2	2.9	1.9	65
	Passenger's Head	0.2	12.0	3.6	1.9	53
	Driver's Waist	0.3	16.9	4.4	2.5	57
	Passenger's Waist	0.3	22.6	5.6	4.3	76
	Driver's Ankle	0.8	25.8	9.3	4.3	46
	Passenger's Ankle	0.8	27.8	10.0	5.4	54
	Avg. at All Positions	0.2	27.8	6.0	4.5	76
60 Hz Power Frequency	Driver's Head	0.0	0.5	0.1	0.1	76
	Passenger's Head	0.0	0.3	0.1	0.1	53
	Driver's Waist	0.0	0.8	0.1	0.1	81
	Passenger's Waist	0.0	0.7	0.2	0.1	85
	Driver's Ankle	0.1	1.1	0.3	0.2	55
	Passenger's Ankle	0.1	1.2	0.3	0.2	64
	Avg. at All Positions	0.0	1.2	0.2	0.2	90
65 - 300 Hz Power Harmonics	Driver's Head	0.2	1.3	0.3	0.1	45
	Passenger's Head	0.1	0.9	0.3	0.2	50
	Driver's Waist	0.1	2.4	0.4	0.3	76
	Passenger's Waist	0.1	2.0	0.5	0.4	78
	Driver's Ankle	0.3	3.6	0.9	0.5	56
	Passenger's Ankle	0.3	3.6	1.0	0.6	61
	Avg. at All Positions	0.1	3.6	0.6	0.5	84
305 - 3000 Hz High Frequencies	Driver's Head	0.2	0.7	0.2	0.1	27
	Passenger's Head	0.1	0.4	0.1	0.1	48
	Driver's Waist	0.1	1.2	0.2	0.2	68
	Passenger's Waist	0.1	1.0	0.3	0.2	58
	Driver's Ankle	0.2	1.7	0.5	0.2	54
	Passenger's Ankle	0.2	1.7	0.5	0.3	54
	Avg. at All Positions	0.1	1.7	0.3	0.2	72
5 - 3000 Hz All ELF Frequencies	Driver's Head	0.4	15.3	3.0	1.9	64
	Passenger's Head	0.3	12.0	3.6	1.9	53
	Driver's Waist	0.4	17.1	4.5	2.5	57
	Passenger's Waist	0.3	22.6	5.6	4.3	76
	Driver's Ankle	1.0	26.1	9.4	4.3	46
	Passenger's Ankle	0.9	27.9	10.1	5.4	53
	Avg. at All Positions	0.3	27.9	6.0	4.6	75
	Number of Samples	66				

Table 4-19
Summary of Average Magnetic Field Levels in Electric Vehicles Measured During the FUDS Test on Dynamometer Compared to Levels Similarly Measured In a Conventional Car

Frequency Band	Sensor Location	Dynamometer A Car 1 (mG)	Dynamometer A EV 1 (mG)	Avg. of All 3 EVs (mG)	Dynamometer B EV 4 (mG)	Dynamometer B EV 5 (mG)	Dynamometer B Car 1 (mG)
Static	Driver's Head	324	337	436	491	479	305
	Right Front Pass. Head	400	269	401	494	441	372
	Left Rear Pass. Head	474	342	342			
	Right Rear Pass. Head	356	217	217			
	Driver's Waist	232	253	326	400	326	200
	Right Front Pass. Waist	242	238	325	460	276	206
	Left Rear Pass. Waist	176	207	207			
	Right Rear Pass. Waist	299	328	328			
	Driver's Ankle	238	456	472	548	411	196
	Right Front Pass. Ankle	204	361	514	702	479	175
	Left Rear Pass. Ankle	149	167	167			
	Right Rear Pass. Ankle	185	497	497			
	All Positions	273	306	408	516	402	242
5 - 55 Hz Low Frequencies	Driver's Head	1.7	1.3	0.6	0.3	0.2	0.5
	Right Front Pass. Head	1.4	1.0	0.4	0.2	0.1	0.4
	Left Rear Pass. Head	1.0	0.7	0.7			
	Right Rear Pass. Head	0.8	0.7	0.7			
	Driver's Waist	3.1	1.9	1.3	1.1	0.8	2.2
	Right Front Pass. Waist	2.4	1.6	1.3	1.5	0.8	2.3
	Left Rear Pass. Waist	1.9	1.1	1.1			
	Right Rear Pass. Waist	1.4	1.0	1.0			
	Driver's Ankle	6.0	3.6	7.5	6.9	12.0	21.4
	Right Front Pass. Ankle	7.1	5.2	10.0	7.6	17.3	23.7
	Left Rear Pass. Ankle	3.6	2.4	2.4			
	Right Rear Pass. Ankle	2.6	3.2	3.2			
	All Positions	2.7	2.0	3.4	2.9	5.2	8.4
60 Hz Power Frequency	Driver's Head	0.5	0.4	0.2	0.1	0.1	0.1
	Right Front Pass. Head	0.6	0.7	0.3	0.1	0.1	0.2
	Left Rear Pass. Head	0.4	0.2	0.2			
	Right Rear Pass. Head	0.5	0.4	0.4			
	Driver's Waist	0.9	0.4	0.4	0.5	0.4	0.6
	Right Front Pass. Waist	2.0	1.3	0.6	0.3	0.3	2.2
	Left Rear Pass. Waist	0.6	0.3	0.3			
	Right Rear Pass. Waist	0.9	0.9	0.9			
	Driver's Ankle	0.6	0.5	1.0	1.2	1.2	1.8
	Right Front Pass. Ankle	0.6	0.7	1.1	1.1	1.4	2.4
	Left Rear Pass. Ankle	2.3	0.6	0.6			
	Right Rear Pass. Ankle	3.7	11.8	11.8			
	All Positions	1.1	1.5	0.9	0.5	0.6	1.2

Table 4-19 (Continued)

Frequency Band	Sensor Location	Dynamometer A Car 1 (mG)	Dynamometer A EV 1 (mG)	Avg. of All 3 EVs (mG)	Dynamometer B EV 4 (mG)	Dynamometer B EV 5 (mG)	Dynamometer B Car 1 (mG)
65 - 300 Hz Power Harmonics	Driver's Head	0.4	0.4	0.3	0.3	0.2	0.1
	Right Front Pass. Head	0.4	0.5	0.3	0.1	0.2	0.1
	Left Rear Pass. Head	0.3	0.2	0.2			
	Right Rear Pass. Head	0.3	0.3	0.3			
	Driver's Waist	0.7	0.4	0.8	0.8	1.2	0.4
	Right Front Pass. Waist	1.4	0.9	0.9	0.6	1.0	1.0
	Left Rear Pass. Waist	0.5	0.3	0.3			
	Right Rear Pass. Waist	0.9	0.7	0.7			
	Driver's Ankle	1.0	1.1	10.6	11.7	18.8	3.3
	Right Front Pass. Ankle	0.9	1.7	7.6	2.6	18.6	2.5
	Left Rear Pass. Ankle	2.1	0.9	0.9			
	Right Rear Pass. Ankle	2.5	9.5	9.5			
	All Positions	0.9	1.4	3.6	2.7	6.7	1.2
305 - 3000 High Frequencies	Driver's Head	0.1	0.1	0.1	0.1	0.1	0.0
	Right Front Pass. Head	0.2	0.2	0.1	0.1	0.1	0.1
	Left Rear Pass. Head	0.1	0.1	0.1			
	Right Rear Pass. Head	0.1	0.1	0.1			
	Driver's Waist	0.3	0.1	0.2	0.2	0.3	0.2
	Right Front Pass. Waist	0.4	0.3	0.2	0.2	0.3	0.3
	Left Rear Pass. Waist	0.2	0.1	0.1			
	Right Rear Pass. Waist	0.3	0.2	0.2			
	Driver's Ankle	0.8	0.3	3.0	3.5	5.0	2.3
	Right Front Pass. Ankle	0.5	0.5	2.2	0.8	5.2	1.2
	Left Rear Pass. Ankle	0.6	0.6	0.6			
	Right Rear Pass. Ankle	0.8	2.6	2.6			
	All Positions	0.4	0.4	1.0	0.8	1.8	0.7
5 - 3000 Hz All ELF Frequencies	Driver's Head	1.9	1.5	0.8	0.4	0.3	0.5
	Right Front Pass. Head	1.6	1.4	0.6	0.3	0.3	0.5
	Left Rear Pass. Head	1.2	0.8	0.8			
	Right Rear Pass. Head	1.1	0.8	0.8			
	Driver's Waist	3.5	2.0	1.7	1.6	1.6	2.4
	Right Front Pass. Waist	3.7	2.4	1.8	1.7	1.4	3.5
	Left Rear Pass. Waist	2.2	1.2	1.2			
	Right Rear Pass. Waist	2.0	1.6	1.6			
	Driver's Ankle	6.2	4.0	14.1	14.5	24.0	22.1
	Right Front Pass. Ankle	7.3	5.8	13.9	8.4	27.4	24.1
	Left Rear Pass. Ankle	5.2	2.8	2.8			
	Right Rear Pass. Ankle	5.4	15.7	15.7			
	All Positions	3.4	3.3	5.7	4.5	9.2	8.8
	Number of Samples	142	145		143	68	136

differences in shielding of the geomagnetic field than static field generation by the electric vehicles.

The magnetic fields in the low frequency band arise primarily from rotating mechanical parts such as tires which themselves have some static magnetization. The frequency of the time-varying fields produced by these components varies with the rotational speed of the part. Dynamometer A did not appear to produce substantial levels of low frequency fields, but Dynamometer B did produce such fields. Differing results in the low frequency measurements within Conventional Car 1 on the two dynamometers demonstrate the extent of that difference. As a result, comparisons in this frequency band can only reliably be made among vehicles tested on the same dynamometer. Low frequency magnetic fields in the conventional vehicle were consistently larger than those in the electric vehicles.

Sixty-hertz fields arise primarily from ambient fields in the dynamometer laboratory and provide little useful comparative information about the vehicles. The apparent high level of 60 Hz magnetic field in EV1 might be relevant. See Section 4.3.1 for more comments about the interpretation of that field component.

Most of the electric vehicles tested produce magnetic fields in the range of frequencies usually occupied by harmonics of the commercial electric power system (65 Hz to 300 Hz). While these frequency components in the magnetic field environment of EV4 and EV5 come principally from the vehicle and exceed levels in the conventional car, they are highly localized around the ankles. The magnetic fields found at ankle level in the back seat of EV1 significantly exceed those in the conventional car but are again highly localized. Refer to Section 4.3.1 for more discussion of the field source in EV1.

Fields produced by the power convertors in several EVs extend well above 300 Hz into the band identified in the table as high frequencies. Preceding comments about fields in the power harmonics frequency range apply in this band as well.

The last frequency band for which data are presented in Table 4-19 is essentially the whole extreme low frequency (ELF) band. The larger low frequency fields in the conventional automobile offset the larger higher frequency fields in the electric vehicles resulting in roughly similar total ELF magnetic field levels in both types of vehicles during the FUDS tests on the dynamometers. The results of the track data are summarized in similar fashion in Table 4-20. Because none of the vehicles showed material field dependence on driving speed and conditions, all of the track data are comparable.

Table 4-20
Summary of Average Magnetic Field Levels in Electric Vehicles
Measured While Driving on the Test Tracks Compared
to Levels Similarly Measured In a Conventional Car

Frequency Band	Sensor Location	EV 1 (mG)	EV 2 (mG)	EV 3 (mG)	Avg. of All EVs (mG)	Conv. Car 1 (mG)
Static	Driver's Head	325	343	329	332	246
	Right Front Pass. Head	272	278	680	410	236
	Left Rear Pass. Head	267	396		331	
	Right Rear Pass. Head	343	365		354	
	Driver's Waist	199	276	545	340	307
	Right Front Pass. Waist	302	249	421	324	272
	Left Rear Pass. Waist	240	336		288	
	Right Rear Pass. Waist	274	240		257	
	Driver's Ankle	310	315	406	344	391
	Right Front Pass. Ankle	360	388	751	500	452
	Left Rear Pass. Ankle	214	316		265	
	Right Rear Pass. Ankle	486	589		538	
	All Positions	299	344	522	388	317
5 - 55 Hz Low Frequencies	Driver's Head	1.5	2.2	0.4	1.4	2.9
	Right Front Pass. Head	1.3	2.1	0.6	1.3	3.6
	Left Rear Pass. Head	0.8	3.2		2.0	
	Right Rear Pass. Head	1.8	3.0		2.4	
	Driver's Waist	1.3	3.8	2.3	2.5	4.4
	Right Front Pass. Waist	1.6	3.1	2.4	2.4	5.6
	Left Rear Pass. Waist	1.2	11.5		6.4	
	Right Rear Pass. Waist	3.0	7.5		5.2	
	Driver's Ankle	2.5	10.2	16.4	9.7	9.3
	Right Front Pass. Ankle	3.4	9.4	15.8	9.5	10.0
	Left Rear Pass. Ankle	3.1	7.6		5.4	
	Right Rear Pass. Ankle	7.2	5.1		6.1	
	All Positions	2.4	5.7	6.3	4.8	6.0
60 Hz Power Frequency	Driver's Head	0.4	0.1	0.0	0.2	0.1
	Right Front Pass. Head	0.6	0.1	0.0	0.2	0.1
	Left Rear Pass. Head	0.2	0.1		0.2	
	Right Rear Pass. Head	0.3	0.1		0.2	
	Driver's Waist	0.3	0.2	0.1	0.2	0.1
	Right Front Pass. Waist	1.2	0.1	0.1	0.5	0.2
	Left Rear Pass. Waist	0.3	0.5		0.4	
	Right Rear Pass. Waist	0.9	0.2		0.6	
	Driver's Ankle	0.3	0.7	1.2	0.7	0.3
	Right Front Pass. Ankle	0.6	0.6	1.0	0.7	0.3
	Left Rear Pass. Ankle	0.5	0.5		0.5	
	Right Rear Pass. Ankle	14.6	0.3		7.4	
	All Positions	1.7	0.3	0.4	0.8	0.2

Table 4-20 (Continued)

Frequency Band	Sensor Location	EV 1 Car 1 (mG)	EV 2 EV 1 (mG)	EV 3 EV 3 (mG)	Avg. of All EVs (mG)	Conv. Car 1 (mG)
65 - 300 Hz Power Harmonics	Driver's Head	0.6	0.3	0.1	0.3	0.3
	Right Front Pass. Head	0.8	0.3	0.1	0.4	0.3
	Left Rear Pass. Head	0.3	0.4		0.3	
	Right Rear Pass. Head	0.4	0.3		0.3	
	Driver's Waist	0.6	0.6	0.4	0.5	0.4
	Right Front Pass. Waist	1.4	0.7	0.6	0.9	0.5
	Left Rear Pass. Waist	0.4	1.4		0.9	
	Right Rear Pass. Waist	1.0	0.9		0.9	
	Driver's Ankle	2.6	3.0	5.3	3.7	0.9
	Right Front Pass. Ankle	3.0	3.0	4.4	3.4	1.0
	Left Rear Pass. Ankle	1.4	3.2		2.3	
	Right Rear Pass. Ankle	17.3	2.5		9.9	
	All Positions	2.5	1.4	1.8	1.9	0.6
305 - 3000 H High Frequencies	Driver's Head	0.2	0.1	0.1	0.1	0.2
	Right Front Pass. Head	0.3	0.2	0.1	0.2	0.1
	Left Rear Pass. Head	0.1	0.2		0.2	
	Right Rear Pass. Head	0.2	0.2		0.2	
	Driver's Waist	0.2	0.2	0.3	0.2	0.2
	Right Front Pass. Waist	0.4	0.2	0.3	0.3	0.3
	Left Rear Pass. Waist	0.1	0.6		0.4	
	Right Rear Pass. Waist	0.4	0.3		0.3	
	Driver's Ankle	0.5	0.9	2.8	1.4	0.5
	Right Front Pass. Ankle	0.6	1.3	1.6	1.2	0.5
	Left Rear Pass. Ankle	0.6	0.5		0.5	
	Right Rear Pass. Ankle	5.4	0.3		2.8	
	All Positions	0.7	0.4	0.9	0.7	0.3
5 - 3000 Hz All ELF Frequencies	Driver's Head	1.7	2.2	0.4	1.4	3.0
	Right Front Pass. Head	1.6	2.1	0.6	1.4	3.6
	Left Rear Pass. Head	0.9	3.2		2.1	
	Right Rear Pass. Head	1.9	3.0		2.4	
	Driver's Waist	1.5	3.9	2.4	2.6	4.5
	Right Front Pass. Waist	2.4	3.2	2.5	2.7	5.6
	Left Rear Pass. Waist	1.3	11.7		6.5	
	Right Rear Pass. Waist	3.3	7.5		5.4	
	Driver's Ankle	3.7	10.8	17.8	10.8	9.4
	Right Front Pass. Ankle	4.6	10.0	16.7	10.4	10.1
	Left Rear Pass. Ankle	3.6	8.7		6.1	
	Right Rear Pass. Ankle	24.4	6.1		15.2	
	All Positions	4.2	6.0	6.7	5.7	6.0
	Number of Samples	43	163	165		66

Although there is variability in the interior magnetic field environments of the three electric vehicles tested on test tracks, their average properties compare to the magnetic field environment within a conventional car in the same ways as previously discussed based on the dynamometer tests. While some vehicles have higher fields at a particular location or in a particular frequency band, the three electric vehicles and the conventional car share very similar average internal ELF magnetic field levels.

4.3.8 Magnetic Fields from Battery Chargers

Two different types of stand-alone battery charges were encounter during the electric vehicle measurement program which are identified herein as "Type A" and "Type B". Additionally, one of the vehicles had its own built-in battery charger.

Magnetic field measurements were made around two battery chargers of each stand-alone type. An effort was made to conduct those measurements at different points in the charge cycle when the charge current was high; and then low. The field measurements were made 10 cm and 110 cm from the front, back, both sides of the charger at a height of 1 meter above the floor. Measurements were also made 10 cm and 110 cm above the Type A charger because the cabinet was low and the area was easily accessible. The Type B charger was in a tall cabinet and the area above was not easily accessible. Consequently, measurements were not made above that charger. Early in the measurement program, repetitive measurements were made at each location to identify any short-term variability in the field characteristics. None was found so many measurements were single samples.

Table 4-21 summarizes the magnetic field levels found around the two types of stand-alone chargers. Figure 4-18 shows the field frequency spectrum at the measurement location 10 cm in front of the charger.

The Type A charger has ELF magnetic field levels ranging from 4 to 63 mG at locations 10 cm from the cabinet. Although the fields around the cabinet are generally lower around the charger with the lower charge current, that trend was not consistent at the measurement point 10 cm above the cabinet. Field levels 1 meter further removed from the charger cabinet were dramatically lower in intensity and averaged less than 1 mG.

The magnetic field spectrum of the Type A charger consists of a 60 Hz fundamental component and varying harmonics thereof. Table 4-21 gives the magnitude of the 60 Hz component and the total harmonic distortion at each measurement location. The actual spectrum of the field is shown for the

Table 4-21
Summary of Magnetic Field Characteristics Around Battery Chargers

Measurement Location	Static Magnetic Field (mG)		ELF Magnetic Field (mG)		60Hz Magnetic Field (mG)		Polarization Axial Ratio (percent)		Total Harmonic Distortion (percent)	
	10 cm	110 cm	10 cm	110 cm	10 cm	110 cm	10 cm	110 cm	10 cm	110 cm
Type A Charger at 20 Amperes										
Front	352	501	7.8	0.6	7.5	0.6	42%	66%	30%	19%
Left Side	702	396	16.9	0.7	16.5	0.7	37%	17%	21%	22%
Rear	385	363	21.1	1.1	20.8	1.0	67%	71%	15%	20%
Right Side	301	512	16.3	0.6	16.0	0.5	42%	15%	19%	18%
Top	735	469	43.1	1.4	43.0	1.4	64%	21%	5%	14%
Average	495	449	21.0	0.9	20.8	0.8	50%	38%	18%	19%
Type A Charger at 4 Amperes										
Front	234	402	4.3	0.4	4.2	0.3	53%	44%	16%	35%
Left Side	293	456	8.9	0.6	8.7	0.5	58%	45%	20%	29%
Rear	257	345	8.7	0.6	8.5	0.4	47%	23%	19%	20%
Right Side	284	377	16.9	0.5	16.7	0.4	20%	4%	14%	27%
Top	522	438	63.3	0.5	63.2	0.4	24%	54%	5%	26%
Average	318	404	20.4	0.5	20.3	0.4	40%	34%	15%	27%
Type B Charger at 15 Amperes										
Front	394	516	18.6	1.5	8.0	0.6	15%	14%	210%	83%
Left Side	439	463	8.9	1.0	5.8	0.5	35%	57%	116%	61%
Rear	372	458	12.5	0.7	8.7	0.5	28%	60%	102%	62%
Right Side	480	497	20.3	0.8	11.1	0.6	26%	28%	154%	61%
Average	421	484	15.1	1.0	8.4	0.6	26%	40%	146%	67%
Type B Charger at 7 Amperes										
Front	392	519	21.3	2.7	10.7	0.8	20%	19%	172%	67%
Left Side	404	455	10.7	0.7	7.7	0.6	40%	22%	97%	53%
Rear	345	453	14.6	0.7	9.6	0.6	29%	49%	114%	63%
Right Side	436	463	25.2	0.9	13.5	0.8	34%	8%	158%	53%
Average	394	472	17.9	1.3	10.4	0.7	31%	24%	135%	59%

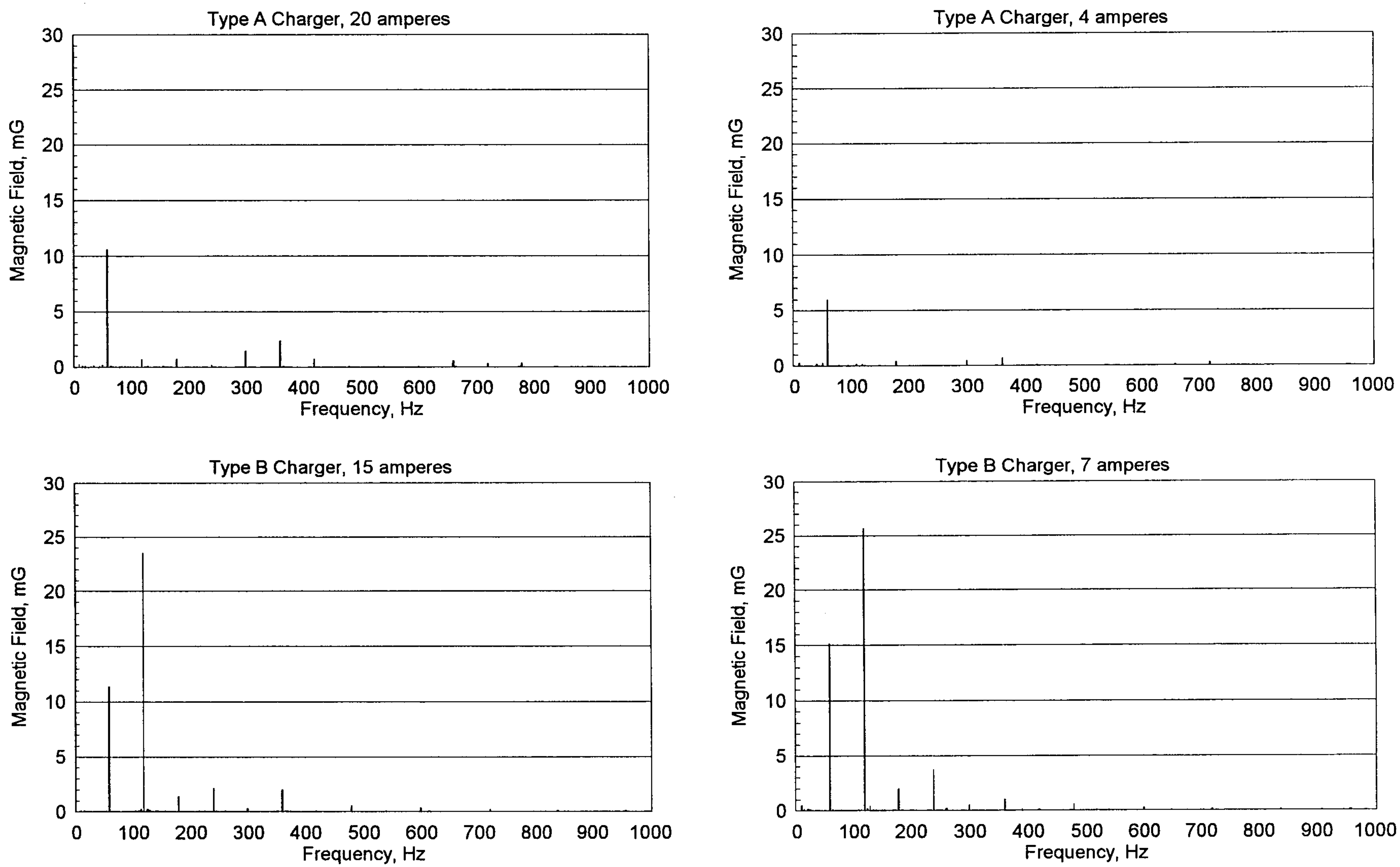


Figure 4-18 Magnetic Field Frequency Spectra Measured 10 cm in Front of the Battery Chargers.

measurements 10 cm in front of the two Type A charger cabinets in Figure 4-18. At both load levels the principal harmonic is the sixth (360 Hz) as one might expect for a three-phase, six-pulse rectifier.

The ELF magnetic fields around the Type B charger tended to be less than those of the Type A charger close to the cabinet (10 cm away). The magnetic field 110 cm from the Type B charger was a milligauss or less at the sides and back of the charger but higher (1.5 and 2.7 mG) 110 cm from the front of the cabinet. The electric vehicles were pulled up very close to the front of these chargers and the 110 cm measurement location was very close to the vehicle. Consequently, some of the field at that location could have come from the vehicle.

The fields of the Type B charger also have a 60 Hz fundamental frequency but the magnitude second harmonic (120 Hz) exceeds the magnitude of the fundamental at most of the 10 cm measurement locations. The total harmonic distortion tabulated in Table 4-21 is the ratio of the total field strength of the harmonics to that of the 60 Hz fundamental. As indicated, the harmonic distortion of the field is the greatest at the front of the cabinet. Figure 4-18 shows the spectra 10 cm in front of the two Type B chargers tested. The dominance of the second harmonic in the magnetic field spectrum near the Type B charger suggests that it is a single-phase, two-pulse rectifier.

One vehicle had an integral battery charger located under the hood at the front of the vehicle. Table 4-22 shows magnetic field levels measured 10 cm and 110 cm from the surface of the vehicle in the front and rear, both sides, and all four corners when the charger was off and again when it was on. All of those measurements were made 1 meter above the floor.

Close (10 cm) to the front of the vehicle and at both front corners, the magnetic field increased above ambient when the charger was on. Field levels at other places around the vehicle were not materially different than ambient. Additional magnetic field measurements were made inside the car at 10 cm and 110 cm from the dashboard along a radial as close as possible to the charger. The field 10 cm from the dashboard (3.5 mG) was similar to that close to the front grill (3.1 mG). At the larger distance from the dashboard, the field was 1.4 mG, but probably arose from an off-vehicle source other than the charger. It had a completely different frequency signature. The final magnetic field measurement was at 10 cm and 110 cm above the vehicle hood directly above the charger. Field level close to the hood was less than that close to the grill or dashboard. The ELF magnetic field measured near the charger on this vehicle was predominantly 60 Hz with only very modest harmonic distortion.

Table 4-22
Summary of Magnetic Field Characteristics In and Around the Vehicle With an Integral Battery Charger While Charging

Measurement Location	Static Magnetic Field (mG)		ELF Magnetic Field (mG)		60Hz Magnetic Field (mG)		Polarization Axial Ratio (percent)		Total Harmonic Distortion (percent)	
	10 cm	110 cm	10 cm	110 cm	10 cm	110 cm	10 cm	110 cm	10 cm	110 cm
Ambient Conditions Around the Vehicle With the Charger Off										
Front	986	600	0.3	0.2	0.2	0.2	29%	32%	29%	34%
Left Front	842	429	0.2	0.2	0.2	0.1	22%	28%	26%	30%
Left Side	871	529	0.6	0.4	0.1	0.1	66%	45%	39%	39%
Left Rear	387	527	0.4	0.6	0.1	0.1	40%	40%	47%	63%
Rear	465	527	0.2	0.3	0.1	0.1	20%	20%	30%	29%
Right Rear	971	445	0.2	0.2	0.1	0.1	29%	27%	31%	29%
Right Side	340	431	0.1	0.3	0.1	0.1	29%	45%	26%	30%
Right Front	481	418	0.2	0.2	0.1	0.1	40%	24%	27%	27%
Average	668	488	0.3	0.3	0.1	0.1	35%	33%	32%	35%
Field Conditions Around the Vehicle With the Charger On										
Front	999	597	3.1	0.3	3.1	0.2	11%	7%	4%	40%
Left Front	811	411	0.7	0.2	0.3	0.1	11%	43%	27%	33%
Left Side	867	529	0.3	0.2	0.1	0.1	49%	21%	28%	25%
Left Rear	373	543	0.1	0.1	0.1	0.1	32%	20%	33%	34%
Rear	485	522	0.2	0.3	0.1	0.1	27%	18%	33%	33%
Right Rear	958	483	0.1	0.1	0.1	0.1	23%	28%	34%	32%
Right Side	339	426	0.1	0.2	0.1	0.1	52%	46%	39%	36%
Right Front	462	415	0.7	0.2	0.6	0.2	13%	13%	12%	33%
Average	662	491	0.7	0.2	0.6	0.1	27%	24%	26%	33%
Field Conditions at Other Locations With the Charger On										
Dashboard	757	389	3.5	1.4	2.0	0.1	30%	50%	9%	71%
Above Hood	623	543	2.0	0.2	1.9	0.2	53%	18%	6%	19%
Average	690	466	2.7	0.8	1.9	0.2	41%	34%	7%	45%

4.4 Electric Field Characteristics

Single-axis electric field waveform measurements were made at a position representing and normal to the chest of the front seat passenger throughout most of the magnetic field test sequences described above. No electric fields attributable to the electric vehicles were detected.

5.0 ELECTRIC BUSES

Electric and magnetic field measurements were made in an electric bus operated by Paul Revere Transportation for Massport. The electric buses are used for shuttle service around Boston's Logan Airport. This chapter describes measurements made in those buses while in service and while parked for charging. Magnetic field measurements were also made outside the parked bus while charging.

5.1 Bus Characteristics

The two electric buses tested were identical 22 passenger vehicles built by Advanced Vehicle Systems of Chattanooga, TN. The vehicles are not mass produced but are limited production prototypes. Figure 5-1 shows sketches of one of the 22 foot long, 8 foot wide vehicles. The middle frame of that figure shows the seating arrangement within the bus. The upper frame indicates the location of the principal electrical components. Three battery assemblies are located beneath the seats and accessible from compartment doors on the outside of the bus. Two of the battery assemblies consist of 2 parallel 300 V sealed lead-acid battery packs. The third battery assembly consists of a single battery pack. The five battery packs are connected in parallel. Traction motors for the bus are connected directly to each of the back wheels, thereby eliminating the need for a transmission. The power control equipment and on-board battery charger are located beneath and behind the rear seat of the bus in a compartment accessible through large doors on the rear of the bus.

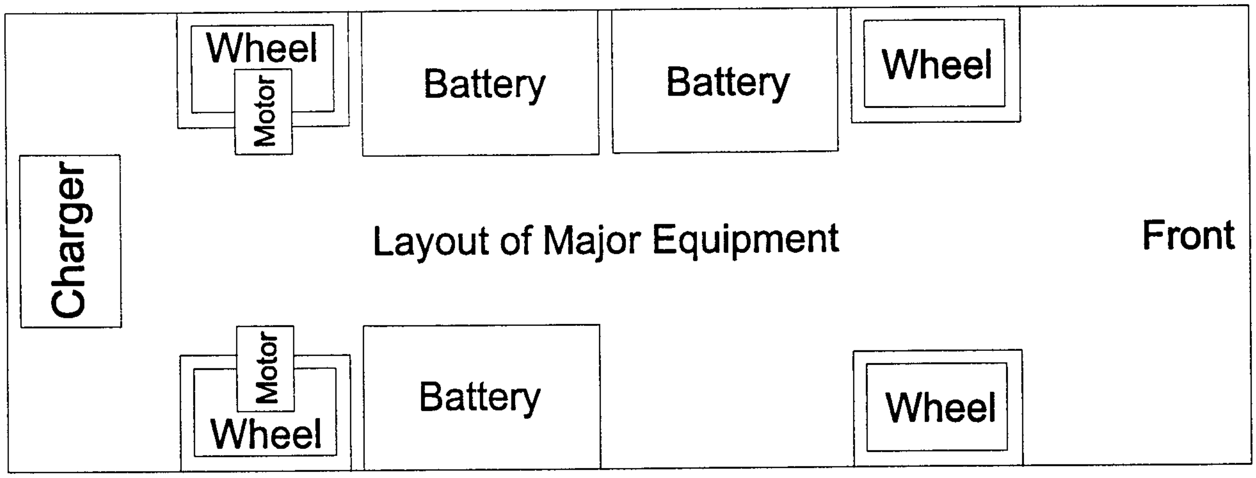
To charge a bus, a 240 V, 60 Hz single phase electric cable is connected to the battery charger inside the back doors of the bus. The charger reportedly draws only about 3 amperes from the 240 V ac supply line and can charge all five battery packs in about 12 hours.

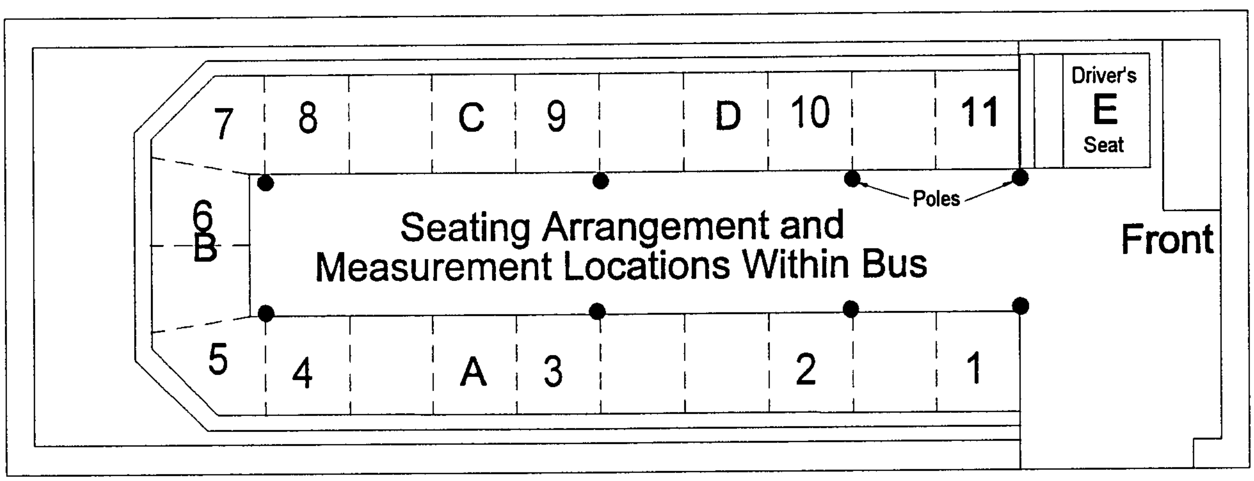
5.2 Test Conditions

The electric buses were tested while operating in shuttle service around the airport and while charging in Paul Revere Transportation's maintenance garage.

5.2.1 In-Service Tests

Electric and magnetic field measurements were made inside Bus Number 600E as it ran its normal shuttle service between three stops on or near Logan Airport. Three-axis static and ELF magnetic field measurements were made at positions representing the head, waist, and ankles of a passenger seated in the 11 seats indicated by numbers in the middle frame of Figure 5-1. Single-axis





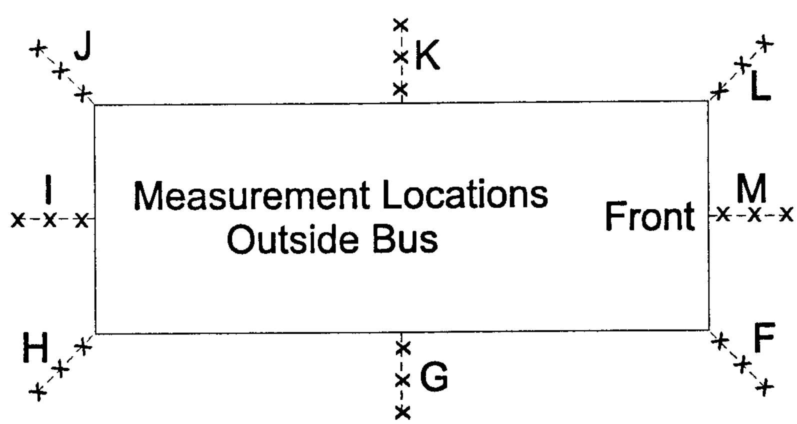


Figure 5-1 **Equipment Layout, Seating Layout, and Measurement Locations In and Around the Electric Bus. Numbered Seats Indicate Locations Where Measurements Were Made While the Bus was in Service and Locations Indicated with Letters Indicate Sites of Measurements While the Bus was Charging.**

electric field measurements were made at a position representing the chest of seated passengers at the 11 numbered locations. Because of the expected temporal variability of the magnetic field as the bus accelerated, decelerated, and ran at various speeds, repetitive field waveform measurements were made every 15 seconds at each measurement location while the bus ran from one stop to the next. Average driving time between successive stops was in excess of 3.5 minutes. Hence, 11 to 18 waveform samples were acquired at most measurement locations. The state of charge of the bus batteries ranged from approximately 75% at the start of the tests to less than 50% at the conclusion.

5.2.2 Charging Tests

Electric and magnetic field measurements were made inside Bus 601E and magnetic field measurements were made outside the same bus while it was charging at its normal location in a corner of the maintenance garage. Inside the bus, three-axis static and ELF magnetic field measurements were made at positions representing the head, waist, and ankles of persons seated at the five locations indicated by the letters A through E in the middle frame of Figure 5-1. Single-axis ELF electric fields were measured at locations representing the chest of persons in the same seats. Three-axis static and ELF magnetic field measurements were made at three distances from the bus (10 cm, 50 cm, and 90 cm) at each corner, the front and back, and both sides as illustrated in the lower frame of Figure 5-1. All of these measurements were made at a height of 1 meter above the ground. At the time of these tests, the bus was already at a 98% state of charge. Since field conditions were not expected to have significant temporal variability, triplicate measurements were made at each location rather than long-term measurements.

5.3 Magnetic Field Characteristics While Operating

5.3.1 Temporal Variability

Figure 5-2 shows a graph of the ELF magnetic field level as a function of frequency and time at waist level in a rear seat of the bus (Location 6 on the middle frame of Figure 5-1) as the vehicle traveled from one stop to the next. The top frame of Figure 5-2 shows the entire ELF frequency range while the bottom frame has an expanded frequency scale to better illustrate the characteristics of the magnetic field at frequencies below 250 Hz. As one might expect, the intensity of the ELF field appears dependent upon the motive power needs of the vehicle. Elevated fields are observed as the vehicle accelerates from its stop at the Airport Media Center in the first samples of the

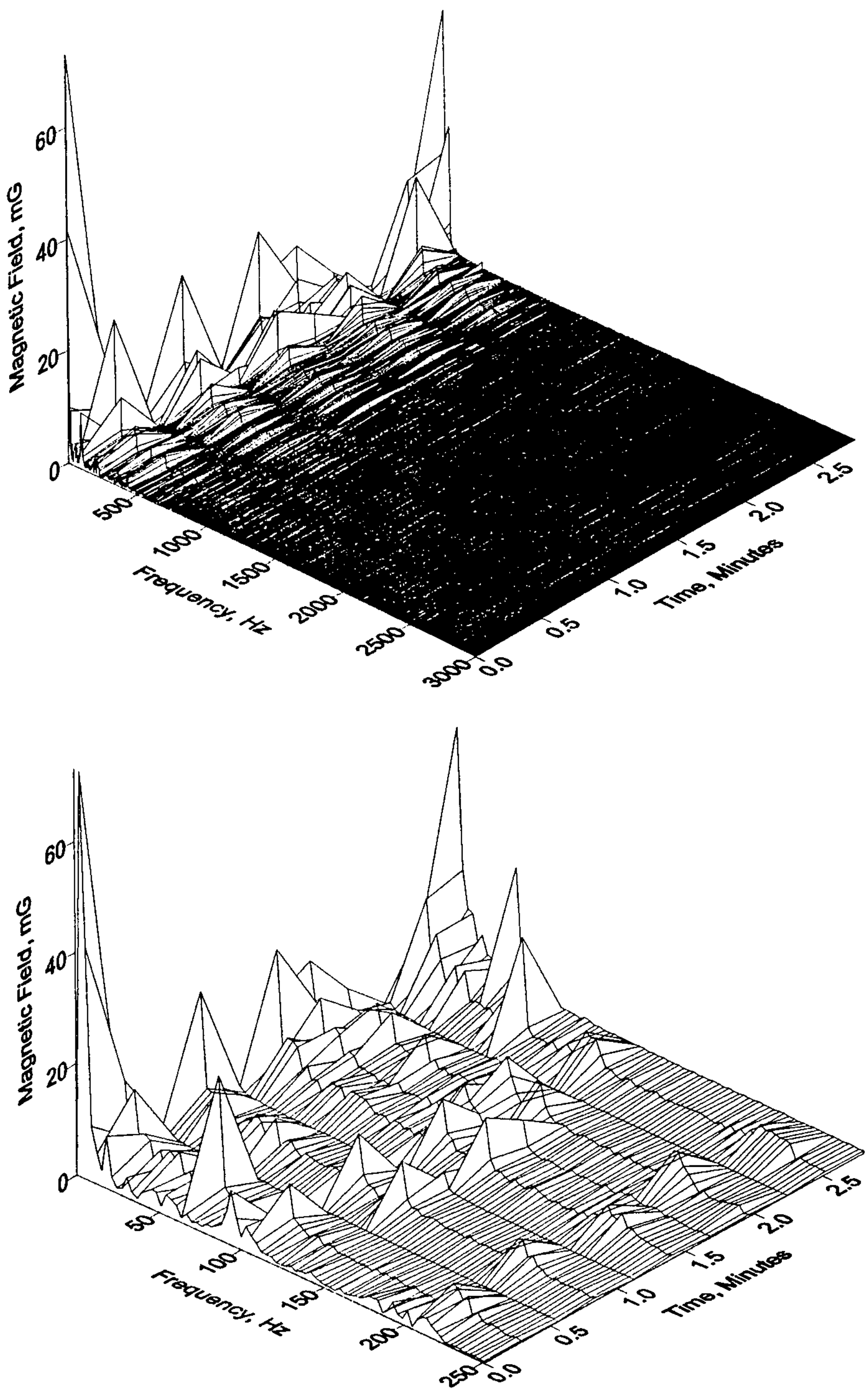


Figure 5-2 Magnetic Field Level as a Function of Frequency and Time at Waist Level in a Rear Seat of the Electric Bus (Seat #6 in Figure 5-1). The Frequency Scale is Expanded in the Bottom Frame to Better Show the Characteristics of the Low Frequency Fields.

record and again at the end of the record as the bus climbs the steep ramp to the Metro Station. Field levels fluctuate in the middle of the record as the bus accelerates or coasts depending upon traffic flow.

The expanded time scale in the bottom frame of Figure 5-2 permits examination of the temporal variability of the magnetic field frequency spectrum as the bus travels from one stop to the next. The first sample, indicated at time zero on the figure, was taken just as the vehicle began to accelerate. Aside from the elevated field level already mentioned, one sees that the principal field components are at quite low frequencies. However, as the vehicle accelerates, prominent field components increase in frequency into the 100 to 130 Hz range before the vehicle slows approaching its stop. As the vehicle slows, the frequency of many field components decrease, in relationship with the vehicle speed.

Static magnetic field levels in the bus also have significant temporal variability. That variability appears to arise from a number of factors, many of which are not associated with the electric propulsion system of the bus. Figure 5-3 shows graphs of the static magnetic field measured at three seat locations within the bus as it traveled from one stop to the next. In each frame of the graph, field levels at locations representing a passenger's head, waist, and ankles are plotted. Note that in general, static field levels are largest at the head level and decrease at lower measurement positions. This suggests that the ambient geomagnetic field is the principal static field source and that source is shielded more effectively by the bus body at the lower measurement locations.

Temporal patterns of the static magnetic field are similar in Seats 1 and 5 (top 2 frames of Figure 5-3) but considerably different in Seat 4 (lower frame) even though that seat is between the other two for which static fields are plotted. Measurements in Seats 1 and 5 were over the same route on successive runs from the Airport Media Center to the Airport Transit Station while the measurement at Seat 4 was made on a different part of the route. These data indicate that the temporal variability of the static magnetic field in the bus, at least at locations above the seats, is principally dependent on fluctuations in the ambient magnetic field along the route and differential shielding associated with bus orientation; not the production of static fields by the bus' electric propulsion system. This conclusion is further supported by the relatively small temporal variability in the static field along the route from the Airport Media Center to the Airport Transit Station where there are few steel structures above the roadway compared to the greater variability along the portion of the route from the Transit Station to the Administration Building which passes

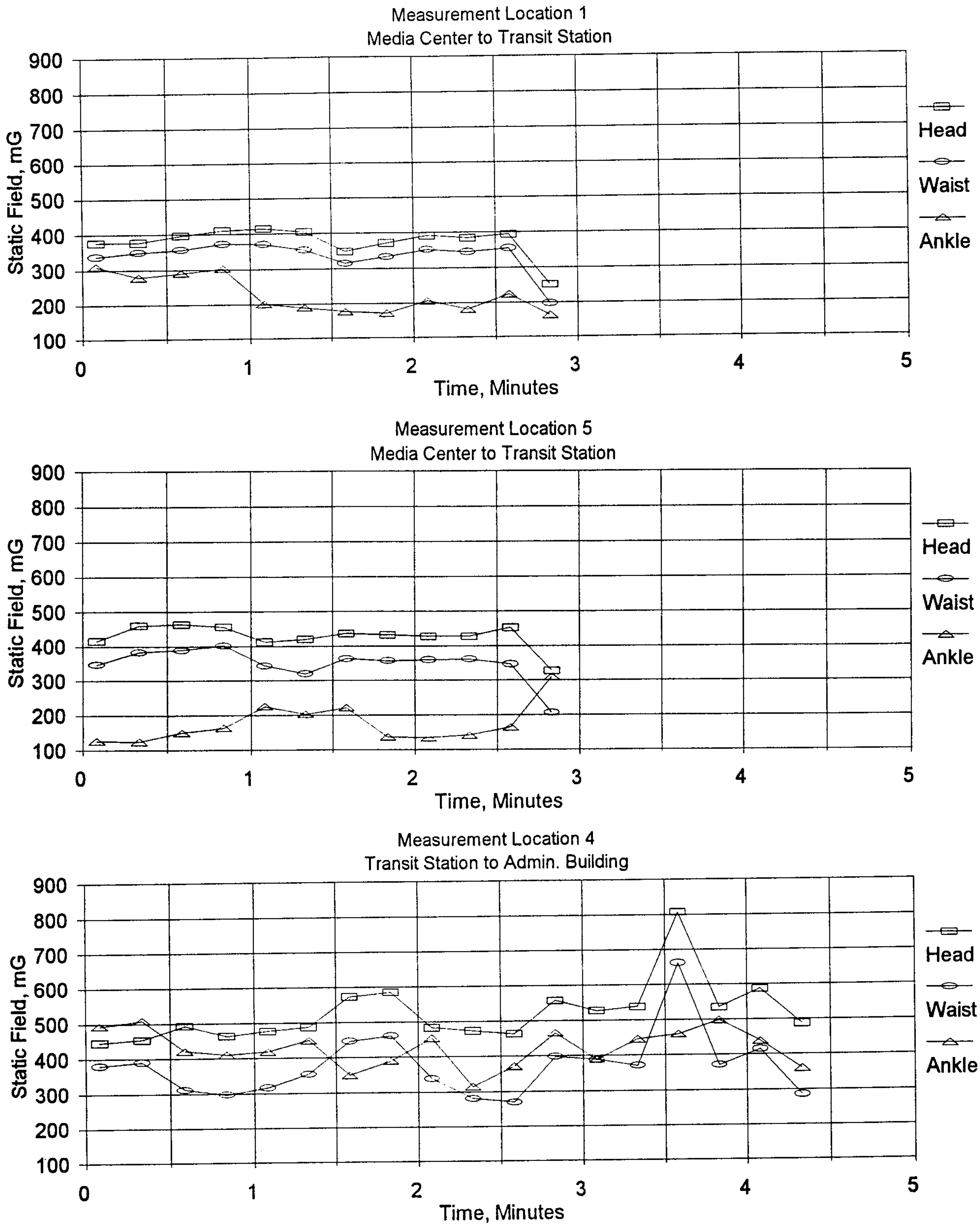


Figure 5-3 Temporal Variability of the Static Magnetic Field at Selected Measurement Locations.

beneath and near sections of highway elevated on steel structures, which are likely to significantly alter the ambient geomagnetic field.

In all three frames of Figure 5-1, the temporal patterns of the static field are similar at the head and waist measurement locations, but differ from the patterns at ankle level. Because of the significant attenuation of the geomagnetic field at ankle level caused by the bus body and because of the close proximity of the ankle locations to the bus electrical equipment, static fields produced by dc current in the batteries and associated wiring appear to affect the ankle-level static fields.

5.3.2 Spatial Variability

Repetitive samples of static and ELF magnetic fields were measured at head, waist, and ankle positions of persons seated in locations numbers 1 through 11 in the middle frame of Figure 5-1 while the bus traveled from one stop to the next. Figure 5-2 shows a graphical representation of the resulting ELF data for one measurement height at one seat location. To facilitate comparison of magnetic field data measured at various heights and in various seats, the spectral data were consolidated into root-mean-square (rms) field levels in various frequency ranges as discussed in section 2 above. Those rms values from each time-point during the drive from one location to the next were then summarized in terms of average, median, and maximum values for each measurement location. Those summary values are reported in Tables 5-1, 5-2, and 5-3 respectively. Complete spectral data are available from the RAPID EMF data base [5].

Average static magnetic field levels in the bus tend to be similar at head and waist level (434 and 435 mG respectively), but markedly lower at ankle level (273 mG). A similar pattern is observed in the median and maximum static field data. This pattern indicates that electrical equipment beneath the floor and seats of the bus is not a significant source of static magnetic fields. The variability with body position is a result of more effective shielding against the geomagnetic field by the frame and body of the bus in the footwell between the battery compartments under the seats than in the more open areas above the seats. The static field data do not reveal a significant spatial pattern in the static field within the bus at any particular measurement height except perhaps for lower ankle-level static fields in the very rear of the bus. That pattern is apparently the result of better geomagnetic field shielding at the rear of the footwell where there are steel panels below, on both sides, and the end of the footwell.

Table 5-1
Average Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations in the Electric Bus While Operating in Shuttle Service

Location in the Bus Keyed to Fig. 5-1	Number of Samples	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz		
		Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
1	12	377	337	225	3.2	7.8	8.1	3.1	7.8	8.0	0.1	0.2	0.2	0.4	0.6	0.6	0.2	0.3	0.3
2	19	311	436	361	3.1	5.1	6.9	3.0	5.1	6.9	0.2	0.2	0.2	0.4	0.5	0.7	0.2	0.3	0.3
3	15	496	622	250	5.5	13.2	36.7	5.4	13.1	36.3	0.2	0.5	1.1	0.6	1.4	3.7	0.3	0.5	1.7
4	18	524	375	424	3.6	11.1	50.0	3.2	9.0	31.9	0.2	0.7	3.1	1.3	5.3	27.0	0.4	1.8	2.9
5	12	428	348	176	4.5	23.6	96.0	4.1	19.5	59.5	0.3	1.6	1.6	1.6	11.3	46.8	0.5	5.4	5.2
6	11	368	387	160	6.6	33.0	143.9	5.8	27.8	75.8	0.4	1.8	6.0	2.5	14.1	83.0	0.9	5.5	5.8
7	9	346	379	205	5.2	16.8	64.7	4.5	12.3	29.8	0.2	0.6	1.5	2.2	9.9	45.9	0.8	4.1	7.0
8	16	441	434	275	3.5	10.2	21.6	3.1	8.4	12.7	0.2	0.7	2.4	1.3	4.5	13.4	0.5	2.3	1.5
9	21	477	550	348	4.1	11.0	6.1	3.8	10.2	5.9	0.3	0.7	0.3	1.1	3.5	1.2	0.5	1.8	0.3
10	13	501	422	318	4.7	16.4	27.0	4.6	16.2	26.7	0.2	0.5	0.9	0.7	2.5	3.1	0.3	1.1	1.3
11	13	500	499	266	3.8	7.5	9.8	3.8	7.4	9.7	0.1	0.2	0.2	0.5	0.9	0.9	0.2	0.4	0.4
Summary of Average Field Levels in the Bus																			
Minimum		311	337	160	3.1	5.1	6.1	3.0	5.1	5.9	0.1	0.2	0.2	0.4	0.5	0.6	0.2	0.3	0.3
Maximum		524	622	424	6.6	33.0	143.9	5.8	27.8	75.8	0.4	1.8	6.0	2.5	14.1	83.0	0.9	5.5	7.0
Median		441	422	266	4.1	11.1	27.0	3.8	10.2	26.7	0.2	0.6	1.1	1.1	3.5	3.7	0.4	1.8	1.5
Average	14.5	434	435	273	4.3	14.1	42.8	4.0	12.4	27.6	0.2	0.7	1.6	1.1	5.0	20.6	0.4	2.1	2.4
Std. Dev.	3.5	70	85	79	1.0	7.7	41.8	0.9	6.3	21.9	0.1	0.5	1.7	0.7	4.5	26.0	0.2	1.9	2.3

Table 5-2
Median Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations in the Electric Bus While Operating in Shuttle Service

Location in the Bus Keyed to Fig. 5-1	Number of Samples	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz		
		Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
1	12	388	352	204	3.1	8.2	7.9	3.0	8.1	7.9	0.1	0.2	0.1	0.4	0.6	0.5	0.2	0.3	0.2
2	19	299	442	342	2.4	4.4	5.5	2.3	4.4	5.4	0.1	0.2	0.2	0.3	0.4	0.7	0.1	0.2	0.2
3	15	498	610	243	2.0	7.6	5.4	1.9	7.2	5.1	0.1	0.3	0.2	0.3	1.0	1.1	0.1	0.3	0.3
4	18	490	371	430	3.3	11.7	46.3	2.9	8.3	15.0	0.2	0.4	1.3	1.2	5.6	24.8	0.4	2.4	2.6
5	12	431	358	157	4.5	27.9	76.1	3.9	20.8	9.7	0.2	1.5	0.9	1.8	14.0	44.1	0.7	7.5	5.8
6	11	346	382	151	6.7	35.1	111.8	5.2	25.1	13.8	0.2	1.7	1.7	2.8	18.4	70.8	1.2	7.9	7.2
7	9	346	382	188	5.3	18.9	54.8	4.6	13.1	11.8	0.2	0.4	1.2	2.4	10.8	53.3	1.0	5.1	8.2
8	16	434	427	295	3.9	12.4	20.5	3.2	10.1	8.3	0.2	0.6	0.9	1.6	5.0	12.6	0.6	2.1	1.8
9	21	440	522	366	4.5	13.2	3.8	4.2	11.4	3.5	0.3	0.6	0.3	1.4	5.0	1.1	0.7	2.7	0.3
10	13	498	413	319	4.1	15.9	26.6	4.0	15.7	26.5	0.1	0.5	0.7	0.6	2.6	2.6	0.3	1.1	0.6
11	13	487	491	265	2.4	5.4	5.9	2.4	5.3	5.8	0.1	0.1	0.2	0.4	0.7	0.5	0.2	0.4	0.2
Summary of Median Field Levels in the Bus																			
Minimum		299	352	151	2.0	4.4	3.8	1.9	4.4	3.5	0.1	0.1	0.1	0.3	0.4	0.5	0.1	0.2	0.2
Maximum		498	610	430	6.7	35.1	111.8	5.2	25.1	26.5	0.3	1.7	1.7	2.8	18.4	70.8	1.2	7.9	8.2
Median		434	413	265	3.9	12.4	20.5	3.2	10.1	8.3	0.2	0.4	0.7	1.2	5.0	2.6	0.4	2.1	0.6
Average	14.5	423	432	269	3.8	14.6	33.1	3.4	11.8	10.3	0.2	0.6	0.7	1.2	5.8	19.3	0.5	2.7	2.5
Std. Dev.	3.5	67	77	86	1.4	9.1	33.9	1.0	6.2	6.2	0.1	0.5	0.5	0.9	5.8	24.3	0.4	2.7	2.9

Table 5-3
Maximum Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations
in the Electric Bus While Operating in Shuttle Service

Location in the Bus Keyed to Fig. 5-1	Number of Samples	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz		
		Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
1	12	415	373	311	6.0	11.3	15.6	5.9	11.2	15.5	0.2	0.3	0.4	0.9	1.3	1.6	0.4	0.7	0.8
2	19	435	613	489	9.1	14.5	29.7	9.1	14.4	29.6	0.7	0.4	1.0	1.2	1.5	2.4	0.6	0.8	1.2
3	15	602	777	320	26.4	65.1	215.2	26.3	64.9	214.8	1.0	2.0	4.1	2.1	4.8	16.8	1.0	2.2	8.4
4	18	808	662	508	7.0	19.5	146.2	6.7	18.9	145.6	0.9	3.2	25.3	2.5	10.8	64.9	0.8	4.0	7.2
5	12	465	402	310	7.7	39.4	278.9	7.4	35.8	277.3	0.6	4.7	5.5	2.8	19.3	110.9	0.8	8.5	10.7
6	11	453	447	287	15.7	88.3	487.8	15.4	85.9	486.7	0.8	4.6	38.8	5.1	27.4	220.5	1.4	9.1	9.8
7	9	437	451	338	7.7	25.3	165.1	7.6	22.7	163.9	0.4	1.1	4.9	3.1	12.7	95.6	1.1	5.8	10.2
8	16	574	605	369	8.7	19.4	45.4	8.2	17.0	44.7	1.2	3.4	24.7	2.7	8.6	34.7	1.2	6.1	2.7
9	21	636	725	497	10.1	21.6	30.9	9.9	20.6	30.8	1.0	1.9	0.9	1.8	5.9	2.6	0.9	3.2	1.1
10	13	564	600	467	16.1	32.2	84.1	15.9	31.8	83.0	0.5	1.2	3.4	2.1	4.6	11.8	1.1	2.1	6.0
11	13	565	627	335	8.7	17.1	30.8	8.6	17.0	30.5	0.3	0.6	0.9	1.3	2.3	3.7	0.7	1.1	1.9
Summary of Maximum Field Levels in the Bus																			
Minimum		415	373	287	6.0	11.3	15.6	5.9	11.2	15.5	0.2	0.3	0.4	0.9	1.3	1.6	0.4	0.7	0.8
Maximum		808	777	508	26.4	88.3	487.8	26.3	85.9	486.7	1.2	4.7	38.8	5.1	27.4	220.5	1.4	9.1	10.7
Median		564	605	338	8.7	21.6	84.1	8.6	20.6	83.0	0.7	1.9	4.1	2.1	5.9	16.8	0.9	3.2	6.0
Average	14.5	541	571	385	11.2	32.2	139.1	11.0	30.9	138.4	0.7	2.1	10.0	2.3	9.0	51.4	0.9	4.0	5.4
Std. Dev.	3.5	112	127	83	5.7	22.9	138.2	5.8	22.5	137.9	0.3	1.5	12.6	1.1	7.8	65.3	0.3	2.9	3.8

As indicated in Table 5-1, average ELF magnetic fields are lowest at head level (average 4.3 mG across the bus), increase at the waist height (14.1 mG), and are highest at ankle height (42.8 mG). Median and maximum ELF magnetic field levels show a similar gradient with height. At all heights and for all measures of ELF field level, the field is larger toward the rear of the bus than toward the front. In general, the lowest ELF fields are at measurement locations 1, 2, and 11 which, as shown on Figure 5-1, are more distant from the electrical equipment than the other locations. Figure 5-4 provides a pictorial representation of the distribution of average ELF magnetic field levels in the electric bus.

5.3.3 Frequency Characteristics

This electric bus does not produce magnetic fields at a fixed discrete frequency but rather a complex and dynamic distribution of field frequencies concentrated below 300 Hz. The spectrum is temporally variable as shown in Figure 5-2 and already discussed in Section 5.3.1. To better quantify the magnitude of the magnetic field in various frequency bands, Tables 5-1 through 5-3 list field levels in ranges from 3 to 57 Hz, 60 Hz, 63-300 Hz, and 300-3000 Hz. At all locations, the field above 300 Hz is only a small fraction of the ELF magnetic field. The 60 Hz field values tabulated in Tables 5-1 through 5-3 are also generally low due to the lack of a strong discrete 60 Hz component in the frequency spectrum of the electric bus magnetic field. The absence of a 60 Hz component in the data provides assurance that the measured ELF field levels do arise from the vehicle rather than external sources which are predominantly 60 Hz.

In areas of higher field at the rear of the bus, especially at the lower heights, the ELF magnetic field is about equally distributed between the low frequency components (3-57 Hz) and components in the usual frequency range of power system harmonics (63-300 Hz). However, at larger distances from an apparent source under the rear seats or beneath the floor near the rear seat, the low frequency components become the major frequency components of the field. Those field components arise in part from fluctuations in current drawn from the battery packs beneath the side seats.

5.4 Magnetic Field Characteristics While Charging

Due to mechanical difficulties, neither electric bus was in service the day before these tests. Consequently, the only electric bus on charge was already at 98% charge and only "float" charging during the measurements reported below.

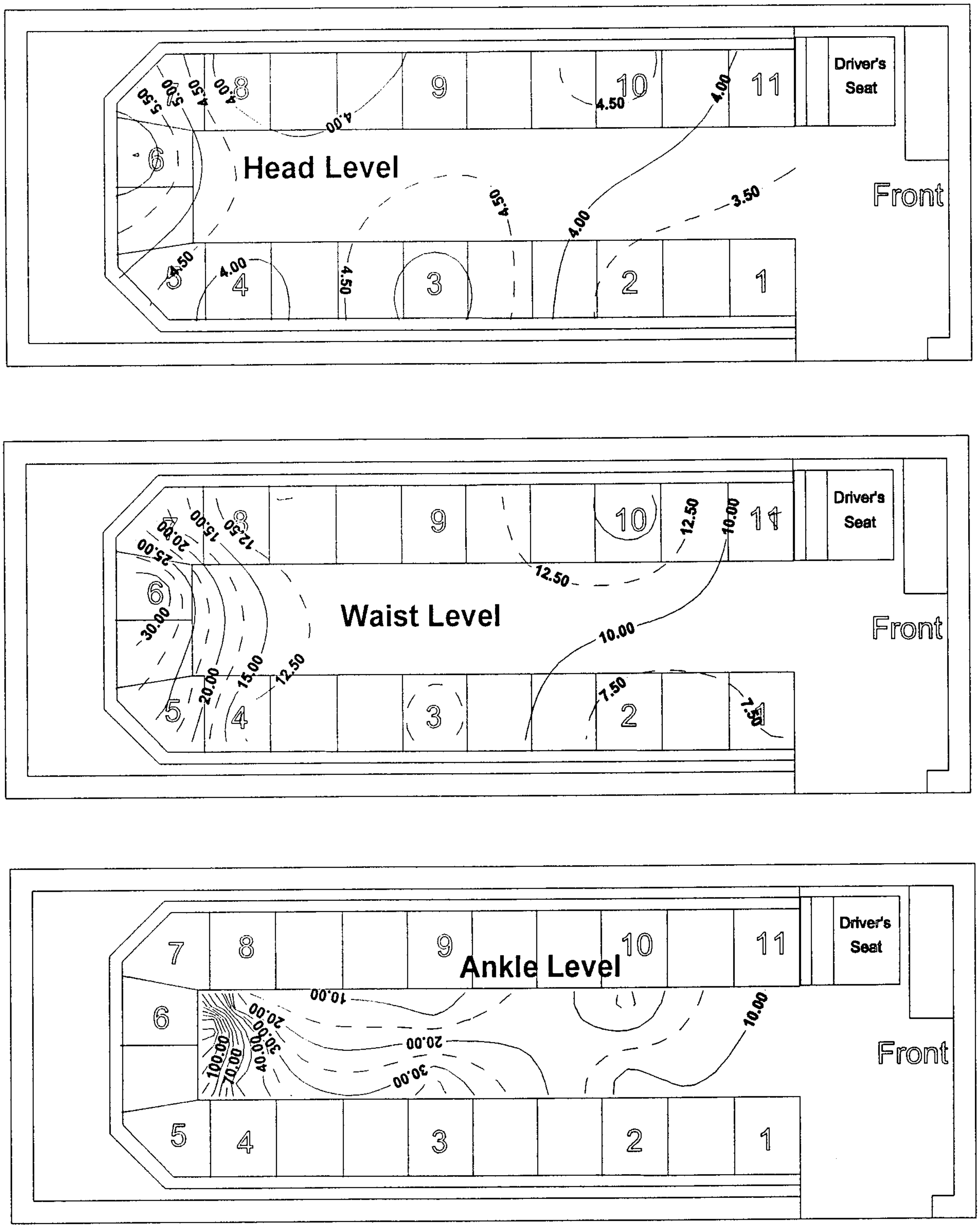


Figure 5-4 Contour Plots of the Average ELF Magnetic Field Strength in Milligauss (mG) at Head, Waist, and Ankle Levels in the Electric Bus.

5.4.1 Temporal Variability

Although no temporal variability was expected in the magnetic field characteristics while the bus was charging, triplicate measurements were made at each test location. No disparity was observed between successive measurements in the bus where the field sensors were in a fixed position. Measurements made outside the bus with the field sensors in a handheld staff showed occasional differences in low frequency components which appear to have arisen from inadvertent sensor movement. No evidence of temporal variability in magnetic fields from the bus, its on-board charger, or the connected power cord were observed.

5.4.2 Spatial Variability

Triplicate three-axis magnetic field waveform measurements were made at locations representing the head, waist, and ankles of a person seated in the five locations indicated A through E in the middle frame of Figure 5-1. Four of those locations were selected because of proximity to the charger (Seat B), or proximity to the battery packs (Seats A, C, and D). The drivers seat was also included (Seat E). The ELF magnetic field levels measured in the bus while charging are shown in Table 5-4. Field levels are low, are principally 60 Hz, and tend to be larger at head level than at waist or foot level. All three of these characteristics suggest that the measured field levels result primarily from ambient fields in the maintenance garage, not from the bus, its charger, or the interconnecting power cord. However, the field at waist level in Seat B directly over the charger in the 63-300 Hz band (0.7 mG with components at 120 Hz and 220 Hz) is clearly from the charger beneath the seat and part of the 60 Hz component at that location might also come from the charger.

Variations in static field level shown in Table 5-4 are believed to be due to shielding of the geomagnetic field by the bus body, not fields from DC charging current.

Magnetic field levels were also measured outside the bus while it was charging. The lower frame of Figure 5-1 shows the locations where those measurements were made. Since the bus was backed into a corner of the maintenance garage, there was very limited clearance between the left side of the bus and garage wall. Consequently, field measurements could not extend very far from the bus. The power connections for the charging cable to the bus were on the garage wall behind the bus. The power cable laid on the floor between the connection box on the garage wall and its connection to the on-board charger inside the back door of the bus.

Table 5-4
Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations in the Electric Bus While Charging (Averages of Triplicate Measurements)

Location in the Bus Keyed to Fig. 5-1	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz		
	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
A	350	261	305	1.2	0.9	0.8	0.2	0.2	0.2	1.2	0.8	0.8	0.2	0.1	0.1	0.0	0.0	0.0
B	337	243	59	1.2	1.4	1.1	0.2	0.5	0.5	1.2	1.1	0.8	0.2	0.7	0.7	0.1	0.2	0.1
C	367	405	332	1.1	0.8	0.8	0.1	0.2	0.1	1.1	0.7	0.8	0.2	0.3	0.1	0.1	0.1	0.0
C	453	554	379	1.1	1.0	1.1	0.1	0.3	0.6	1.1	0.9	0.8	0.2	0.3	0.2	0.1	0.2	0.0
E	469	328	106	1.3	1.0	0.9	0.1	0.1	0.1	1.3	0.9	0.9	0.2	0.2	0.3	0.0	0.1	0.2
Summary of Average Field Levels in the Bus																		
Minimum	337	243	59	1.1	0.8	0.8	0.1	0.1	0.1	1.1	0.7	0.8	0.2	0.1	0.1	0.0	0.0	0.0
Maximum	469	554	379	1.3	1.4	1.1	0.2	0.5	0.6	1.3	1.1	0.9	0.2	0.7	0.7	0.1	0.2	0.2
Median	367	328	305	1.2	1.0	0.9	0.1	0.2	0.2	1.2	0.9	0.8	0.2	0.3	0.2	0.1	0.1	0.0
Average	395	358	236	1.2	1.0	0.9	0.1	0.3	0.3	1.2	0.9	0.8	0.2	0.3	0.3	0.1	0.1	0.1
Std. Dev.	55	113	128	0.1	0.2	0.1	0.0	0.1	0.2	0.1	0.1	0.1	0.0	0.2	0.2	0.0	0.1	0.1

Triplicate field measurements were made simultaneously at 10 cm, 50 cm, and 90 cm from the bus at a height of 1 m from the floor. The three field sensors were attached to a rigid staff which was held in position during each set of triplicate measurements. On some occasions, the staff was inadvertently moved during the waveform measurements giving rise to spurious low-frequency field values. These erroneous results were culled by examining the consistency of each triplicate set of measurements, deleting the outlier, and averaging the remaining two. The results of the measurements are shown in Table 5-5. Sixty hertz magnetic fields may be slightly elevated above ambient near the sides and back of the bus as suggested by the gradient in field levels at increasing distances from the bus. However, none of the measurements dramatically exceed 60 Hz field levels elsewhere in the maintenance garage. The low frequency fields reported in the "low ELF" column of Table 5-5 are believed from their spectral distributions to be artifacts of slight movement of the handheld field sensor staff in the strongly perturbed static field close to the steel bus body. They do not appear to be real fields produced by the bus charging system.

5.4.3 Frequency Characteristics

The principal ELF field frequency component measured near or inside the electric bus while charging was the 60 Hz component. Much of this 60 Hz field undoubtedly comes from he wiring, lighting, and other electrical equipment in the maintenance garage. Other small ELF field components, principally 120 Hz, 220 Hz, and harmonics of 220 Hz were observed inside and outside the bus near the charger and on the outside of the bus near the battery assembly doors on the left side of the vehicle. None of these higher frequency components exceeded 1 mG.

5.5 Electric Field Characteristics

ELF electric field waveform measurements were made at all of the seat locations inside the bus each time a magnetic field waveform measurement was made. No electric fields attributable to the bus could be detected above the instrument noise threshold of 3 V/m. Measurable electric fields were detected during three of the 159 samples taken while the bus was in operation. All three of these samples were within a period of less than 5 minutes, indicated fields of 20 to 26 volts per meter, and consisted of frequency components below 12 Hz. It would appear as though those fields were produced by the movement of a particular passenger having a substantial static electric charge on his or her clothing.

Table 5-5
Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations and Various Distances Outside the Electric Bus While Charging (Averages of Duplicate Measurements)

Location Outside Bus Keyed to Fig. 5-1	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz		
	10 cm	50 cm	90 cm	10 cm	50 cm	90 cm	10 cm	50 cm	90 cm	10 cm	50 cm	90 cm	10 cm	50 cm	90 cm	10 cm	50 cm	90 cm
F	824	507	487	2.2	1.8	1.8	1.3	0.6	0.6	1.7	1.7	1.6	0.3	0.2	0.2	0.1	0.1	0.1
G	490	397	419	2.7	2.2	2.1	1.3	0.6	0.6	2.3	2.1	2.0	0.3	0.3	0.3	0.1	0.1	0.1
H	461	458	433	2.7	2.6	2.6	0.7	0.5	0.7	2.6	2.5	2.5	0.5	0.4	0.4	0.1	0.1	0.1
I	337	362	406	3.4	2.7	2.8	1.0	0.6	0.7	3.2	2.6	2.6	0.8	0.4	0.3	0.2	0.1	0.1
J	294	375	761	2.6	2.5	2.6	0.3	0.4	1.3	2.6	2.4	2.2	0.4	0.3	0.4	0.1	0.1	0.1
K	352	358	349	4.1	2.6	2.4	0.6	0.3	0.3	4.0	2.5	2.4	0.7	0.3	0.3	0.2	0.1	0.1
L	200	371	451	2.6	2.5	2.7	0.4	0.5	0.7	2.5	2.4	2.5	0.4	0.3	0.4	0.1	0.1	0.1
M	549	435	429	2.1	1.9	1.9	0.8	0.6	0.5	1.8	1.8	1.7	0.8	0.2	0.2	0.4	0.1	0.1
Summary of Average Field Levels Outside the Bus																		
Minimum	200	358	349	2.1	1.8	1.8	0.3	0.3	0.3	1.7	1.7	1.6	0.3	0.2	0.2	0.1	0.1	0.1
Maximum	824	507	761	4.1	2.7	2.8	1.3	0.6	1.3	4.0	2.6	2.6	0.8	0.4	0.4	0.4	0.1	0.1
Median	406	386	431	2.7	2.5	2.5	0.7	0.5	0.7	2.5	2.4	2.3	0.4	0.3	0.3	0.1	0.1	0.1
Average	438	408	467	2.8	2.3	2.3	0.8	0.5	0.7	2.6	2.3	2.2	0.5	0.3	0.3	0.2	0.1	0.1
Std. Dev.	180	50	117	0.6	0.3	0.4	0.3	0.1	0.3	0.7	0.3	0.4	0.2	0.1	0.1	0.1	0.0	0.0

6.0 ELECTRIC COMMUTER TRAINS WITH AC DRIVE

Electric and magnetic field measurements were made in two Arrow-3, self-powered commuter railroad cars on the New Jersey Transit System. This Chapter describes those measurements, the characteristics of the fields observed, and the apparent field sources.

6.1 Commuter-Rail Car and Infrastructure Characteristics

The vehicles tested were Arrow-3, self-powered rail cars operated by the New Jersey Transit for Commuter Transportation into the New York/Newark area. Unlike conventional railroad trains in which powered locomotives pull a string of unpowered coaches, these self-powered cars have their own electric motors and necessary electrical equipment to collect electric power from overhead catenary wires and propel themselves along the track. Typically, several of these self-powered cars are coupled together to make up a 'consist' or train of individual units which can be operated by a single engineer.

The measurements reported herein were conducted in a three-car consist operating from Hoboken, New Jersey to Gladstone, New Jersey and back to Hoboken. Although the tests were conducted mid-day to minimize the inconvenience to commuters, the work was done on a normally scheduled run and passengers were present in the two cars where measurements were not currently underway.

The rail line between Hoboken and Gladstone includes a portion of the Morris and Essex (M&E) line from Hoboken to Summit, New Jersey and the Gladstone Branch from Summit to Gladstone. The M&E Line is principally two-track line while the Gladstone Branch is single track with occasional turn-out sidings to permit trains to pass one another. Catenary voltage is 27.5 kV, 60 Hz for the whole route. Because of the large number of stops between Hoboken and Gladstone, 22, the commuter train attains only moderate speed except along the longer section from Hoboken to Newark.

The 85 foot long Arrow cars are approximately 25 years old but were refitted with new ac drive propulsion systems between 1992 and 1995 by ABB (formerly ASEA). The design of this modern propulsion system is materially different from earlier designs which are found in most existing electrified rail transportation systems including urban mass transportation systems. The traditional dc traction motors are replaced by three-phase ac motors. Since the speed of the ac motors is controlled by the frequency of the electric power supplied to the motors, the speed of the train is controlled by adjusting the frequency of the electric power applied to the motors. High-power electronics beneath the cars convert 60 Hz, single-phase ac power from the catenary to dc power and ultimately to three-phase power at the frequency appropriate for the speed of the train.

The upper frame of Figure 6-1 shows a side view of the three Arrow-3 cars which made up the consist in which measurements were made. Side views of individual cars are expanded in Figure 6-2 to show the placement of principal pieces of electric power equipment. It is apparent from the figure that all three cars differ from one another in the presence or absence of key equipment. Yet, all Arrow-3 cars in the NJT fleet are one of the three types shown in Figure 6-2.

Some Arrow-3 cars are designed to be entirely self-sufficient. Those cars are designated as stand-alone or "S" cars. The upper frame of Figure 6-3 shows such a car. Other Arrow-3 cars are designed to work in pairs, thereby reducing weight and cost be eliminating some redundant equipment. Cars that are paired together or "married" are designated as "A" cars or "B" cars depending on the equipment on that particular car. The lower frames of Figure 6-2 show the two units of a "married pair" of cars.

In the stand-alone car, 27.5 kV, 60 Hz, single-phase electric power is obtained from the overhead catenary by the roof-mounted pantograph. A current transformer (ct), potential transformer (pt) and surge arrestor are mounted on the roof next to the pantograph to monitor the incoming power and protect the vehicle's electrical system from voltage surges. A vacuum switch allows the operator to connect the high voltage electric power from the pantograph to a high voltage cable which carries the electric power along the car roof and down through the center of the car to the main power transformer beneath the floor in the center of the car. The auxiliary transformer reduces the voltage of the incoming power and routes it to the power rectifier for traction power needs and to other auxiliary equipment to supply power for lighting, heating, air-conditioning, and other auxiliary services such as compressed air for the air brakes. Many of those auxiliary power loads are located beneath the floor of the car as is most of the interconnecting wiring.

Lower voltage, 60 Hz ac power for traction leaves the main power transformer and goes to the power rectifier in the adjacent under-floor cabinet where it is rectified to produce direct current (dc). Electronic invertors in the two truck control cabinets convert the direct current electric power to three-phase ac electric power of the appropriate frequency. Invertors in the two cabinets provide the ac power for ac traction motors on the two trucks of the car. Digital control circuitry for the invertors and other parts of the propulsion system are in a cabinet in a wall inside the center doors of the car.

Aside from the power electronics in the under-floor cabinets, the process of conversion from 60 Hz, single-phase power to variable frequency, three-phase power

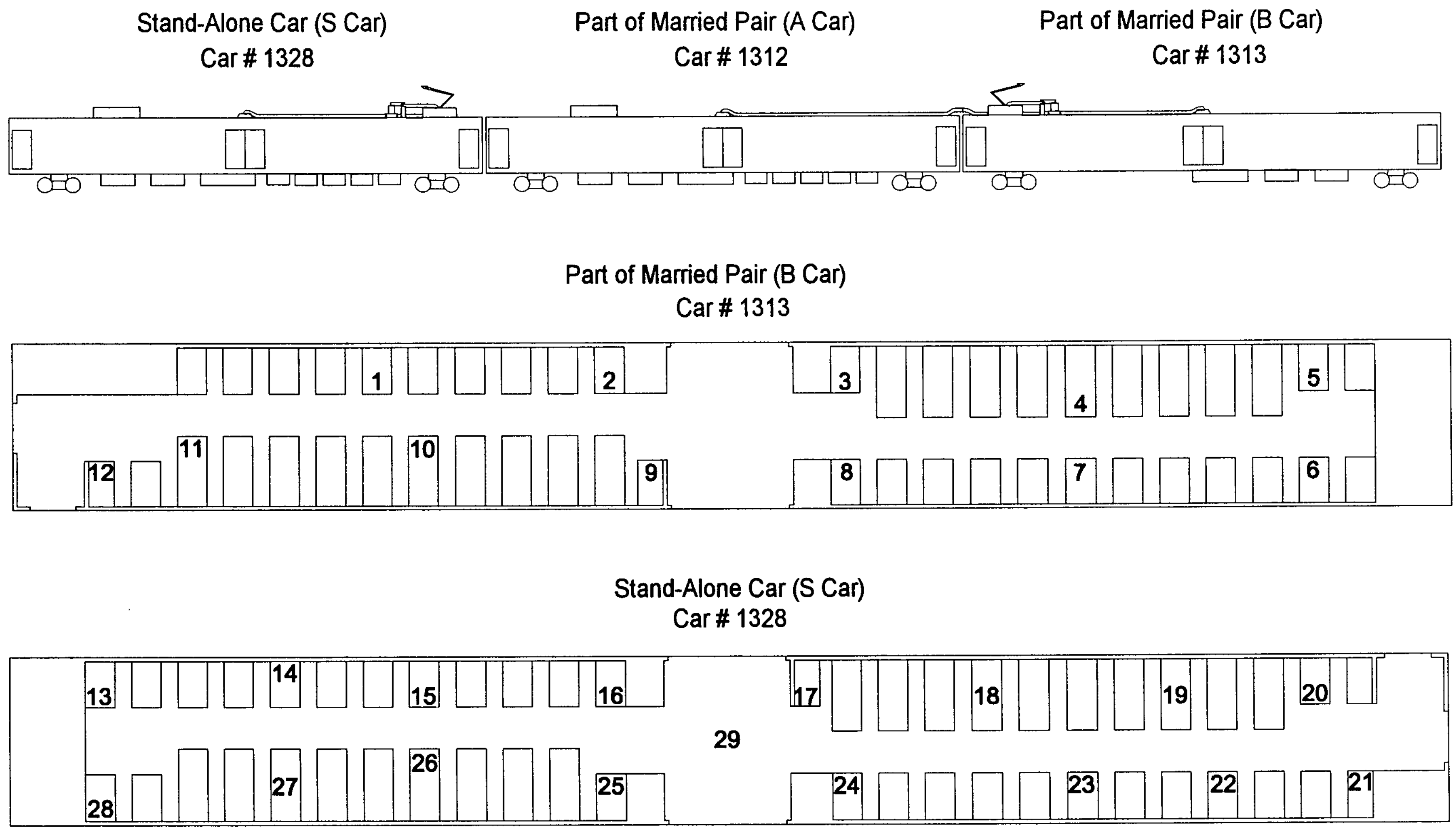


Figure 6-1 **Arrangement of the Three Cars in the Consist and the Seating Arrangement in the Cars Where Measurements Were Made. Numbered Seats Indicate Measurement Locations.**

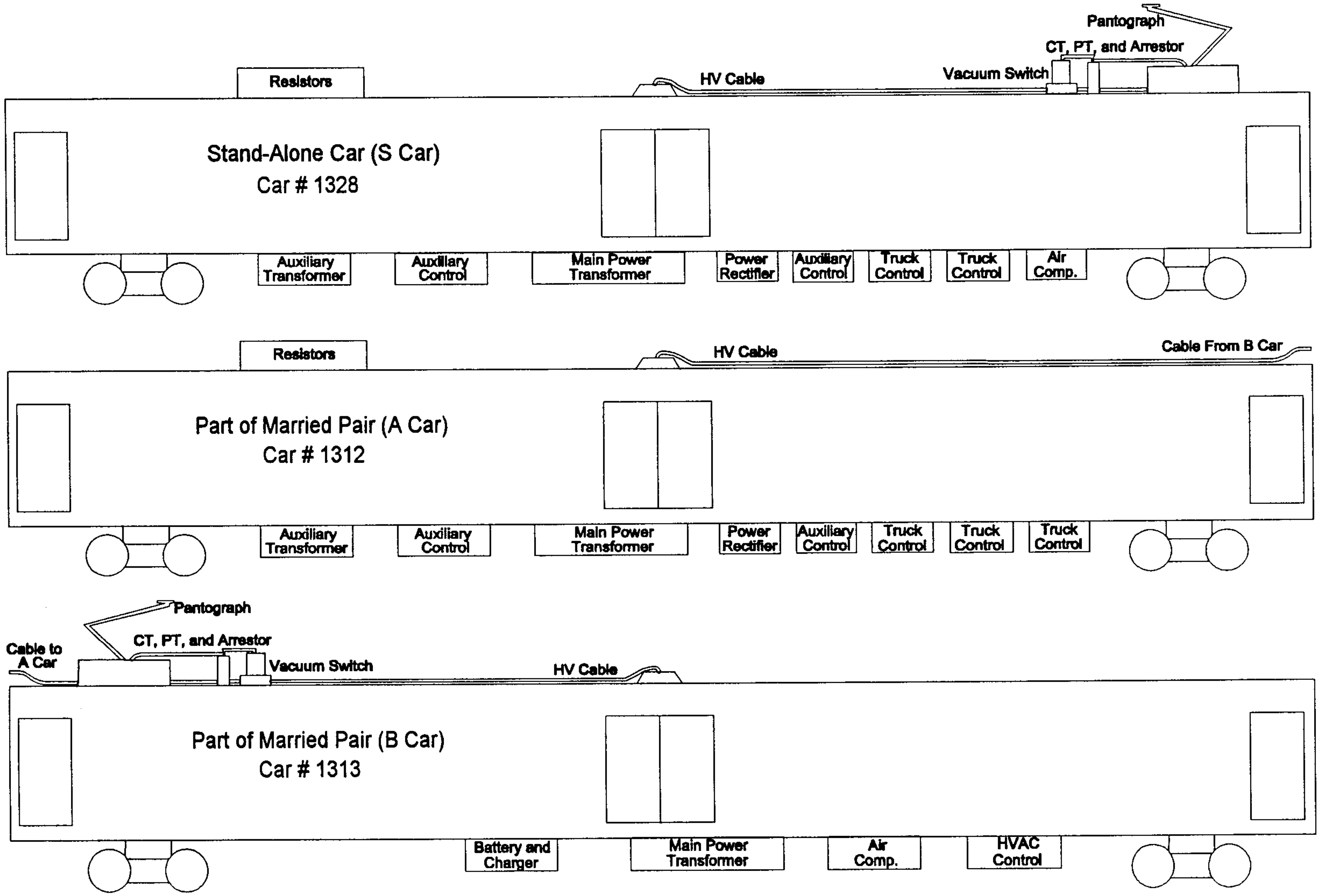


Figure 6-2 Placement of the Major Power Equipment on the Three Types of Arrow-3 Cars.

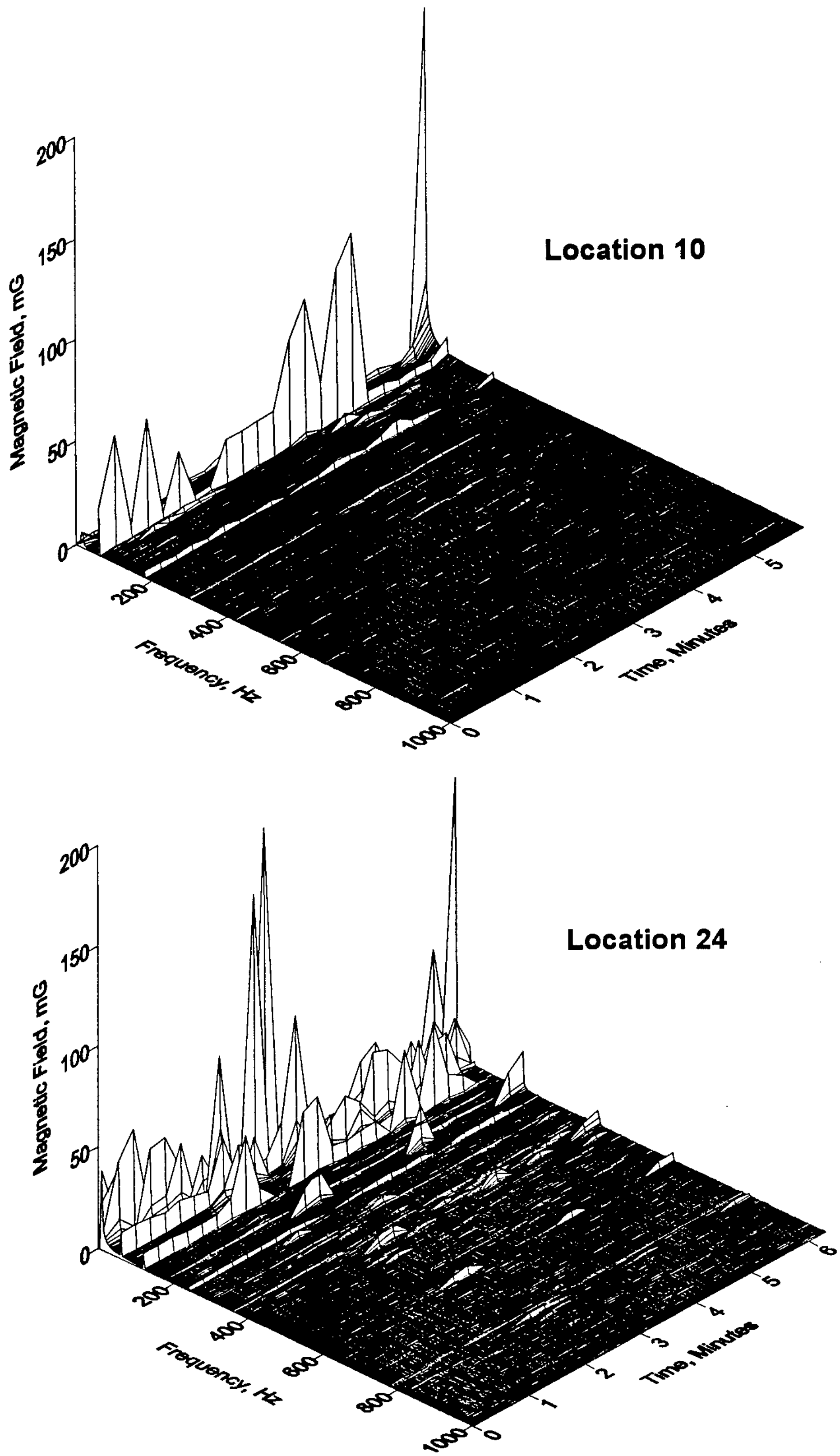


Figure 6-3 Magnetic Field Level as a Function of Frequency and Time at Waist Level at Two Locations in the Commuter Train. The Static (0 Hz) Field is Suppressed.

requires an auxiliary transformer or reactor and a capacitor bank which are also mounted beneath the floor of the car behind the auxiliary transformer. The electric propulsion system also uses dynamic braking, the resistors for which are on the roof of the car.

Cars in married pairs have the same power equipment for propulsion and auxiliary services but share some of the devices. For example, the pantograph, ct, pt, surge arrestor and vacuum switch on the B car provides 27.5 kV, 60 Hz electric power to the main power transformers on both cars via high voltage cables running along the roofs and down through the centers of both cars. Only the A car has the power rectifiers, invertors, auxiliary transformer, capacitor bank and braking resistors required to produce variable frequency ac power for the ac traction motors. It has three invertors; two to power the two trucks on the A car and a third to power the truck on the B car beneath the pantograph. The second truck on the B car is not powered. To make room for the third invertor on the A car, most of the auxiliary equipment is mounted beneath the floor of the B car.

6.2 Test Conditions

Three-axis, magnetic field waveform measurements were made at locations representing the head, waist, and ankles of a passenger seated in the seats numbered 1 through 28 in Figure 6-1 and at locations representing the head, waist, and ankles of a passenger standing between the center doors of one car (position 29 in Figure 6-1). Single-axis, electric field waveform measurements were made at positions representing the chest of passengers at the above described locations. Because of the expected large temporal variability in magnetic field conditions, repetitive field waveform samples were collected every 15 seconds while the train was in motion from one station to another. In many cases where stations were close together, field conditions were sampled between the two stations in order to collect a larger measurement sample. In all cases, the first sample at a location was taken as the train began to accelerate leaving the station and every 15 seconds thereafter until the recording was stopped concurrent with the stopping of the train at the next station. Because of the non-uniform distance and travel time between stations, the number of waveform samples at each location varied between 6 and 48, but averaged about 15 samples (just under 4 minutes travel time).

6.3 Magnetic Field Characteristics

6.3.1 Temporal Variability

Both the amplitude and frequency characteristics of the magnetic field in the commuter train change markedly as the train varies in speed and traction power requirements. Moreover, the nature of this temporal variability differs greatly from one location to another in the train depending on proximity to various field sources. Figure 6-3 shows plots of resultant magnetic field level measured at waist level at two locations in the train while it travels between stations (the measurements at the two locations are not concurrent). At location 10 in the B car, the principal field component is the 60 Hz power frequency with a low level of third harmonics. The magnitude of the field appears to fluctuate in proportion to the traction power needs of the train. A very low frequency component appears only near the end of the trip. The spectral characteristics of the magnetic field are quiet at location 24 (the lower frame of Figure 6-3) in the S car. The 60 Hz field is no longer dominant. Low frequency components are present in the field which vary in both amplitude and frequency. Furthermore, large field components are present at frequencies higher than 60 Hz. Some components are even harmonics, primarily the second harmonic, which presumably arise from the rectified 60 Hz current. Other components such as 200 Hz and harmonics thereof are present from time-to-time. The temporal of these various frequency components have no obvious temporal correlation. As a result of these complexities and inconsistencies from one location to another, one can make no general conclusions about the temporal variability of the magnetic fields in the commuter train except to say that it is generally quite large and highly site-specific.

6.3.2 Spatial Variability

Average static and ELF magnetic field levels measured at head, foot, and ankle level at the 29 locations in the Arrow-3 cars are reported in Table 6-1. To better show the frequency distribution of the time-varying magnetic field in the ELF band, the table also contains listings of average field levels in more limited frequency bands. Scanning the table reveals large spatial variability throughout both cars.

The average static field level in the measured commuter train was 538 mG which is consistent with the typical geomagnetic field strength. The static field tends to be higher near the floor (587 mG at ankle level) and lower at waist level (501 mG). The average static field levels did not differ materially between the two types of cars (536 mG in the B car and 539 mG in the S car), but the average variation in field strength with height above the floor was quite different.

Average ELF field levels differed by car type. While the average was 49.6 mG for both cars, the field in the B car with less electrical equipment was 37.6 mG compared to 58.0 mG in the S car which had the largest complement of

Table 6-1
Average Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations
in the Commuter Train with Variable-Frequency AC Traction Motors

Location in the Train Keyed to Fig. 6-1	Number of Samples	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz			Non-60 Hz ELF 3 Hz to 3 kHz except 60 Hz		
		Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
1	12	535	585	315	21.7	55.1	183.5	7.1	10.8	26.9	18.9	51.9	173.2	3.2	7.3	33.8	0.6	1.7	10.9	8.3	14.2	48.6
2	12	436	537	583	33.9	32.7	37.3	3.6	4.9	7.2	32.5	30.5	34.4	4.3	5.0	5.0	1.1	1.3	3.0	6.2	7.8	9.7
3	13	606	841	1026	43.8	78.6	152.1	7.0	8.5	14.1	37.8	71.7	136.9	5.1	9.2	19.2	10.8	12.4	27.4	14.5	18.6	37.8
4	13	607	556	468	31.7	31.5	61.5	13.0	12.8	24.3	26.2	25.8	45.9	4.2	4.3	10.0	3.6	6.0	18.1	14.8	15.4	33.7
5	48	704	638	269	18.9	21.0	31.2	6.6	8.3	13.7	16.0	17.2	22.9	3.4	3.5	5.7	2.1	2.7	8.8	8.1	9.8	18.1
6	7	584	626	415	3.6	4.2	5.9	2.2	2.6	3.8	2.3	2.5	3.4	0.9	1.1	2.0	1.1	1.0	0.7	2.6	3.1	4.6
7	12	608	653	631	3.9	4.6	6.7	2.1	2.7	4.2	2.9	3.1	4.4	1.2	1.3	2.1	0.3	0.5	0.7	2.5	3.1	4.8
8	30	396	418	553	15.1	45.5	104.9	5.5	11.2	20.9	10.9	36.8	89.5	4.5	14.8	31.2	1.6	3.4	6.1	8.3	21.5	42.9
9	9	384	468	537	7.9	14.1	56.2	3.2	5.1	15.8	6.2	10.9	46.2	2.2	4.3	17.2	0.5	1.0	4.6	4.3	7.6	26.5
10	23	679	462	251	19.4	35.1	61.2	9.4	13.0	20.2	12.9	26.3	49.0	2.5	4.0	8.0	0.6	1.1	3.0	10.1	14.3	23.3
11	10	630	426	245	17.0	21.6	25.3	12.9	18.6	21.9	7.0	5.5	6.2	2.6	4.5	4.8	0.8	1.3	1.6	13.6	20.2	23.6
12	26	578	614	437	11.5	15.6	41.1	4.4	7.9	22.0	9.8	11.1	22.4	2.0	3.9	14.8	0.3	0.5	5.1	5.2	9.9	32.0
13	6	549	606	632	18.5	17.6	50.2	7.7	8.3	24.3	10.7	11.2	20.1	5.9	4.8	28.1	8.3	5.1	8.1	13.3	11.4	44.0
14	11	588	355	406	19.6	24.6	62.1	11.8	13.7	27.6	12.4	14.3	21.9	4.8	10.6	42.7	1.4	2.0	7.2	13.4	18.6	56.5
15	17	619	312	669	13.5	13.8	32.0	7.1	8.4	22.2	6.6	8.2	14.3	5.1	4.1	10.6	2.1	1.5	3.4	10.4	10.1	27.4
16	13	194	430	775	27.2	70.8	200.5	7.3	19.0	86.3	23.4	59.3	127.9	7.5	20.7	71.0	2.0	4.4	18.4	11.7	32.3	134.5
17	11	366	539	867	24.0	54.4	243.2	9.6	25.4	101.8	15.9	34.0	161.5	9.4	21.5	93.8	3.9	6.8	30.9	15.7	37.6	162.9
18	8	618	692	1290	29.9	70.7	221.0	15.6	34.9	124.3	13.1	18.4	62.6	16.8	48.2	129.9	2.3	6.7	20.2	25.4	67.1	205.9
19	9	568	389	954	11.0	18.1	98.9	3.8	7.9	38.3	8.9	9.8	34.5	3.0	8.3	53.4	0.7	2.0	18.6	5.3	13.5	81.5
20	8	581	457	761	7.0	13.1	49.8	3.7	6.7	22.0	4.9	6.7	16.8	2.1	6.6	29.5	0.4	0.8	4.8	4.5	10.7	44.3
21	10	546	564	343	10.8	16.9	42.0	7.0	13.6	29.6	5.9	5.7	10.8	1.0	1.7	9.6	0.3	0.9	14.6	7.2	14.1	39.3
22	8	661	440	404	20.1	28.7	58.0	9.5	17.0	29.0	13.2	15.1	36.9	2.8	4.7	10.6	0.6	1.4	4.0	10.5	18.4	32.9
23	22	502	378	568	36.4	71.6	157.5	12.4	20.7	38.4	28.9	60.3	136.9	10.7	16.8	33.4	1.4	2.6	14.1	18.1	29.6	58.0
24	25	525	533	594	32.6	63.9	109.8	23.8	46.3	61.2	9.4	16.4	60.6	12.6	27.4	46.5	2.3	5.0	23.8	30.3	60.7	87.9
25	6	298	381	771	37.1	50.6	117.2	8.2	14.1	28.0	28.1	42.7	97.3	8.8	10.0	28.5	14.0	7.9	18.9	18.7	20.1	47.4
26	6	614	337	599	37.7	49.8	107.6	12.6	23.2	48.2	30.0	39.0	84.7	7.1	10.4	28.5	3.4	5.3	22.4	15.6	27.8	64.8
27	8	546	421	616	26.4	31.2	45.2	5.2	7.7	18.1	24.8	28.7	34.8	3.2	4.7	9.3	3.0	5.2	15.0	6.9	10.7	26.9
28	5	453	599	566	21.5	22.3	33.1	3.1	5.1	9.4	20.1	20.4	28.4	3.3	2.6	5.3	3.3	1.8	4.5	5.7	6.3	12.3
29	21	264	261	482	33.3	26.7	281.7	9.9	14.1	84.0	28.2	18.2	224.3	6.0	7.3	98.6	3.1	3.1	20.7	12.6	16.9	145.3
Summary of Average Field Levels in the B Car (Locations 1-12)																						
Minimum		384	418	245	3.6	4.2	5.9	2.1	2.6	3.8	2.3	2.5	3.4	0.9	1.1	2.0	0.3	0.5	0.7	2.5	3.1	4.6
Maximum		704	841	1026	43.8	78.6	183.5	13.0	18.6	26.9	37.8	71.7	173.2	5.1	14.8	33.8	10.8	12.4	27.4	14.8	21.5	48.6
Median		595	571	453	17.9	26.6	48.6	6.1	8.4	18.0	11.9	21.5	40.2	2.9	4.3	9.0	0.9	1.3	4.8	8.2	12.1	25.0
Average	17.9	562	569	478	19.0	30.0	63.9	6.4	8.9	16.2	15.3	24.4	52.9	3.0	5.3	12.8	1.9	2.7	7.5	8.2	12.1	25.5
Std. Dev.	11.4	101	115	209	11.8	20.8	53.4	3.6	4.5	7.5	11.0	20.2	51.8	1.3	3.6	10.3	2.8	3.3	7.7	4.2	6.0	13.8
Summary of Average Field Levels in the S Car (Locations 13-29)																						
Minimum		194	261	343	7.0	13.1	32.0	3.1	5.1	9.4	4.9	5.7	10.8	1.0	1.7	5.3	0.3	0.8	3.4	4.5	6.3	12.3
Maximum		661	692	1290	37.7	71.6	281.7	23.8	46.3	124.3	30.0	60.3	224.3	16.8	48.2	129.9	14.0	7.9	30.9	30.3	67.1	205.9
Median		546	430	616	24.0	28.7	98.9	8.2	14.1	29.6	13.2	18.2	36.9	5.9	8.3	29.5	2.3	3.1	15.0	12.6	18.4	56.5
Average	11.4	500	453	665	23.9	37.9	112.3	9.3	16.8	46.6	16.7	24.0	69.1	6.5	12.4	42.9	3.1	3.7	14.7	13.3	23.9	74.8
Std. Dev.	6.0	133	115	224	9.5	21.2	77.9	4.9	10.6	32.2	8.6	16.8	59.7	4.1	11.4	35.0	3.3	2.2	7.9	6.8	16.9	53.4
Summary of Average Field Levels in Both B and S Cars (Locations 1-29)																						
Minimum		194	261	245	3.6	4.2	5.9	2.1	2.6	3.8	2.3	2.5	3.4	0.9	1.1	2.0	0.3	0.5	0.7	2.5	3.1	4.6
Maximum		704	841	1290	43.8	78.6	281.7	23.8	46.3	124.3	37.8	71.7	224.3	16.8	48.2	129.9	14.0	12.4	30.9	30.3	67.1	205.9
Median		568	468	568	20.1	28.7	61.2	7.1	11.2	24.3	13.1	18.2	36.9	4.2	5.0	19.2	1.6	2.0	8.8	10.4	14.3	39.3
Average	14.1	526	501	587	21.9	34.6	92.3	8.1	13.5	34.1	16.1	24.2	62.4	5.0	9.4	30.4	2.6	3.3	11.7	11.2	19.0	54.4
Std. Dev.	9.2	125	128	237	10.8	21.4	72.8	4.7	9.5	29.2	9.7	18.3	57.1	3.6	9.7	31.3	3.1	2.7	8.6	6.4	14.7	48.4

electrical equipment. Average ELF field levels in both cars (as at most specific measurement locations) showed a strong gradient with height above the floor being strongest near the floor and weaker at increasing heights. That observation is consistent with the abundance of electrical equipment beneath the floor of the vehicles and indicates that the under-floor equipment represent significant magnetic field sources. This situation is different from that in non-powered railroad coaches where the predominant field source was current in the catenary-track circuit [1].

In situations such as on the commuter train where magnetic field levels have a very large temporal variability, a few samples of high field levels strongly affect the calculated average field level. This is especially true when the overall number of samples is not large. In such cases, it is often useful to look at the median field level which better represents a "typical" condition. Median field levels are tabulated in Table 6-2 in a format identical to that used in Table 6-1 for average field levels.

As one would expect, median static field levels shown in Table 6-2 are not materially different than average levels shown in Figure 6-1 because the static field is predominantly geomagnetic and has a nearly gaussian distribution resulting from random shielding or enhancement depending on position in the train, orientation of the train with respect to magnetic north, and proximity to ferromagnetic objects along the route.

Median ELF magnetic fields, on the other hand, are materially less than corresponding average values. While the average of all ELF field measurements in the train was 49.6 mG, the average of the median values at all locations was only 31 mG. Patterns of variability with height above the floor and between cars observed in the average field levels and discussed above are present in the median field data as well.

The maximum magnetic field levels encountered at each measurement location are reported in Table 6-3. At most locations, the maximum static field is only modestly larger than the average value because of the limited temporal variability in that field component. For ELF fields, however, most locations had maximum field levels more than twice as large as the average.

A convenient indicator of the variability in a set of data is the coefficient of variation (cv) which is simply the standard deviation of the data set normalized by dividing by the mean value. Table 6-4 shows the coefficient of variation in the repetitive field samples at each measurement location. The tabulated values indicate the relative amounts of temporal variability in the field at various locations in the train. For example, it has already been observed that

Table 6-2

Median Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations in the Commuter Train with Variable-Frequency AC Traction Motors

Location in the Train Keyed to Fig. 6-1	Number of Samples	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz			Non-60 Hz ELF 3 Hz to 3 kHz except 60 Hz		
		Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
1	12	543	597	329	17.7	30.2	60.9	8.0	10.1	19.0	14.5	27.0	42.7	2.1	5.5	26.2	0.7	1.4	5.7	9.3	15.8	47.8
2	12	442	553	606	6.6	8.0	12.8	4.2	5.6	8.1	5.7	5.9	8.3	3.2	3.6	3.5	0.5	0.6	2.7	5.3	7.4	10.0
3	13	605	854	1046	15.1	16.5	37.3	5.5	7.6	13.2	9.0	8.8	19.7	3.5	6.4	14.2	10.9	12.2	27.8	12.7	14.9	33.6
4	13	601	551	456	29.2	29.4	56.2	6.9	10.3	16.7	19.2	23.3	25.0	4.1	4.6	10.2	3.6	6.0	17.9	9.1	12.2	26.0
5	48	713	654	272	16.4	17.5	23.4	4.8	6.3	10.4	13.4	13.5	14.6	3.5	3.6	5.1	2.1	2.7	8.9	6.3	8.1	14.8
6	7	586	629	412	3.5	4.4	6.5	2.1	2.5	3.4	2.4	3.1	4.4	1.0	1.5	2.5	1.2	1.1	0.8	2.5	2.9	4.9
7	12	613	658	635	3.3	3.6	5.9	1.8	2.5	4.0	2.1	2.2	3.3	1.1	1.2	2.1	0.3	0.5	0.7	2.2	2.8	4.5
8	30	398	423	549	9.4	26.5	88.2	2.6	5.3	9.5	6.5	21.3	51.4	4.4	14.5	30.7	1.4	2.4	4.3	5.2	15.2	32.3
9	9	378	474	555	5.3	8.1	31.8	2.4	3.8	9.0	4.3	5.2	9.8	1.4	2.1	6.4	0.4	0.7	3.2	3.0	4.6	15.2
10	23	692	461	251	13.4	21.9	29.3	2.7	4.0	6.8	9.3	21.4	28.5	1.5	3.3	6.4	0.3	0.5	1.8	4.5	5.9	10.3
11	10	632	429	255	6.7	13.7	15.7	4.0	7.8	10.0	2.7	2.7	2.6	2.0	2.8	2.8	0.6	1.4	1.6	6.3	13.3	15.4
12	26	580	615	438	9.3	12.4	26.8	3.3	5.3	9.5	8.0	7.8	8.7	1.6	2.7	10.8	0.3	0.5	5.1	4.4	7.7	20.6
13	6	549	604	633	15.4	12.9	31.8	5.7	5.7	10.8	8.2	7.7	11.8	5.6	4.4	22.7	8.3	5.2	8.7	11.9	9.0	29.5
14	11	592	345	404	11.1	15.0	58.4	7.5	9.0	17.2	4.7	5.1	6.3	4.1	8.3	33.0	1.3	2.1	7.3	9.0	14.7	58.3
15	17	611	296	685	12.9	11.8	22.0	4.0	4.8	14.7	4.8	6.9	12.0	2.5	3.8	10.4	1.0	1.3	3.0	7.7	6.2	17.3
16	13	174	416	778	18.0	39.1	104.7	4.7	12.6	43.5	15.6	30.5	60.6	6.8	17.4	47.9	1.7	3.6	15.2	8.8	21.8	90.8
17	11	369	542	874	15.7	34.9	184.0	4.2	9.4	44.8	9.6	17.5	90.4	6.6	17.1	57.5	1.4	4.5	35.2	8.0	19.9	110.2
18	8	667	724	1173	17.3	46.5	126.4	6.4	14.6	40.9	4.7	6.8	24.6	14.2	41.2	113.2	2.3	6.6	22.6	16.0	45.7	124.0
19	9	564	386	943	9.8	14.1	78.2	2.6	3.9	14.2	7.6	7.6	12.0	3.4	9.5	63.8	0.7	2.0	18.4	5.1	12.2	68.2
20	8	562	433	738	5.5	11.5	41.9	2.5	4.7	11.9	3.7	3.6	4.8	1.9	6.0	26.6	0.3	0.7	4.4	3.6	10.0	41.3
21	10	554	575	341	6.2	7.0	25.6	3.1	4.7	12.8	5.0	4.7	8.1	0.9	1.6	9.7	0.3	0.9	17.3	3.3	5.1	22.6
22	8	645	416	390	13.2	19.6	48.3	5.0	7.7	16.5	3.7	3.9	8.2	2.5	3.4	8.9	0.4	0.8	3.4	7.0	10.8	24.7
23	22	509	369	546	14.1	24.5	52.2	5.4	8.4	17.4	7.8	15.5	37.9	6.5	11.0	27.9	0.9	1.9	14.4	12.5	19.5	40.7
24	25	525	535	597	26.0	51.9	90.3	20.6	31.5	56.7	5.1	11.6	59.6	13.1	26.5	39.2	1.5	3.4	23.0	25.5	50.3	68.5
25	6	285	376	773	19.3	19.8	46.8	7.2	10.4	20.7	9.0	10.7	23.6	8.3	7.3	22.8	14.0	7.7	18.9	17.7	17.6	42.2
26	6	609	330	603	21.5	36.4	99.1	10.6	24.4	52.9	7.0	21.4	75.9	5.0	6.8	20.2	3.4	5.3	22.3	17.4	29.3	68.4
27	8	553	426	619	23.3	29.0	41.1	5.0	6.3	19.2	21.6	26.1	33.8	3.0	4.5	8.9	3.2	5.8	16.6	7.1	10.3	24.3
28	5	462	608	563	14.3	15.8	24.0	2.7	4.4	7.8	12.5	11.9	14.0	3.0	2.0	4.2	3.3	1.8	4.5	5.0	5.5	9.9
29	21	272	254	468	22.2	25.7	235.6	9.3	14.8	43.4	15.6	12.9	65.2	4.6	5.4	55.0	2.4	2.5	19.7	12.8	16.7	118.4
Summary of Median Field Levels in the B Car (Locations 1-12)																						
Minimum		378	423	251	3.3	3.6	5.9	1.8	2.5	3.4	2.1	2.2	2.6	1.0	1.2	2.1	0.3	0.5	0.7	2.2	2.8	4.5
Maximum		713	854	1046	29.2	30.2	88.2	8.0	10.3	19.0	19.2	27.0	51.4	4.4	14.5	30.7	10.9	12.2	27.8	12.7	15.8	47.8
Median		593	575	447	9.3	15.1	28.0	3.6	5.5	9.5	7.2	8.3	12.2	2.1	3.4	6.4	0.6	1.2	3.7	5.2	7.9	15.3
Average	17.9	565	575	484	11.3	16.0	32.9	4.0	5.9	10.0	8.1	11.9	18.2	2.5	4.3	10.1	1.8	2.5	6.7	5.9	9.2	19.6
Std. Dev.	11.4	103	117	213	7.2	9.0	23.6	1.9	2.5	4.4	5.1	8.7	15.2	1.2	3.4	9.0	2.9	3.3	7.8	3.0	4.6	12.5
Summary of Median Field Levels in the S Car (Locations 13-29)																						
Minimum		174	254	341	5.5	7.0	22.0	2.5	3.9	7.8	3.7	3.6	4.8	0.9	1.6	4.2	0.3	0.7	3.0	3.3	5.1	9.9
Maximum		667	724	1173	26.0	51.9	235.6	20.6	31.5	56.7	21.6	30.5	90.4	14.2	41.2	113.2	14.0	7.7	35.2	25.5	50.3	124.0
Median		553	416	619	15.4	19.8	52.2	5.0	8.4	17.4	7.6	10.7	23.6	4.6	6.8	26.6	1.5	2.5	16.6	8.8	14.7	42.2
Average	11.4	500	449	655	15.6	24.4	77.1	6.3	10.4	26.2	8.6	12.0	32.3	5.4	10.4	33.6	2.7	3.3	15.0	10.5	17.9	56.4
Std. Dev.	6.0	138	124	207	5.6	12.9	57.5	4.2	7.3	16.0	4.9	7.7	26.8	3.6	9.9	26.8	3.4	2.1	8.5	5.8	12.7	35.3
Summary of Median Field Levels in Both B and S Cars (Locations 1-29)																						
Minimum		174	254	251	3.3	3.6	5.9	1.8	2.5	3.4	2.1	2.2	2.6	0.9	1.2	2.1	0.3	0.5	0.7	2.2	2.8	4.5
Maximum		713	854	1173	29.2	51.9	235.6	20.6	31.5	56.7	21.6	30.5	90.4	14.2	41.2	113.2	14.0	12.2	35.2	25.5	50.3	124.0
Median		562	474	563	14.1	17.5	41.9	4.7	6.3	14.2	7.6	8.8	14.6	3.4	4.6	14.2	1.3	2.0	8.7	7.1	12.2	29.5
Average	14.1	527	501	584	13.8	21.0	58.8	5.3	8.6	19.5	8.4	12.0	26.5	4.2	7.9	23.9	2.4	3.0	11.6	8.6	14.3	41.2
Std. Dev.	9.2	128	136	226	6.6	12.1	51.4	3.6	6.2	14.9	5.0	8.1	23.8	3.2	8.5	24.3	3.2	2.7	9.2	5.3	11.0	33.5

Table 6-3
Maximum Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations in the Commuter Train with Variable-Frequency AC Traction Motors

Location in the Train Keyed to Fig. 6-1	Number of Samples	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz			Non-60 Hz ELF 3 Hz to 3 kHz except 60 Hz		
		Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
1	12	558	615	360	53.5	135.3	517.8	15.5	18.8	60.1	52.4	133.5	507.1	9.6	23.0	102.2	0.9	3.2	26.7	15.8	24.0	104.8
2	12	469	567	618	130.6	118.3	125.7	6.6	9.2	12.8	129.5	116.7	124.2	16.1	18.3	16.6	3.0	3.6	4.7	16.8	19.3	19.4
3	13	661	902	1085	119.8	228.8	442.5	27.0	24.5	24.0	117.2	227.4	439.6	10.5	20.5	42.2	12.6	15.3	32.5	30.7	33.2	55.4
4	13	723	650	544	83.0	79.6	121.7	31.9	29.7	72.7	77.6	73.9	109.4	10.9	7.9	13.9	4.6	7.2	21.1	34.0	30.7	75.9
5	48	853	790	457	56.2	49.2	76.6	32.2	43.7	63.4	55.8	48.0	55.2	7.7	7.9	13.0	3.1	3.5	10.9	32.7	44.5	65.4
6	7	620	657	441	4.9	5.3	7.9	3.1	4.0	6.3	3.4	3.9	6.0	1.3	1.6	3.7	1.3	1.2	0.8	3.6	4.3	6.4
7	12	653	696	683	12.5	13.5	18.6	3.7	4.2	6.7	11.4	12.3	16.8	3.4	3.7	5.5	0.5	0.8	0.9	5.0	5.5	7.9
8	30	439	453	617	81.8	309.2	655.7	35.7	68.8	144.7	80.8	307.1	651.5	12.3	43.1	85.5	7.0	20.3	37.4	36.1	71.9	149.7
9	9	435	502	587	27.3	53.0	290.2	8.4	12.9	54.8	25.5	49.5	274.2	7.7	14.7	76.0	1.1	2.6	15.9	9.8	18.9	95.1
10	23	710	487	368	132.2	178.9	263.5	131.1	177.8	256.3	40.3	88.9	167.5	13.1	14.5	28.6	6.8	7.4	8.5	131.9	178.5	258.1
11	10	649	444	282	42.9	51.0	72.4	34.9	50.3	71.7	40.3	29.6	34.4	7.4	17.5	18.1	1.6	2.5	3.2	35.1	50.6	72.0
12	26	598	638	478	31.0	34.7	107.0	12.0	24.5	74.2	30.3	31.7	79.4	6.2	13.5	53.7	0.5	1.0	7.2	12.1	24.6	75.0
13	6	563	624	651	32.3	35.6	92.5	19.5	20.3	89.0	30.6	34.4	66.6	8.1	6.5	62.7	9.1	5.3	9.2	21.8	21.5	90.8
14	11	736	461	489	60.3	64.8	131.1	41.7	36.6	68.5	42.4	46.9	71.8	10.0	25.4	102.3	2.4	3.0	11.7	42.9	44.6	109.7
15	17	681	508	745	26.2	27.0	79.0	25.5	26.0	77.1	17.3	18.4	26.8	22.8	11.2	30.0	8.1	2.3	10.4	25.8	26.6	78.6
16	13	308	568	821	89.8	330.1	799.3	34.6	94.3	354.1	87.7	323.7	738.8	19.1	63.9	303.3	3.1	8.1	35.0	35.7	98.7	361.0
17	11	424	601	905	60.3	143.2	682.9	35.5	89.8	453.5	47.2	107.2	497.8	24.6	64.3	320.4	29.6	33.2	48.7	42.5	95.0	467.5
18	8	688	768	1969	92.1	199.1	628.4	46.0	116.0	407.9	63.4	94.2	346.7	48.6	147.3	340.3	3.8	8.9	31.0	66.8	175.4	524.1
19	9	614	437	1047	24.7	39.5	197.2	10.5	27.8	142.7	24.1	37.3	185.0	5.1	12.4	73.5	0.9	2.7	26.4	10.6	27.9	143.9
20	8	732	616	935	14.3	26.2	94.5	10.9	14.1	50.8	13.5	20.0	62.4	4.4	15.9	80.3	0.9	1.3	9.0	11.3	16.9	82.3
21	10	565	584	373	45.8	99.2	190.8	45.5	99.0	190.1	13.8	14.4	24.6	1.9	3.4	16.6	0.5	1.9	23.4	45.5	99.0	190.5
22	8	802	616	631	49.8	82.2	138.8	42.4	81.2	111.3	49.2	58.0	136.2	6.7	10.5	23.0	2.0	5.6	9.4	42.5	82.1	113.0
23	22	541	482	782	121.3	258.3	587.8	58.5	93.6	179.7	118.5	254.3	580.9	25.8	44.7	87.5	3.3	5.3	21.4	63.1	99.7	188.3
24	25	577	604	703	92.9	177.1	220.4	89.6	171.8	200.2	45.0	72.8	122.1	26.3	60.3	97.5	5.4	11.6	42.7	90.9	175.6	211.2
25	6	336	441	803	99.0	163.3	396.0	14.5	31.5	54.8	96.6	161.2	389.2	13.7	21.6	65.2	15.0	8.7	19.8	23.9	34.6	73.1
26	6	682	399	641	88.7	85.9	137.4	22.5	40.0	86.1	87.1	80.2	116.6	13.8	27.8	66.5	4.9	5.9	23.7	23.5	40.7	90.6
27	8	594	485	657	56.6	59.5	80.8	9.3	14.3	30.3	56.1	58.5	77.2	4.4	6.3	13.1	3.7	6.0	17.8	10.2	16.0	34.9
28	5	487	633	581	58.5	59.7	87.4	5.0	10.0	18.4	58.1	59.4	86.4	5.8	5.2	11.1	3.6	2.2	4.8	7.3	10.4	19.5
29	21	329	340	626	79.3	56.1	788.8	20.4	29.8	267.2	78.3	49.7	728.0	13.9	15.6	293.3	10.9	10.3	32.8	24.0	34.2	303.6
Summary of Maximum Field Levels in the B Car (Locations 1-12)																						
Minimum		435	444	282	4.9	5.3	7.9	3.1	4.0	6.3	3.4	3.9	6.0	1.3	1.6	3.7	0.5	0.8	0.8	3.6	4.3	6.4
Maximum		853	902	1085	132.2	309.2	655.7	131.1	177.8	256.3	129.5	307.1	651.5	16.1	43.1	102.2	12.6	20.3	37.4	131.9	178.5	258.1
Median		635	627	511	54.8	66.3	123.7	21.2	24.5	61.8	46.4	61.7	116.8	8.7	14.6	23.4	2.3	3.4	9.7	23.8	27.7	73.5
Average	17.9	614	617	543	64.6	104.7	225.0	28.5	39.0	70.6	55.4	93.5	205.4	8.9	15.5	38.3	3.6	5.7	14.2	30.3	42.2	82.1
Std. Dev.	11.4	119	132	200	42.9	89.6	202.9	33.2	45.8	67.2	37.7	87.9	206.1	3.9	10.4	32.2	3.5	5.9	12.1	32.8	45.0	66.2
Summary of Maximum Field Levels in the S Car (Locations 13-29)																						
Minimum		308	340	373	14.3	26.2	79.0	5.0	10.0	18.4	13.5	14.4	24.6	1.9	3.4	11.1	0.5	1.3	4.8	7.3	10.4	19.5
Maximum		802	768	1969	121.3	330.1	799.3	89.6	171.8	453.5	118.5	323.7	738.8	48.6	147.3	340.3	29.6	33.2	48.7	90.9	175.6	524.1
Median		577	568	703	60.3	82.2	190.8	25.5	36.6	111.3	49.2	58.5	122.1	13.7	15.9	73.5	3.7	5.6	21.4	25.8	40.7	113.0
Average	11.4	568	539	786	64.2	112.2	313.7	31.3	58.6	163.6	54.6	87.7	250.4	15.0	31.9	116.9	6.3	7.2	22.2	34.6	64.6	181.3
Std. Dev.	6.0	145	104	336	29.4	84.9	262.2	21.0	44.7	130.1	29.9	82.4	239.6	11.6	35.3	113.3	6.9	7.2	12.3	22.2	51.1	144.5
Summary of Maximum Field Levels in Both B and S Cars (Locations 1-29)																						
Minimum		308	340	282	4.9	5.3	7.9	3.1	4.0	6.3	3.4	3.9	6.0	1.3	1.6	3.7	0.5	0.8	0.8	3.6	4.3	6.4
Maximum		853	902	1969	132.2	330.1	799.3	131.1	177.8	453.5	129.5	323.7	738.8	48.6	147.3	340.3	29.6	33.2	48.7	131.9	178.5	524.1
Median		598	584	631	58.5	79.6	138.8	25.5	29.8	74.2	49.2	58.5	122.1	10.0	15.6	62.7	3.3	5.3	17.8	25.8	34.2	90.8
Average	14.1	587	571	685	64.4	109.1	277.0	30.1	50.5	125.2	54.9	90.1	231.8	12.5	25.1	84.3	5.2	6.6	18.9	32.8	55.3	140.3
Std. Dev.	9.2	137	123	312	35.6	87.0	243.4	26.8	46.2	117.8	33.4	84.7	227.5	9.7	29.0	97.3	5.9	6.7	12.8	27.2	49.9	128.2

Table 6-4
Coefficient of Variation of the Magnetic Field Levels in Percent at the Indicated Measurement Locations in the Commuter Train with Variable-Frequency AC Traction Motors

Location in the Train Keyed to Fig. 6-1	Number of Samples	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz			Non-60 Hz ELF 3 Hz to 3 kHz except 60 Hz		
		Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
1	12	4%	5%	11%	55%	75%	97%	60%	59%	73%	69%	82%	104%	83%	83%	79%	47%	64%	85%	50%	49%	59%
2	12	5%	7%	10%	129%	120%	110%	57%	57%	51%	136%	131%	122%	98%	95%	83%	92%	84%	27%	67%	61%	48%
3	13	5%	5%	4%	101%	114%	112%	86%	64%	39%	125%	130%	130%	57%	69%	67%	9%	11%	10%	34%	33%	25%
4	13	6%	6%	6%	61%	50%	49%	86%	68%	78%	72%	65%	75%	62%	36%	28%	13%	10%	9%	72%	50%	47%
5	48	9%	11%	16%	53%	49%	54%	81%	89%	88%	66%	60%	73%	39%	36%	36%	18%	16%	16%	60%	71%	62%
6	7	4%	3%	5%	18%	20%	33%	24%	28%	32%	37%	53%	64%	31%	45%	66%	21%	21%	19%	18%	20%	27%
7	12	5%	4%	5%	71%	65%	59%	39%	36%	35%	94%	95%	90%	68%	70%	63%	17%	17%	16%	42%	37%	35%
8	30	5%	4%	4%	102%	126%	113%	148%	155%	144%	137%	155%	133%	56%	62%	57%	68%	105%	105%	92%	79%	69%
9	9	6%	6%	10%	89%	104%	149%	73%	78%	107%	113%	132%	177%	101%	117%	131%	61%	73%	90%	63%	70%	97%
10	23	8%	3%	12%	135%	113%	106%	279%	273%	251%	81%	97%	102%	106%	79%	78%	208%	137%	64%	260%	247%	216%
11	10	2%	4%	9%	88%	74%	82%	97%	83%	92%	160%	149%	156%	73%	106%	103%	66%	44%	46%	91%	73%	83%
12	26	2%	2%	4%	65%	56%	70%	70%	82%	105%	77%	72%	104%	80%	96%	100%	26%	32%	15%	54%	60%	67%
13	6	2%	2%	2%	38%	51%	59%	69%	68%	121%	86%	96%	104%	18%	22%	56%	7%	7%	16%	29%	40%	57%
14	11	11%	18%	15%	81%	69%	54%	93%	69%	73%	111%	109%	107%	52%	67%	70%	42%	36%	44%	79%	54%	49%
15	17	5%	17%	12%	54%	51%	64%	96%	92%	105%	65%	51%	41%	122%	63%	63%	116%	34%	61%	77%	71%	78%
16	13	30%	18%	3%	77%	117%	101%	116%	128%	122%	90%	138%	148%	48%	64%	99%	26%	37%	41%	67%	72%	77%
17	11	7%	5%	3%	74%	75%	79%	110%	114%	124%	90%	98%	101%	79%	75%	89%	207%	125%	46%	86%	80%	80%
18	8	23%	16%	20%	86%	77%	82%	113%	118%	130%	148%	157%	172%	74%	81%	65%	30%	18%	30%	74%	72%	74%
19	9	3%	5%	4%	51%	49%	42%	69%	98%	117%	70%	102%	161%	42%	44%	43%	21%	21%	23%	37%	40%	30%
20	8	10%	13%	9%	55%	48%	47%	79%	66%	84%	73%	92%	131%	58%	68%	78%	57%	37%	40%	60%	34%	38%
21	10	5%	5%	4%	111%	163%	119%	185%	209%	181%	57%	59%	58%	40%	48%	30%	30%	50%	48%	177%	201%	129%
22	8	11%	19%	29%	84%	92%	79%	133%	145%	113%	121%	124%	122%	59%	70%	57%	100%	113%	56%	118%	133%	97%
23	22	6%	9%	12%	100%	105%	104%	114%	120%	112%	124%	124%	123%	71%	67%	49%	65%	56%	31%	78%	82%	68%
24	25	6%	7%	8%	66%	63%	39%	101%	100%	87%	101%	81%	24%	50%	52%	51%	63%	62%	38%	68%	65%	54%
25	6	9%	9%	3%	81%	107%	111%	40%	65%	61%	120%	133%	141%	35%	55%	62%	5%	6%	3%	16%	43%	37%
26	6	6%	10%	5%	82%	52%	19%	48%	48%	49%	116%	71%	20%	64%	79%	62%	22%	7%	4%	37%	35%	27%
27	8	5%	8%	4%	66%	47%	33%	38%	45%	53%	74%	54%	50%	23%	22%	23%	26%	26%	29%	25%	26%	21%
28	5	6%	5%	1%	90%	87%	85%	31%	49%	49%	99%	100%	106%	42%	52%	55%	6%	12%	5%	20%	34%	32%
29	21	15%	12%	16%	73%	53%	79%	49%	56%	84%	95%	85%	100%	58%	56%	76%	76%	72%	26%	40%	45%	56%
Summary of the Coefficient of Variation of the Field Levels in the B Car (Locations 1-12)																						
Minimum		2%	2%	4%	18%	20%	33%	24%	28%	32%	37%	53%	64%	31%	36%	28%	9%	10%	9%	18%	20%	25%
Maximum		9%	11%	16%	135%	126%	149%	279%	273%	251%	160%	155%	177%	106%	117%	131%	208%	137%	105%	260%	247%	216%
Median		5%	4%	7%	80%	75%	90%	77%	73%	83%	88%	96%	104%	71%	75%	72%	37%	38%	23%	61%	61%	60%
Average	17.9	5%	5%	8%	81%	81%	86%	92%	89%	91%	97%	102%	111%	71%	75%	74%	54%	51%	42%	75%	71%	70%
Std. Dev.	11.4	2%	2%	4%	32%	33%	33%	64%	63%	58%	35%	35%	33%	23%	26%	27%	53%	40%	34%	59%	56%	49%
Summary of the Coefficient of Variation of the Field Levels in the S Car (Locations 13-29)																						
Minimum		2%	2%	1%	38%	47%	19%	31%	45%	49%	57%	51%	20%	18%	22%	23%	5%	6%	3%	16%	26%	21%
Maximum		30%	19%	29%	111%	163%	119%	185%	209%	181%	148%	157%	172%	122%	81%	99%	207%	125%	61%	177%	201%	129%
Median		6%	9%	5%	77%	69%	79%	93%	92%	105%	95%	98%	106%	52%	63%	62%	30%	36%	31%	67%	54%	56%
Average	11.4	9%	10%	9%	75%	77%	70%	87%	93%	98%	97%	98%	101%	55%	58%	61%	53%	42%	32%	64%	66%	59%
Std. Dev.	6.0	7%	5%	7%	18%	31%	28%	39%	42%	34%	24%	29%	45%	23%	17%	19%	50%	34%	17%	39%	42%	28%
Summary of the Coefficient of Variation of the Field Levels in Both B and S Cars (Locations 1-29)																						
Minimum		2%	2%	1%	18%	20%	19%	24%	28%	32%	37%	51%	20%	18%	22%	23%	5%	6%	3%	16%	20%	21%
Maximum		30%	19%	29%	135%	163%	149%	279%	273%	251%	160%	157%	177%	122%	117%	131%	208%	137%	105%	260%	247%	216%
Median		6%	6%	6%	77%	74%	79%	81%	78%	88%	94%	97%	104%	58%	67%	63%	30%	36%	30%	63%	60%	57%
Average	14.1	8%	8%	8%	77%	78%	77%	89%	92%	95%	97%	100%	105%	62%	65%	66%	53%	46%	36%	69%	68%	63%
Std. Dev.	9.2	6%	5%	6%	25%	32%	31%	51%	52%	46%	29%	32%	41%	24%	22%	24%	51%	37%	26%	49%	48%	38%

the temporal variability of the static field is modest but the temporal variability of the ELF field is quite high. CV values in Table 6-4 help to quantify the extent of that difference by showing that the average cv of the ELF field at the measurement sites in the train is tenfold larger than the average cv for the static field.

It is interesting to note that while average ELF field values differed between cars and with height above the floor, the amount of temporal variability in the field as measured by the cv was very similar. However, the amount of temporal variability is very site-specific within both cars depending on the temporal characteristics of the nearby sources.

Median static field levels at waist height are shown in Figure 6-4. While the values differ from location to location, there is no apparent relationship between static field levels and position in the car or proximity to electric power equipment

Spatial distribution of the ELF field within the rail cars is complex due to the number and complexity of sources. Data from the 29 measurement locations provides a reliable statistical description of the fields which a passenger is likely to encounter, but is not a sufficiently fine distribution of spatial data points to map field contours within the train. Nevertheless, to help visualize the spatial distribution of field levels relative to key pieces of equipment, Figures 6-5 through 6-11 have been prepared to place measured median field levels at spatially appropriate locations on sketches of the commuter rail cars.

Median waist-level ELF magnetic field levels are shown in Figure 6-5. In the S car, there is a clear tendency for higher field levels near the center of the car and above the major under-floor traction power equipment (see Figure 6-2). ELF field levels in the B car are generally less than in the S car consistent with less under-floor electric power equipment.

Figures 6-6 through 6-10 show similar pictorials of the median field distributions in smaller portions of the ELF band.

6.3.3 Frequency Characteristics

Figure 6-3 shows graphs of magnetic field strength as a function of frequency and time at two locations in the Arrow-3 cars. Full spectral data are available from the EMF Rapid Database (EMF Database Reference). Although Figure 6-3 shows only a minute portion of the spectral data obtained in these commuter rail cars, it is sufficient to demonstrate the range frequency characteristics encountered.

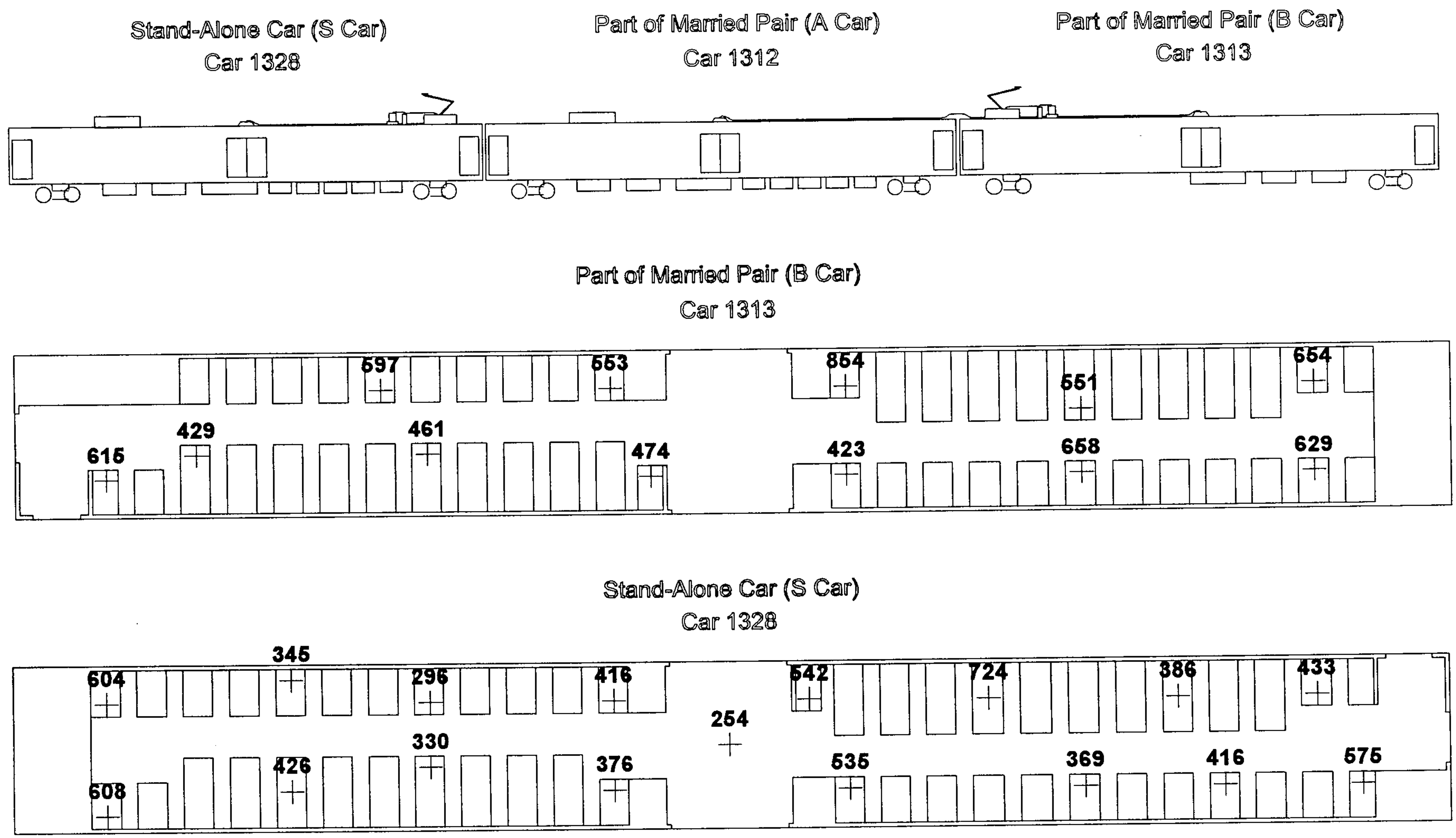


Figure 6-4 Median Static Magnetic Field Levels in Milligauss (mG) Measured at Waist Height at Various Locations in the Arrow-3 Commuter Rail Cars.

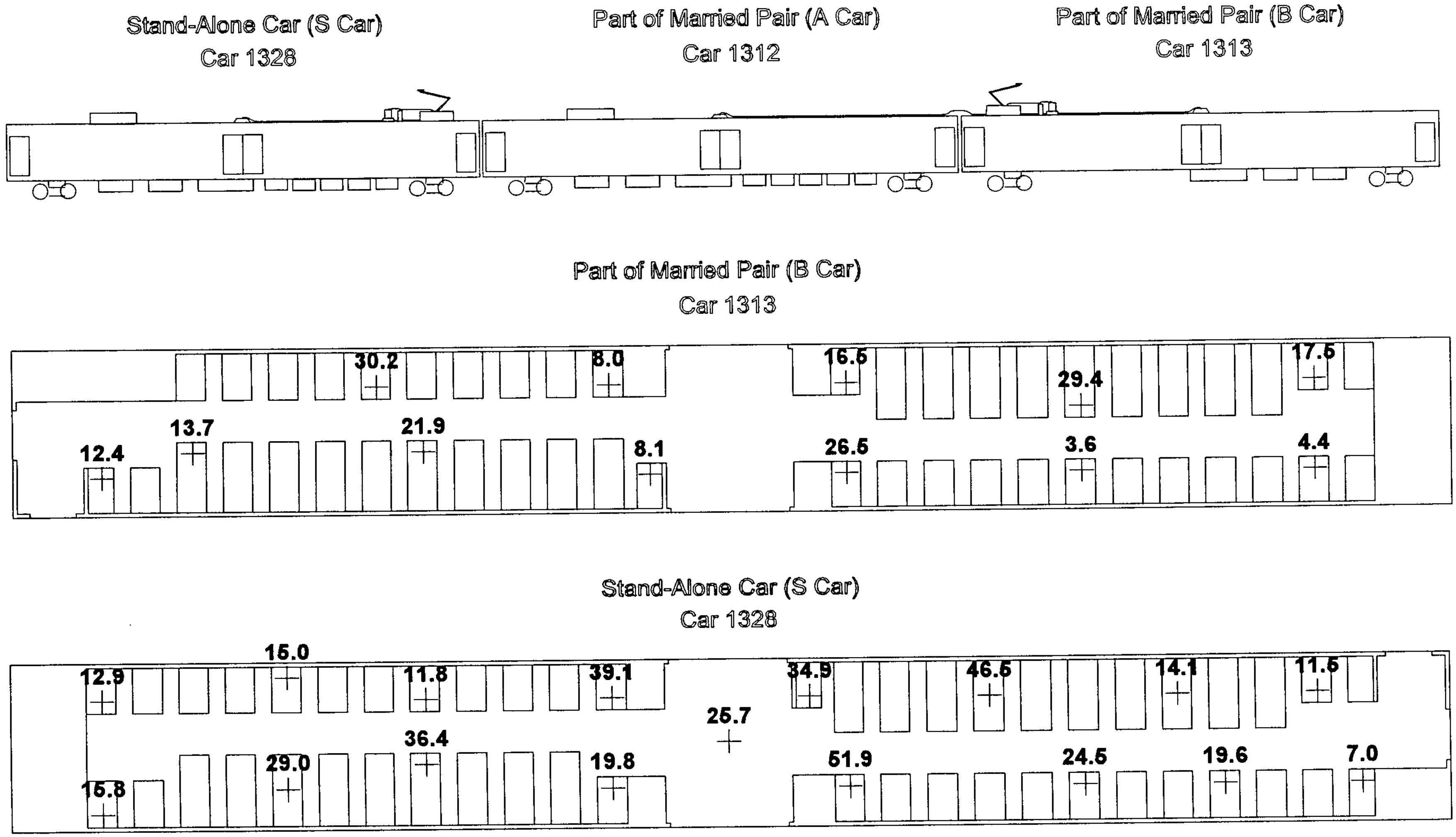


Figure 6-5 Median ELF Magnetic Field Levels in Milligauss (mG) Measured at Waist Height at Various Locations in the Arrow-3 Rail Commuter Cars.

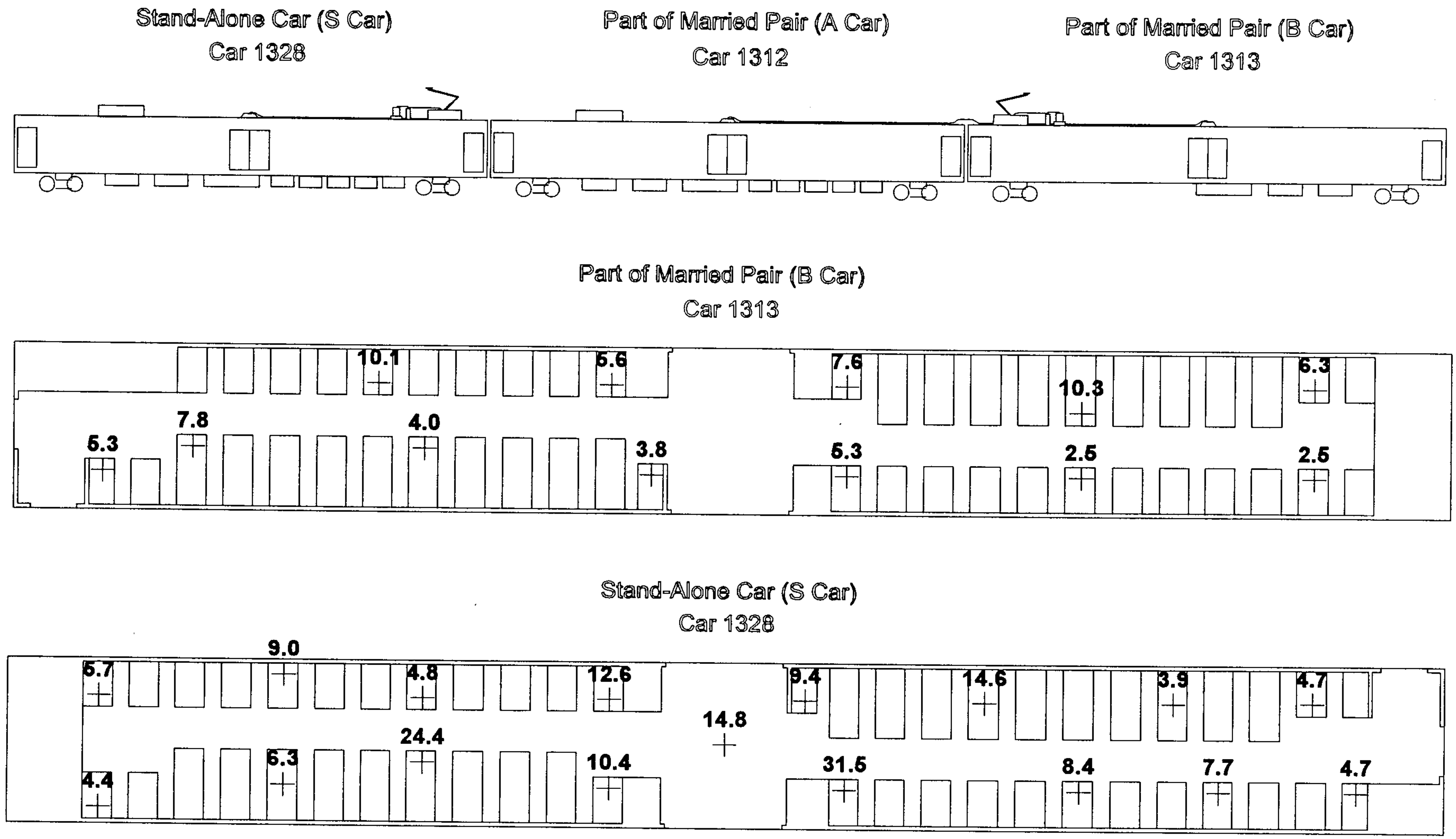


Figure 6-6 **Median Low Frequency ELF (3-57 Hz) Magnetic Field Levels in Milligauss (mG) Measured at Waist Height at Various Locations in the Arrow-3 Rail Commuter Cars.**

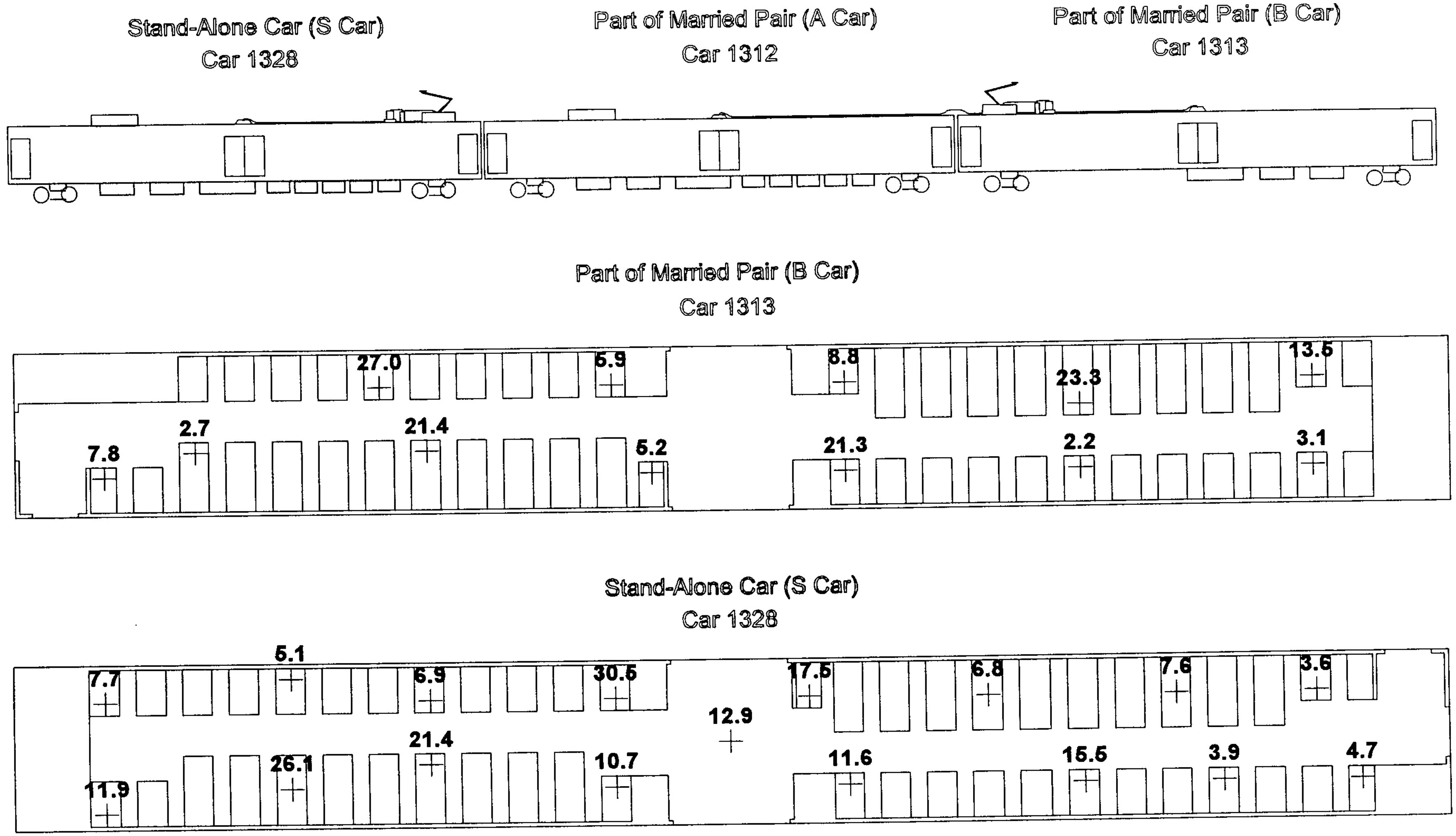


Figure 6-7 **Median Power Frequency (60 Hz) Magnetic Field Levels in Milligauss (mG) Measured at Waist Height at Various Locations in the Arrow-3 Rail Commuter Cars.**

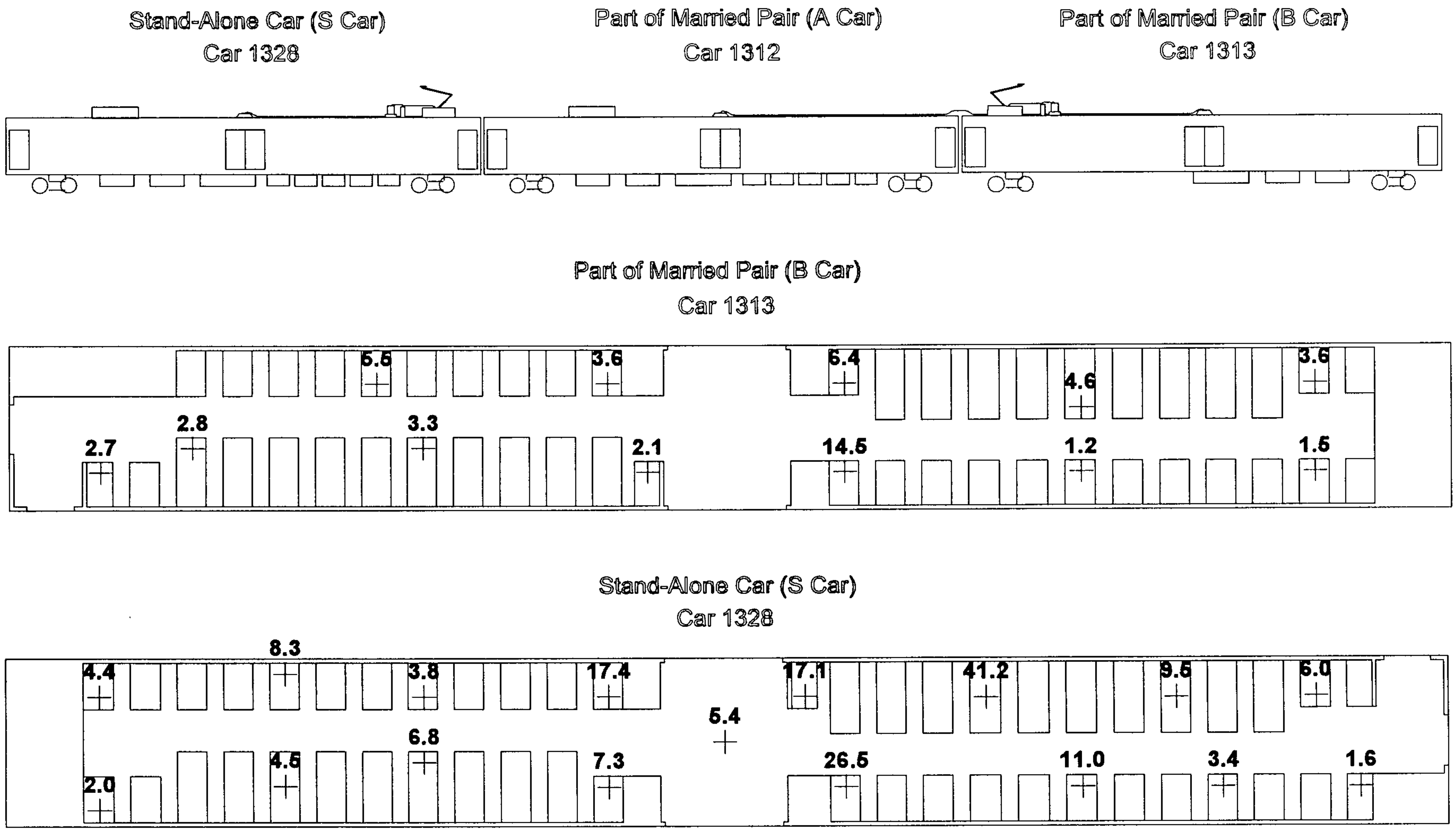


Figure 6-8 Median Levels of ELF Magnetic Field in the Power Harmonic Frequency Range (63-300 Hz) in Milligauss (mG) Measured at Waist Height at Various Locations in the Arrow-3 Rail Commuter Cars.

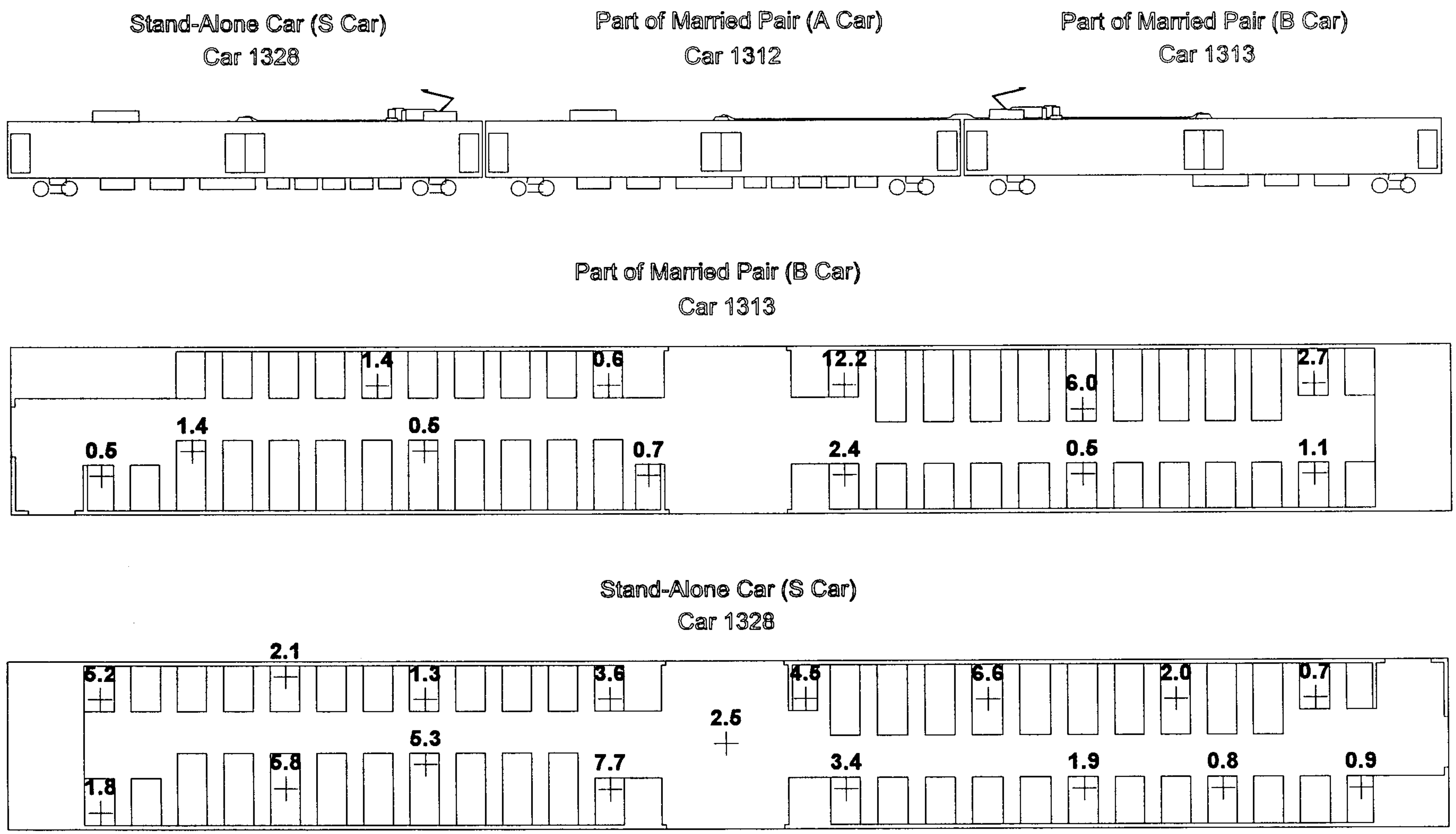


Figure 6-9 Median High Frequency ELF (303-3000 Hz) Magnetic Field Levels in Milligauss (mG) Measured at Waist Height at Various Locations in the Arrow-3 Rail Commuter Cars.

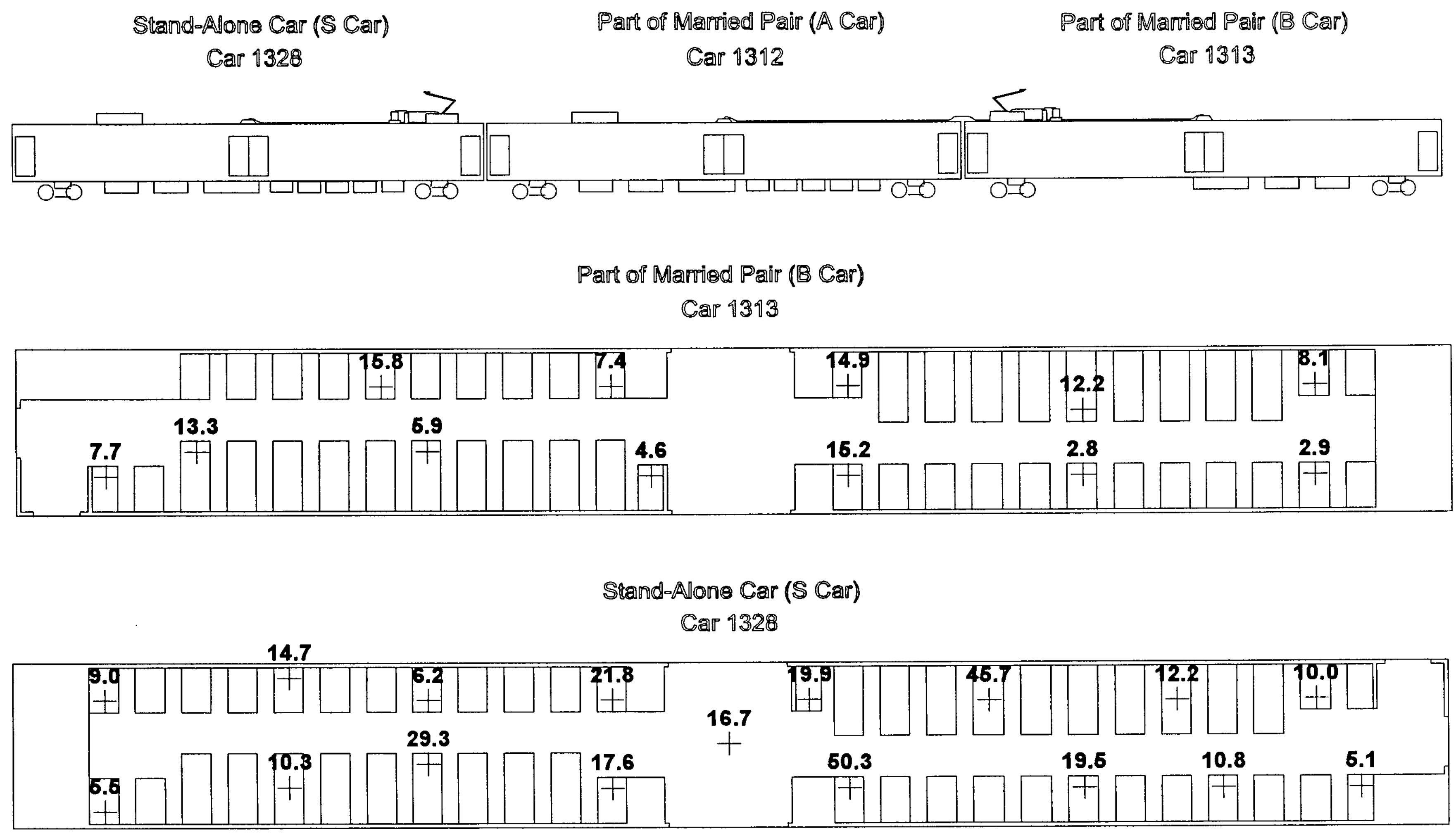


Figure 6-10 Median Non-Power-Frequency ELF (3 Hz - 3 kHz, Excluding 60 Hz) Magnetic Field Levels in Milligauss (mG) Measured at Waist Height at Various Locations in the Arrow-3 Rail Commuter Cars.

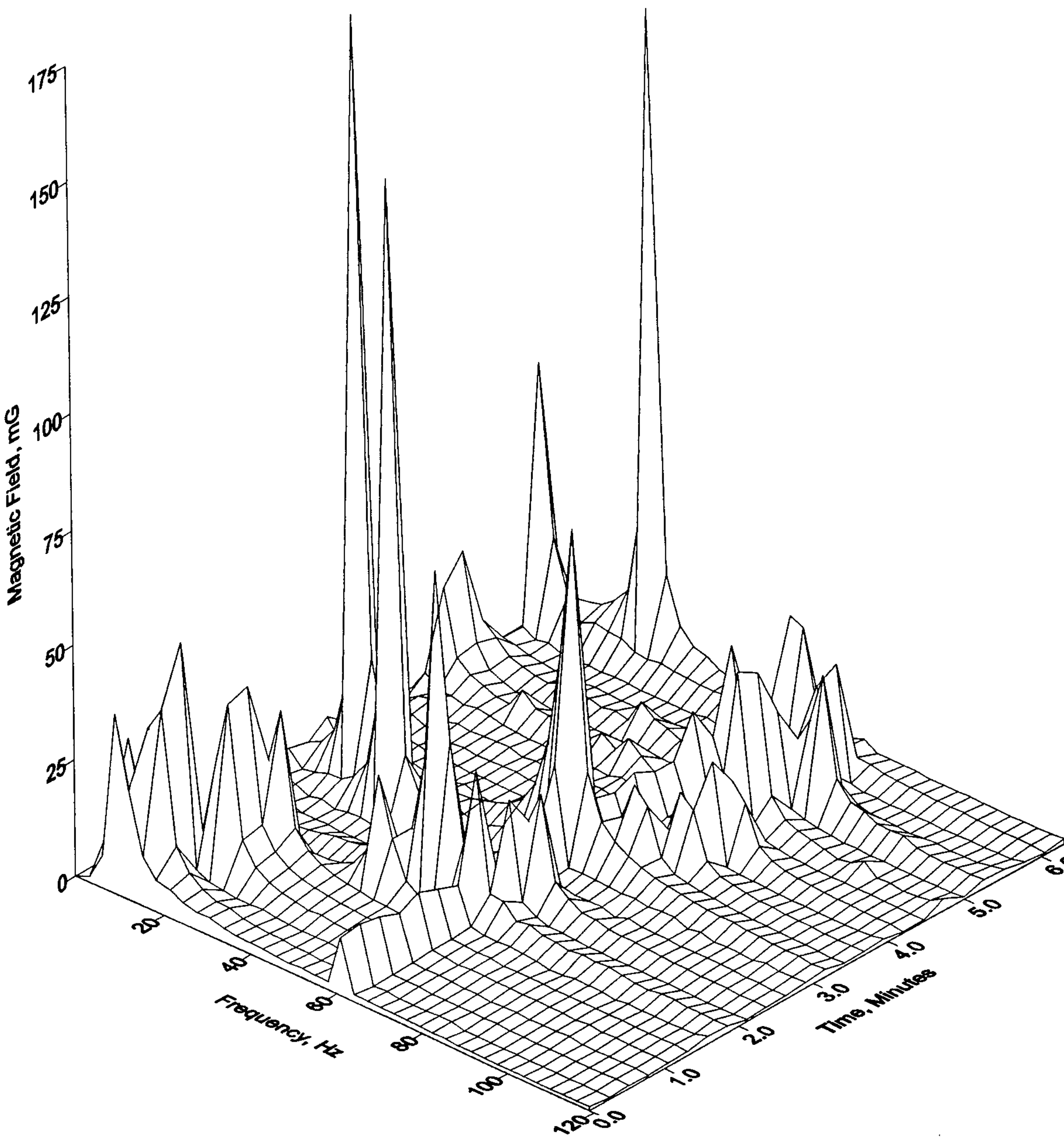


Figure 6-11 Magnetic Field Level as a Function of Frequency and Time at Waist Level at Location 24 in the Commuter Train. The Static (0 Hz) Field is Suppressed.

The top frame of Figure 6-3 shows data collected at waist height at location 10 in the B car. There is no significant equipment beneath the floor of the car at that location (refer to Figures 6-1 and 6-2). At this location, the principal ELF field component is at the 60 Hz power frequency. ELF fields at other frequencies are small as indicated in Tables 6-1 and 6-2 and Figure 6-6 and Figures 6-8 to 6-10. Since there is a strong negative gradient in field level with increasing height above the floor, the predominant source seems to be beneath the floor: probably the secondary power cables running from the main power transformer in the center of the car to the adjacent A car to help provide traction power needs of the married pair of cars. Current in the catenary and track circuit is probably an important secondary source which has the same predominantly 60 Hz with odd harmonic frequency spectrum observed at Location 10.

Magnetic fields at waist height at Location 24 (lower frame of Figure 6-3) have a very complex frequency spectrum which vividly contrasts that of the upper frame. The 60 Hz power frequency is no longer the dominant component. A strong second harmonic (120 Hz) component and weaker fourth harmonic component (240 Hz) are now present as a result of the traction power rectification process accomplished in cabinets beneath the car floor near this location (see Figures 6-1 and 6-2).

Magnetic field components are also seen from time-to-time at 200 Hz and harmonics thereof (400, 600 and 800 Hz). While the source of those fields is uncertain, their occurrence at times when the 120 Hz field is small suggests that they are associated with the dynamic braking which involves the power electronics in the boxes beneath the floor of the car just beyond the power rectifiers. Finally, there is considerable complexity in the field at frequencies less than 100 Hz which are not apparent in Figure 6-3 so the lower frequency portion of the graph is expanded and replotted in Figure 6-11. In that expanded graph, the fields from the variable frequency electric power generated to power the vehicle are clearly evident ranging from 9 Hz in the first sample (time zero on the graph) when the train was just beginning to gain speed to about 85 Hz when the train was at higher speed between 4 and 5 minutes. The high field levels (greater than 75 mG) with successively decreasing frequencies around 2.5 minutes and at the end of the sample appear associated with dynamic braking. They are correlated in time with the 200 Hz field mentioned above and occur just as the train is stopping for a station in the middle of the sample and another at the end of the sample.

Magnetic fields at other locations in the train have different frequency spectra but are for the most part different combinations of the frequency components discussed above depending on proximity to various sources. Tables 6-1 through 6-4 show field levels in various portions of the ELF band at each measurement location thereby providing an indication of the frequencies present, at least in a general way. Similarly, Figures 6-6 through 6-10 show the distribution of magnetic fields within the train for specific portions of the ELF band allowing the reader to visualize spatial patterns of magnetic fields having similar frequency components.

6.4 Electric Field Characteristics

Electric fields were measurable at a position representing the chest of a passenger seated at positions in the train identified as I-28 in Figure 6-1 or at the chest of a passenger standing at position 29. Examination of the electric field spectra revealed only one measurable frequency component, the 60 Hz power-frequency component, in each of the samples. Consequently, the computer analysis of the electric field waveforms was limited to that specific component to reduce noise and improve the precision of the resulting data.

6.4.1 Temporal Characteristics

Electric fields changed in intensity over time at all of the measurement locations. The extent of the temporal variation was moderate and resulted in a typical coefficient of variation in the repetitive measurement at each location. Those changes showed no repeatable pattern associated with train speed, acceleration or deceleration. Moreover, the temporal patterns differed dramatically from one measurement location to another. Table 6-5 shows the coefficient of variation in repetitive field measurements at each test location. Based on a number of factors described below, it appears as though the electric field arose from the 27.5 kV catenary and a small portion of the external electric field penetrated the otherwise shielded cars through the non-conductive windows. Temporal fluctuations in the measured interior electric fields appears strongly dependant upon the perturbation of the electric field outside the cars which varies dramatically along the route depending on the presence of buildings and tall vegetation adjacent to the tracks.

6.4.2 Spatial Variability

Table 6-5 shows the average, median, and maximum intensity of the chest-height, 60 Hz electric fields measured at each test location as well as summary statistics on all of the measurements in each car or both cars combined. The table also lists coefficients of variation in the data at each measurement location to provide a quantitative indication of the temporal variability in the electric field at that location. While the average 60 Hz electric field in both

Table 6-5
Power Frequency (60 Hz) Electric Field Levels in Volts per meter (V/m) at the Indicated Measurement Locations in the Commuter Train with Variable-Frequency AC Traction Motors

Location in the Train Keyed to Fig. 6-1	Number of Samples	Average Chest Height	Median Chest Height	Maximum Chest Height	Coefficient of Variation Chest Height
1	12	0.9	0.7	1.8	82%
2	12	1.5	1.5	1.8	16%
3	13	1.5	1.5	2.8	41%
4	13	3.7	3.4	6.0	33%
5	48	2.0	2.1	4.4	51%
6	7	6.8	3.0	13.1	69%
7	12	1.7	1.8	2.9	46%
8	30	0.8	0.6	1.9	60%
9	9	1.3	1.0	3.0	54%
10	23	1.0	1.1	1.9	35%
11	10	0.7	0.5	2.5	97%
12	26	0.1	0.1	0.3	48%
13	6	0.2	0.2	0.3	52%
14	11	7.6	6.8	18.2	61%
15	17	4.2	2.3	13.3	100%
16	13	0.9	1.0	1.3	42%
17	11	1.7	1.5	3.1	44%
18	8	2.1	2.3	2.5	13%
19	9	3.3	2.9	6.3	41%
20	8	0.2	0.2	0.3	37%
21	10	0.5	0.4	1.2	64%
22	8	3.7	4.3	4.9	36%
23	22	0.5	0.4	0.9	51%
24	25	5.3	3.5	15.8	86%
25	6	1.4	1.6	1.9	45%
26	6	1.0	1.2	1.4	49%
27	8	11.4	13.6	16.7	47%
28	5	0.2	0.2	0.3	53%
29	21	0.5	0.5	1.0	39%
Summary of Average Field Levels in the B Car (Locations 1-12)					
Minimum		0.1	0.1	0.3	16%
Maximum		6.8	3.4	13.1	97%
Median		1.4	1.3	2.7	50%
Average	17.9	1.8	1.4	3.5	53%
Std. Dev.	11.4	1.7	1.0	3.2	21%
Summary of Average Field Levels in the S Car (Locations 13-29)					
Minimum		0.2	0.2	0.3	13%
Maximum		11.4	13.6	18.2	100%
Median		1.4	1.5	1.9	47%
Average	11.4	2.6	2.5	5.3	51%
Std. Dev.	6.0	3.0	3.3	6.2	19%
Summary of Average Field Levels in Both B and S Cars (Locations 1-29)					
Minimum		0.1	0.1	0.3	13%
Maximum		11.4	13.6	18.2	100%
Median		1.4	1.5	2.5	48%
Average	14.1	2.3	2.1	4.6	51%
Std. Dev.	9.2	2.6	2.6	5.2	20%

cars was 2.3 V/m, the average in the S car was slightly higher (2.6 V/m) than the average in the B car (1.8 V/m). The difference in average 60 Hz electric field levels between the two cars is small compared to the wide spatial variation in each car.

The overhead catenary, pantographs, and other roof-mounted, high-voltage equipment, are obvious potential sources of electric fields because they are energized at a high voltage (27.5 kV) and are not enclosed in shielded metallic enclosures. Furthermore, they operate at fixed potential and frequency regardless of the train operating condition which is consistent with the fixed frequency of the electric field and lack of any apparent correlation between field level and train operating condition. Finally, the waveform of the voltage on the catenary is a well controlled sinusoid with little harmonic distortion as is the waveform of the electric field waveform.

As shown in Table 6-5, the largest electric fields measured in the B and S cars were at locations 6 and 27, respectively. Referring to Figure 6-1, one sees that, in both cases, the measurement location with the highest electric field is at the end of the car opposite the pantograph. Hence, the pantograph and other roof-mounted, high voltage components do not appear to be significant contributors to the electric field.

To test the alternative possibility that the catenary is the principal field source, field levels measured while the train was on the two-track (and hence two pantograph) Morris and Essix line (locations 1-5, 13-15, and 25-28) were compared to measurements while the train was on the single-track Gladstone Branch (locations 6-12 and 16-24). The average electric field in the train while operating on the two-track M&E line was 3.0 V/m compared to 1.9 V/m while it was on the single-track Gladstone Branch. Hence, the catenary seems to be the principal field source.

To examine the assumption that external electric fields penetrate the cars through the non-conductive glass windows, average field levels were compared in window seats to those second or third in from the windows. Average field levels were 2.6 V/m in seats along the windows, 2.4 V/m at the second seat in and 1.2 V/m at the third seat in from the window. Unfortunately, the number of measurements in window and third seats was small, making this analysis uncertain.

Electric field levels tend to be lower in seats against the bulkhead at the front or back of the seating compartments (average 1.3 V/m) than in seats at least one seat away from the bulkhead (average 3.2 V/m). This difference is probably a result of field attenuation by the conductive bulkhead. If the bulkhead seats are removed from the analysis of electric field strength as a function of distance from the window, the relationship becomes stronger. The average electric field at the only non-bulkhead window seat is 7.6 V/m compared to an average of 2.9 V/m at the second seat in (average of 10 seats) and 1.0 V/m at the third seat in from the window (2 seats).

Based on the available evidence, the weak 60 Hz electric fields in the Arrow-3 cars appear to result from penetration through the windows of external electric fields produced by the catenary. The fact that the cars are self-powered does not appear to add to those electric fields.

6.4.3 Frequency Characteristics

The only electric fields detected within the Arrow-3 cars were at the 60 Hz power frequency. No fields were detectable at harmonics of 60 catenary power frequency nor any of the other frequencies generated by the on-board electric traction power equipment.

7.0 AIRCRAFT

To gauge levels of EMF in a commercial domestic air carrier common jet, electric and magnetic field measurements were made in a McDonnel-Douglas DC-9 Jetliner while taxiing. This chapter describes those measurements, the characteristics of the fields observed, and the apparent field sources.

7.1 Aircraft Characteristics

The aircraft tested was a McDonnel-Douglas DC-9 Series 31 Jetliner which is currently part of the active fleet of several U.S. commercial domestic air carriers. The aircraft is configured with 12 seats in the first class forward cabin and 80 seats in the coach cabin as illustrated in Figure 7-1. Two lavatories are located at the rear of the coach cabin. The galley is in front of the first class cabin opposite the cabin door. The galley is equipped with electric coffee makers along the forward bulkhead against the cockpit; well removed from the passenger seating area.

The DC-9 is equipped with two engines attached on either side of the fuselage at the rear of the aircraft. Generators on the engines produce 400 Hz ac electric power for the aircraft while the engines are in operation. Electric power is carried from the rear of the aircraft to the forward cockpit area via cables beneath the cabin floor.

The first class and coach cabins are illuminated using indirect lighting from luminaries in the bulkheads. Individual reading lights are located above each seat in the underside of overhead storage compartments. Wiring to these light fixtures is in the base of the overhead storage compartments.

Heated or air conditioned air is dispensed above each seat but there are no electrically-powered components of the ventilation system near the passenger seating areas. Heat and air conditioning are derived from the engines directly or through mechanical means and ducted throughout the aircraft.

7.2 Test Conditions

Because neither the propulsion nor control of the aircraft rely extensively on electric power, the electric and magnetic field measurements reported below were conducted in the aircraft as it taxied on the ground. All electrical systems in the vicinity of the passenger cabins were operated as they would be operated during an actual flight. Half of the individual reading lights (alternate rows) were on representing a "typical" usage level as reported by airline personnel.

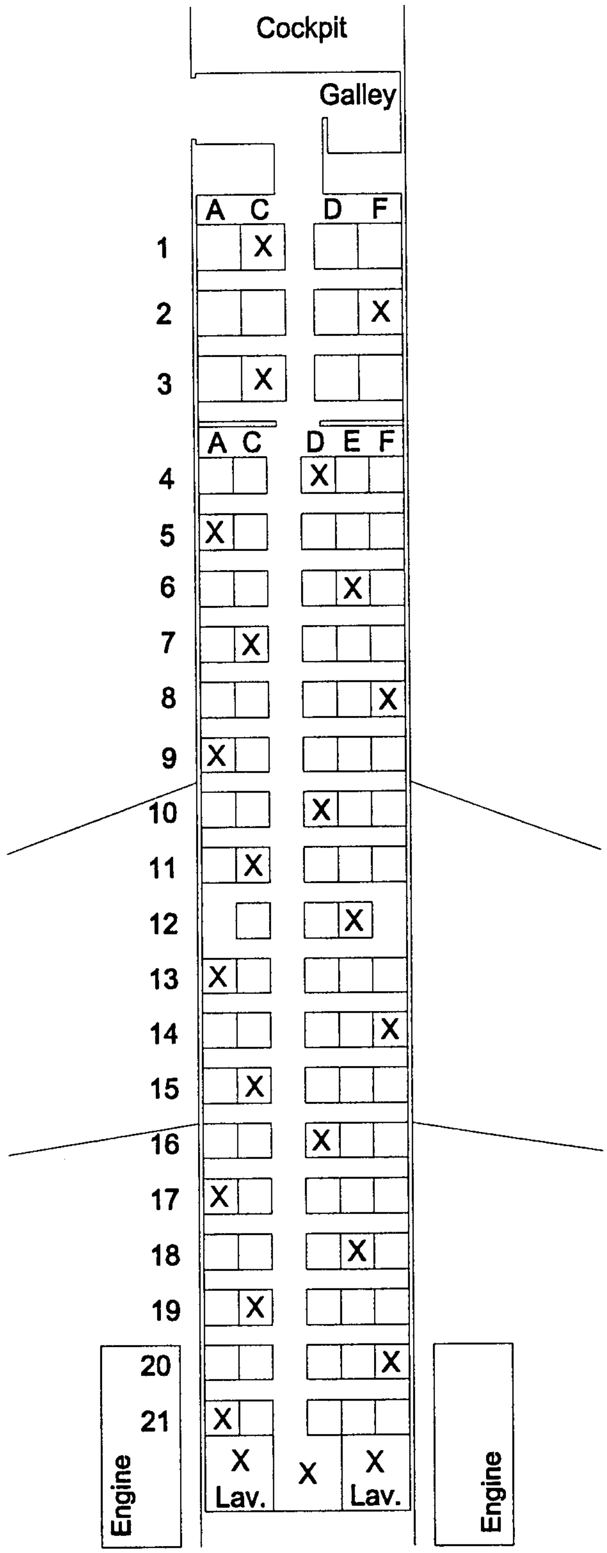


Figure 7-1 Seat Arrangement in the DC-9 Jetliner with Measurement Locations Marked with an "X".

Field conditions were measured at the 24 locations indicated by an "x" on Figure 7-1. Duplicate three-axis magnetic field waveforms were recorded at locations representing the head, waist, and ankle of seated passengers in one seat of each row and in the two lavatories. Similar measurements were made at locations representing the head, waist, and ankle of a standing passenger in the aisle between the lavatories. Duplicate single-axis electric field waveform measurements were made at locations representing the passenger's chest (measurement axis normal to the chest) at each location where magnetic field measurements were conducted.

Long-term magnetic field measurements were not made at each measurement location because the fields were not expected to have large temporal variability. To verify the validity of that assumption, repetitive three-axis magnetic field waveform measurements were made at one location every 15 seconds throughout the period of time when measurements were being made in the other locations.

7.3 Magnetic Field Characteristics

7.3.1 Temporal Variability

Long-term magnetic field measurements were made for fifteen minutes at a fixed location in the first row of the coach cabin. During this time, the aircraft taxied, turned and held in position. The sensor was fixed at a position representing the approximate waist of a passenger seated in Seat 4C (see Figure 7-1 for seat numbering on this aircraft). Measured resultant field levels are shown graphically as a function of frequency and time on Figure 7-2. The static field component had only small variability (574 mG ± 3.2 mG standard deviation) and is not plotted to better show the characteristics of the ELF field components.

The data in Figure 7-2 reveal that the principal frequency component of the ELF magnetic field is 400 Hz, the oscillatory frequency of the ac electric power used in aircraft. Additional ELF field components are present at 800, 1200, 2400, and 2800 Hz, the second through seventh harmonics of the aircraft power frequency respectively.

The intensity and spectral distribution of the ELF magnetic field are moderately stable over time (4.8 mG, 0.6 mG standard deviation). Even harmonics, although small, tend to have slightly less temporal variability than the fundamental. On the other hand, the odd harmonics, principally the third and fifth, appear more temporally variable. Variations in all field components appear to arise from moment-to-moment fluctuations in power consumption with no identifiable correlation with aircraft maneuver or operation.

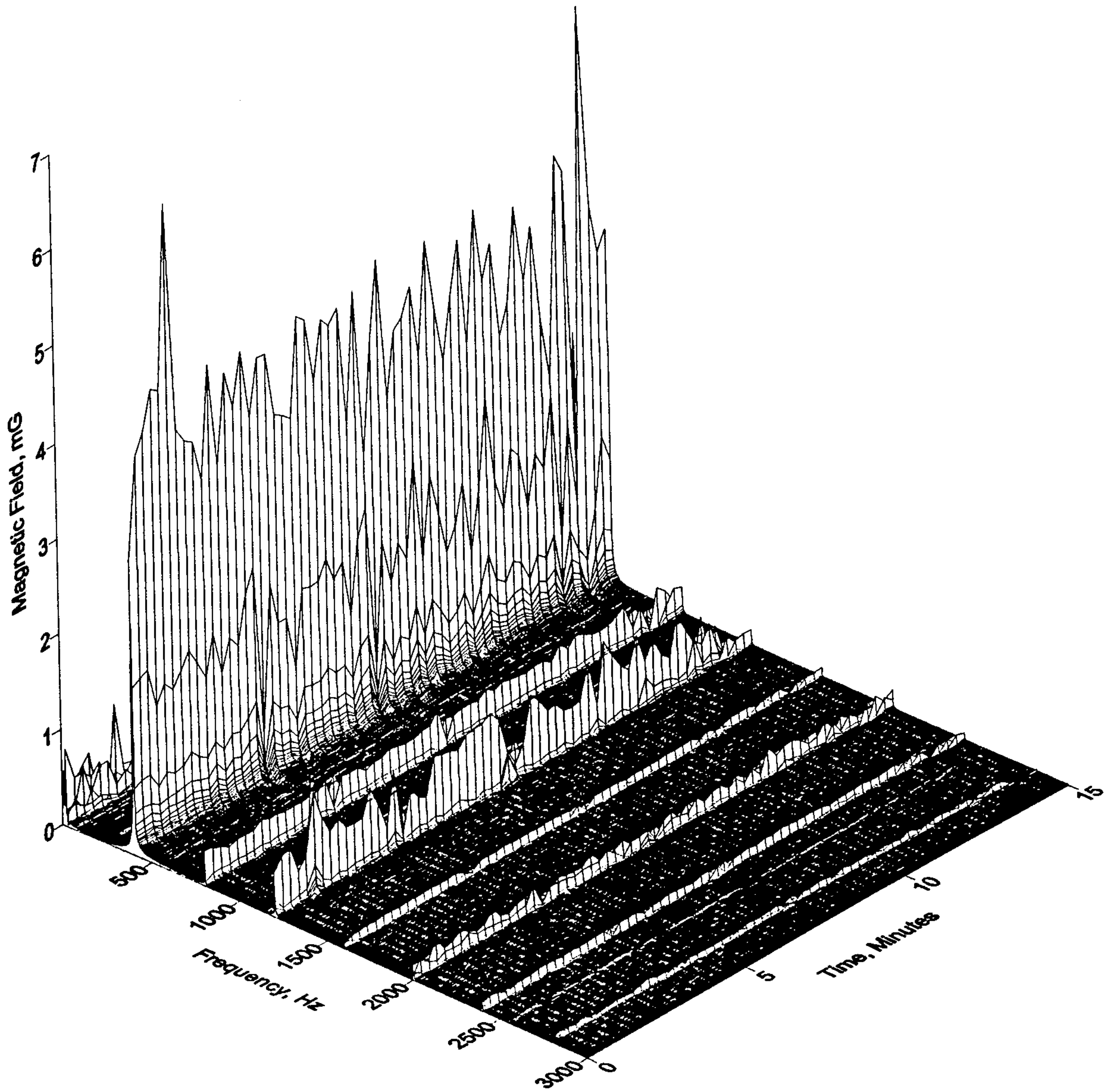


Figure 7-2 **Plot of Magnetic Field Strength as a Function of Frequency and Time at the Waist of a Passenger Seated in Seat 4C. The Static Field (0 Hz) is Not Plotted.**

7.3.2 Spatial Variability

Duplicate magnetic field measurements were made at the location of the head, waist, and ankle of a passenger in the 24 locations indicated with a heavy "x" on Figure 7-1. These measurements were made during the time period spanned by the continuous measurements reported in Section 7.3.1 above. The consistency of the 24 pairs of duplicate measurements was less than expected based on the variability observed in the long-term measurements. This high level of consistency was probably due to the short period of time between the duplicate measurements; typically 4 seconds. The lack of discordance leads us to believe that all of the measurements are valid so the duplicate measurements were averaged to determine the field condition at each measurement location.

The results of the spatial measurements are reported in Table 7-1. Data are given for static field intensity, total ELF field intensity, and the intensity of the magnetic field within various frequency ranges. The degree of total harmonic distortion is also tabulated to provide an indication of magnitude of the combined 800, 1200, 1600, 2000, 2400, and 2800 Hz field components relative to the 400 Hz fundamental. In addition to data for each measurement location, summary data are computed for the first class cabin, and the aircraft as a whole.

Static magnetic field levels are essentially uniform throughout the aircraft cabin. They appear to be the normal geomagnetic field with minimal perturbation (due to the limited use of iron in aircraft construction). There is no evidence that the aircraft circuitry produces static magnetic fields.

The ELF magnetic field is produced almost entirely by the aircraft. The most predominant ambient ELF magnetic field component in North America is 60 Hz and it is essentially absent at all locations. The ELF magnetic field has large spatial variability. To better visualize that spatial variability, the resultant ELF field levels are printed above their measurement location on Figure 7-3. From that figure and Table 7-1, it is evident that the field is much larger at the ankle position of passengers seated in seats along the left side of the aircraft ("A" seats) and in the left lavatory than elsewhere in the cabin. The main power cable from the rear of the aircraft to the cockpit is apparently routed beneath the floor near that location.

On the right side of the aircraft away from the power cable, the magnetic field is consistently larger at head level than at floor level. This suggests that the wiring for lighting and other services routed in the base of the overhead

Table 7-1
Magnetic Field Levels in Milligauss (mG) at the Indicated Measurement Locations in the Commercial Airliner (Means of Duplicate Samples)

Seat Number or Location	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz			Aircraft Power Frequency 400 Hz			Non-400 Hz ELF 3 Hz to 3 kHz except 400 Hz			Total Harmonic Distortion of the 400 Hz Field		
	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle	Head	Waist	Ankle
1C	561	669	508	4.9	6.0	16.7	0.3	0.4	1.0	0.0	0.0	0.1	0.3	0.3	0.6	4.9	6.0	16.7	4.2	5.7	16.0	2.2	1.9	4.8	70%	36%	28%
2F	544	576	457	11.6	4.2	3.3	0.2	0.2	0.3	0.0	0.0	0.0	0.4	0.2	0.1	11.6	4.2	3.3	11.4	4.1	3.2	2.3	0.8	0.7	17%	15%	15%
3C	551	550	501	2.3	2.8	9.7	0.2	0.2	0.5	0.0	0.0	0.0	0.1	0.1	0.4	2.2	2.8	9.6	2.1	2.7	9.5	0.8	0.6	1.9	38%	19%	17%
4D	544	547	526	4.8	3.1	3.4	0.5	0.4	0.7	0.0	0.0	0.0	0.2	0.1	0.1	4.7	3.0	3.4	4.5	3.0	3.3	1.6	0.6	0.8	34%	16%	11%
5A	556	565	566	3.3	7.0	164.0	0.5	0.6	3.1	0.0	0.0	0.3	0.1	0.2	3.6	3.2	7.0	163.9	3.0	6.9	162.9	1.2	1.4	19.2	34%	17%	10%
6E	557	530	552	3.7	2.2	1.9	0.4	0.3	0.4	0.0	0.0	0.0	0.2	0.1	0.1	3.7	2.2	1.8	3.4	2.1	1.8	1.5	0.7	0.6	43%	29%	22%
7C	563	546	540	2.4	3.5	5.9	0.7	0.6	1.3	0.0	0.0	0.0	0.1	0.1	0.3	2.3	3.5	5.7	2.0	3.4	5.7	1.3	0.8	1.6	55%	13%	14%
8F	550	548	548	4.3	1.5	1.1	0.3	0.3	0.6	0.0	0.0	0.0	0.2	0.1	0.1	4.3	1.5	0.9	4.0	1.4	0.9	1.6	0.6	0.6	40%	38%	32%
9A	559	547	574	4.1	7.0	147.6	0.3	0.6	3.5	0.0	0.0	0.5	0.2	0.3	6.1	4.1	7.0	147.4	3.8	6.9	146.7	1.6	1.2	15.8	42%	13%	7%
10D	558	530	594	5.0	2.3	2.0	0.2	0.2	0.4	0.0	0.0	0.0	0.2	0.1	0.1	5.0	2.3	2.0	4.6	2.2	1.9	2.0	0.6	0.6	42%	23%	19%
11C	569	545	554	3.2	1.9	7.8	0.2	0.3	0.5	0.0	0.0	0.0	0.1	0.1	0.3	3.2	1.9	7.7	1.6	1.7	7.5	2.8	0.9	1.9	179%	49%	23%
12E	571	550	551	3.1	1.2	1.0	0.2	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.1	3.1	1.2	0.9	2.1	1.1	0.9	2.2	0.6	0.4	103%	57%	43%
13A	566	595	461	4.2	4.5	57.2	0.2	0.4	1.8	0.0	0.0	0.2	0.2	0.2	2.2	4.2	4.4	57.1	3.7	4.4	56.7	2.0	0.8	7.3	54%	16%	9%
14F	572	575	651	1.6	0.8	0.6	0.2	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	1.6	0.8	0.6	1.1	0.7	0.5	1.1	0.3	0.3	109%	45%	51%
15C	578	556	555	2.7	3.6	10.8	0.3	0.3	0.5	0.0	0.0	0.0	0.1	0.2	0.4	2.6	3.6	10.8	2.0	3.5	10.6	1.8	1.0	1.8	89%	26%	14%
16D	556	553	562	1.9	1.0	1.1	0.3	0.2	0.4	0.0	0.0	0.0	0.2	0.1	0.1	1.9	1.0	1.0	1.0	0.8	0.9	1.6	0.6	0.6	149%	66%	44%
17A	566	543	565	4.3	11.8	212.5	0.3	0.5	3.5	0.0	0.0	0.6	0.2	0.4	8.1	4.3	11.8	212.4	4.2	11.7	211.2	1.0	1.6	23.9	22%	10%	7%
18E	565	531	555	3.0	1.2	1.3	0.2	0.2	0.6	0.0	0.0	0.0	0.2	0.1	0.1	3.0	1.2	1.1	2.5	1.1	1.1	1.5	0.6	0.7	59%	50%	30%
19C	578	566	572	2.4	3.6	6.4	0.3	0.3	0.6	0.0	0.0	0.0	0.1	0.1	0.3	2.4	3.5	6.4	1.7	3.4	6.3	1.7	0.9	1.5	133%	27%	21%
20F	539	505	543	7.1	1.7	0.8	0.3	0.2	0.2	0.0	0.0	0.0	0.3	0.1	0.1	7.1	1.6	0.8	6.8	1.5	0.7	1.8	0.6	0.4	25%	35%	47%
21A	578	579	538	7.3	9.8	16.7	0.3	0.6	1.4	0.0	0.0	0.1	0.2	0.3	0.7	7.3	9.8	16.6	6.9	9.6	16.3	2.6	1.7	3.4	36%	15%	17%
Left Lav	535	600	528	7.8	24.2	61.3	0.3	0.7	1.3	0.0	0.1	0.1	0.4	0.9	2.3	7.8	24.2	61.3	6.9	21.6	54.9	3.5	10.8	27.0	51%	50%	49%
Right Lav	534	476	533	4.2	7.4	11.5	0.6	0.6	0.5	0.0	0.0	0.0	0.2	0.2	0.4	4.1	7.4	11.5	3.7	6.9	10.3	2.0	2.7	5.1	54%	38%	49%
Outside Lav	541	530	498	5.4	4.4	11.1	0.6	0.4	0.6	0.0	0.0	0.0	0.4	0.2	0.4	5.3	4.4	11.1	4.7	4.2	10.4	2.7	1.5	3.7	54%	32%	34%
Summary of Magnetic Field Levels in the First Class Cabin (Rows 1-3)																											
Minimum	544	550	457	2.3	2.8	3.3	0.2	0.2	0.3	0.0	0.0	0.0	0.1	0.1	0.1	2.2	2.8	3.3	2.1	2.7	3.2	0.8	0.6	0.7	17%	15%	15%
Maximum	561	669	508	11.6	6.0	16.7	0.3	0.4	1.0	0.0	0.0	0.1	0.4	0.3	0.6	11.6	6.0	16.7	11.4	5.7	16.0	2.3	1.9	4.8	70%	36%	28%
Median	551	576	501	4.9	4.2	9.7	0.2	0.2	0.5	0.0	0.0	0.0	0.3	0.2	0.4	4.9	4.2	9.6	4.2	4.1	9.5	2.2	0.8	1.9	38%	19%	17%
Average	552	598	489	6.3	4.3	9.9	0.2	0.3	0.6	0.0	0.0	0.0	0.3	0.2	0.4	6.2	4.3	9.8	5.9	4.2	9.6	1.8	1.1	2.4	42%	23%	20%
Std. Dev.	7.2	51.1	22.8	3.9	1.3	5.5	0.0	0.1	0.3	0.0	0.0	0.0	0.1	0.1	0.2	3.9	1.3	5.5	4.0	1.2	5.2	0.7	0.6	1.7	22%	9%	6%
Summary of Magnetic Field Levels in the Coach Cabin (Rows 4-21)																											
Minimum	539	505	461	1.6	0.8	0.6	0.2	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	1.6	0.8	0.6	1.0	0.7	0.5	1.0	0.3	0.3	22%	10%	7%
Maximum	578	595	651	7.3	11.8	212.5	0.7	0.6	3.5	0.0	0.0	0.6	0.3	0.4	8.1	7.3	11.8	212.4	6.9	11.7	211.2	2.8	1.7	23.9	179%	66%	51%
Median	564	547	554	3.5	2.7	4.7	0.3	0.3	0.6	0.0	0.0	0.0	0.2	0.1	0.2	3.5	2.7	4.6	3.2	2.6	4.5	1.6	0.8	1.1	49%	27%	20%
Average	563	550	556	3.8	3.8	35.7	0.3	0.3	1.1	0.0	0.0	0.1	0.2	0.1	1.3	3.8	3.7	35.6	3.3	3.6	35.3	1.7	0.9	4.5	69%	30%	23%
Std. Dev.	10.9	20.1	34.9	1.5	3.1	64.5	0.1	0.2	1.1	0.0	0.0	0.2	0.1	0.1	2.3	1.5	3.1	64.4	1.7	3.1	64.1	0.5	0.4	7.1	45%	17%	14%
Summary of Magnetic Field Levels in All Locations (Rows 1-29 and Lavatories)																											
Minimum	534	476	457	1.6	0.8	0.6	0.2	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	1.6	0.8	0.6	1.0	0.7	0.5	0.8	0.3	0.3	17%	10%	7%
Maximum	578	669	651	11.6	24.2	212.5	0.7	0.7	3.5	0.0	0.1	0.6	0.4	0.9	8.1	11.6	24.2	212.4	11.4	21.6	211.2	3.5	10.8	27.0	179%	66%	51%
Median	558	549	549	4.2	3.5	7.1	0.3	0.3	0.6	0.0	0.0	0.0	0.2	0.1	0.3	4.1	3.5	7.1	3.7	3.4	6.9	1.7	0.8	1.7	52%	28%	22%
Average	558	555	543	4.4	4.9	31.5	0.3	0.4	1.0	0.0	0.0	0.1	0.2	0.2	1.1	4.3	4.8	31.4	3.8	4.6	30.8	1.9	1.4	5.2	64%	31%	26%
Std. Dev.	13.2	35.4	39.6	2.2	4.9	57.1	0.1	0.2	1.0	0.0	0.0	0.1	0.1	0.2	2.0	2.2	4.9	57.1	2.3	4.5	56.7	0.6	2.0	7.7	41%	16%	14%

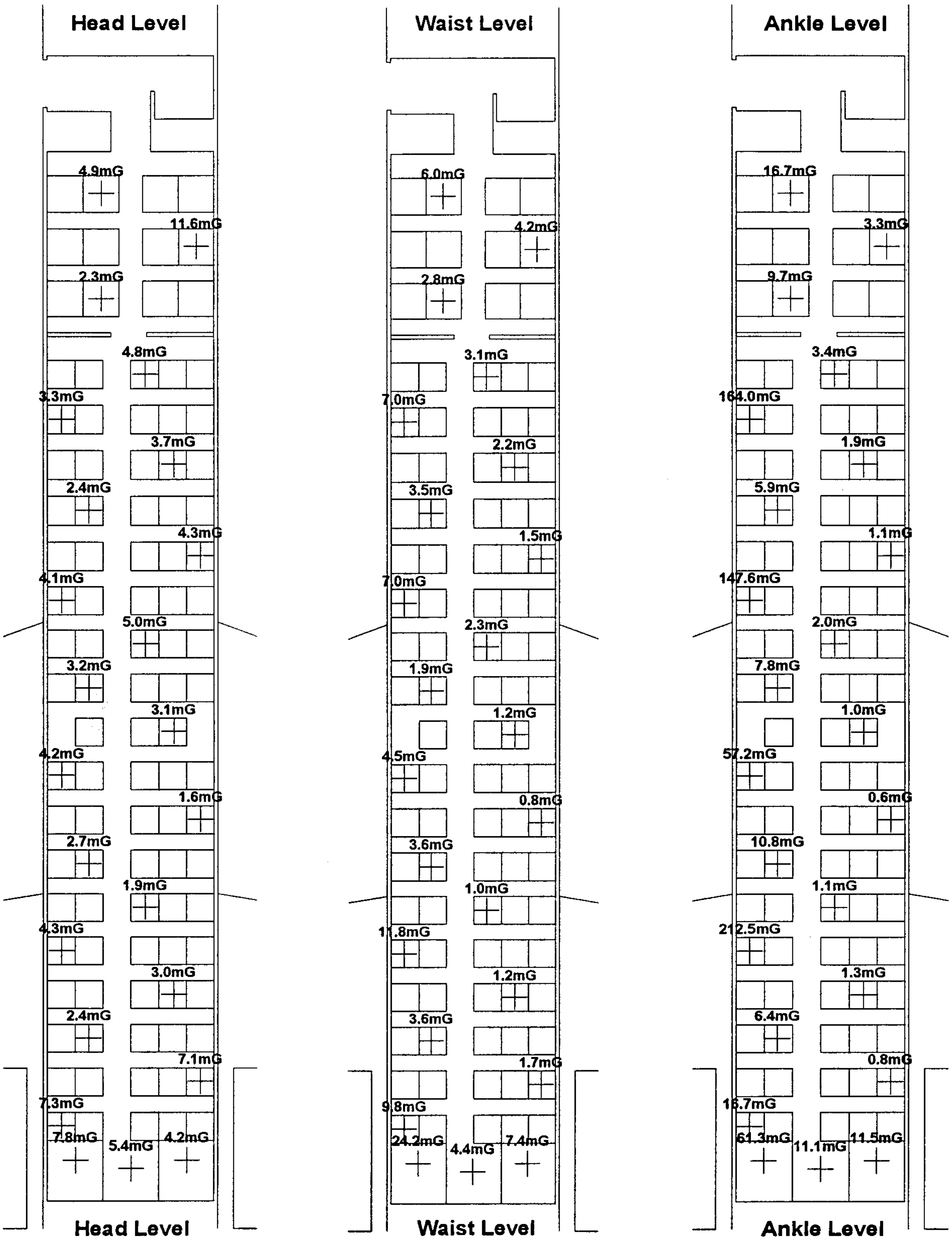


Figure 7-3 Distribution of Measured ELF Magnetic Field Levels at Head, Waist, and Ankle Level (Means of Duplicate Measurements).

storage compartments or the lights themselves represent another important field source.

7.3.3 Frequency Characteristics

As previously mentioned, aircraft magnetic fields are unusual in that the predominant frequency component of the field at most locations within the cabin is the 400 Hz aircraft power frequency. The intensity of that individual frequency component is tabulated on Table 7-1 along with the intensity of the total ELF field. The magnitude of the 400 Hz field is generally within one milligauss of the total ELF field.

The total harmonic distortion data on Table 7-1 is a concise indicator of the intensity of the harmonic frequency components relative to the intensity of the 400 Hz field. On average, the total field of the harmonics is 40% of the 400 Hz magnetic field throughout the aircraft cabin. The harmonic distortion is consistently higher at head level (average of 64%) than at waist or ankle level (31% and 26% respectively) suggesting that the field sources associated with the lights and wiring in the base of the overhead storage compartments are rich in harmonics. At five head-level locations near the center of the aircraft (between Rows 11 and 19), the field of the harmonics exceeded the 400 Hz field. The upper frame of Figure 7-4 shows the magnetic field frequency spectrum at one such location where the 800 Hz field component (second harmonic) is well in excess of the 400 Hz fundamental.

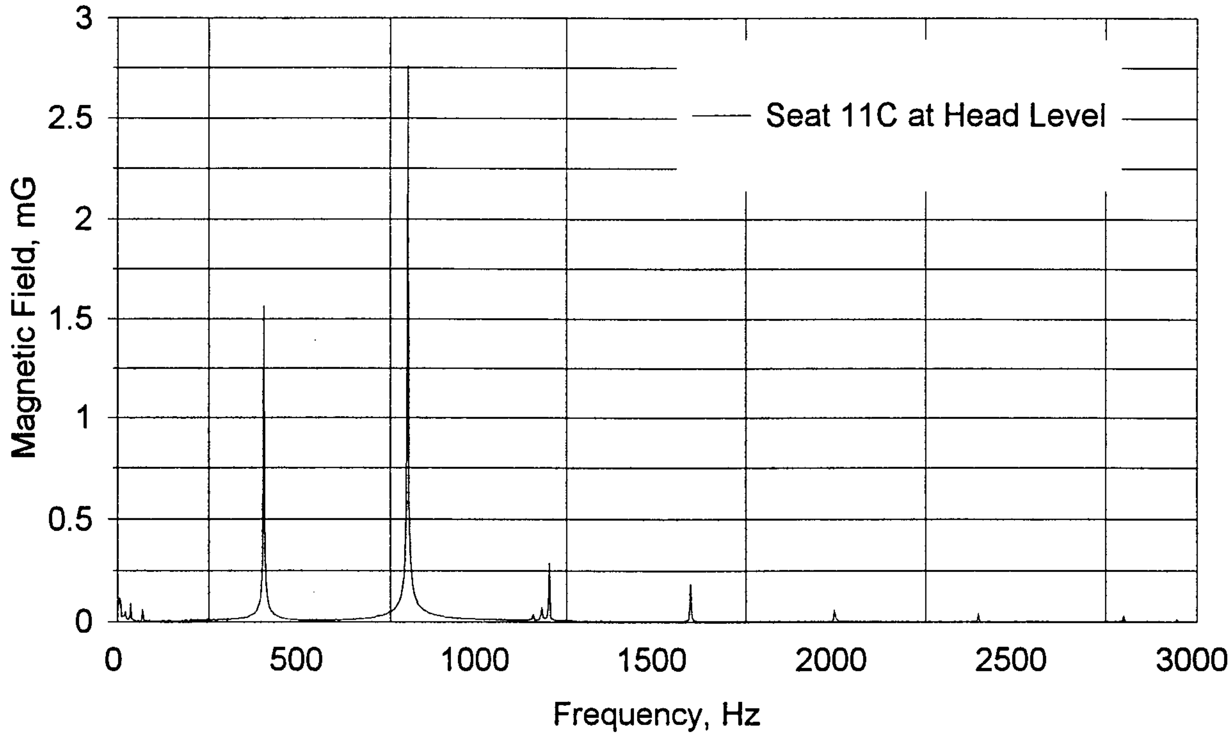
At ankle-level locations on the left side of the aircraft where large fields are produced by the under-floor power cables, the harmonic distortion of the field is very low. An example of the magnetic field frequency spectrum near the floor in front of Seat 9A is shown in the lower frame of Figure 7-4.

7.3.4 Polarization

At most locations throughout the jetliner cabin, the 400 Hz magnetic field has significant elliptical polarization. The average axial ratio of the polarization ellipse (ratio of the semi-minor-axis to the semi-major-axis) is 31%. The elliptical polarization apparently arises from the use of 400 Hz polyphase electric power generation and distribution within the aircraft.

7.4 Electric Field Characteristics

ELF electric fields were measured at positions representing the chest of a passenger at the 24 measurements locations indicated on Figure 7-1. At fourteen locations,



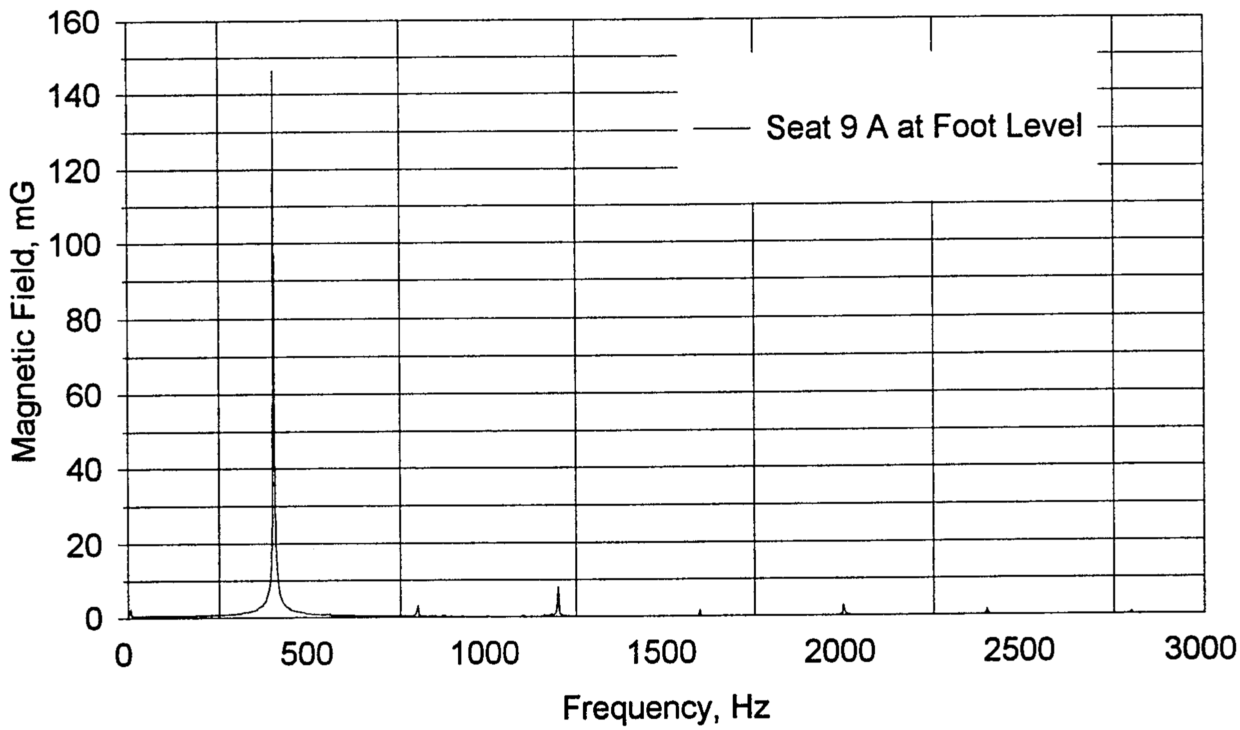


Figure 7-4 **Mean Magnetic Field Frequency Spectra at Locations with High and Low Harmonic Distortion (Head Level in Seat 11C and Ankle Level in Seat 9A Respectively).**

there were no measurable fields above the sensitivity of the instrument (3 V/m). Measurable fields at the remaining ten locations were generally inconsistent with a time-varying electric field observed during one of the duplicate samples but not the other. In the twelve samples with measurable fields, the electric field strength averaged 6.5 V/m and never exceeded 12 V/m. Examination of the electric field waveforms and frequency spectra reveals only field components less than 30 Hz. There was no evidence of electric fields at frequencies associated with the aircraft's electrical system. Based on the electric field waveforms and the inconsistency of replicate samples, it appears as though those very low ELF electric fields resulted from static electric charges on the clothing of the test personnel as they moved about in the vicinity of the measurement site. None of the measurable electric fields appear to come from the aircraft.

8.0 FERRY BOAT

Electric and magnetic field measurements were made in a diesel-powered ferry boat operated by New York Waterways on the Hudson River between Manhattan Island and Hoboken, NJ. This passenger ferry carries commuters between the Hoboken Railroad Station and Lower Manhattan's World Financial Center. Crossing time is less than fifteen minutes.

8.1 Boat Characteristics

The Hoboken ferry boats were double deck diesel-powered boats. Figure 8-1 shows an outline sketch of the lower and upper decks of the boat on which these measurements were made. It differed from most of the other ferry boats in the New York Waterways fleet in that it contained a snack bar and service area in the left rear corner of the boat. Most of the boats have seating on the left side similar to that on the right.

The lower deck of the boat is enclosed and provides both seats and standing areas for passengers. Passenger entry is by doors in the front center and left rear of the cabin. Rows of bench seats or handrails for standing passengers occupy most of the passenger space in the cabin. A rectangular area in the center rear of the cabin is enclosed. That enclosed area which extends above the upper deck presumably encloses mechanical equipment, exhaust stacks, airways and access to the below-deck mechanical areas. A stairway to this upper deck is in the left rear corner of the boat.

The upper deck passenger area is smaller than the lower deck passenger cabin. The forward portion of the upper deck contains the pilot house and is not accessible to passengers. Aside from the enclosed stack in the rear center of the boat, the remainder of the upper deck is available to passengers. The forward section of the upper deck from the pilot house back to the end of the center row of seats is covered by a roof. The remainder of the upper deck is uncovered.

8.2 Test Conditions

The magnetic field measurements reported herein were made while the boat was in passenger service, but, because it was evening, the number of passengers was small. Hence, measurement personnel had no difficulty obtaining access to 50 measurement locations distributed throughout the boat.

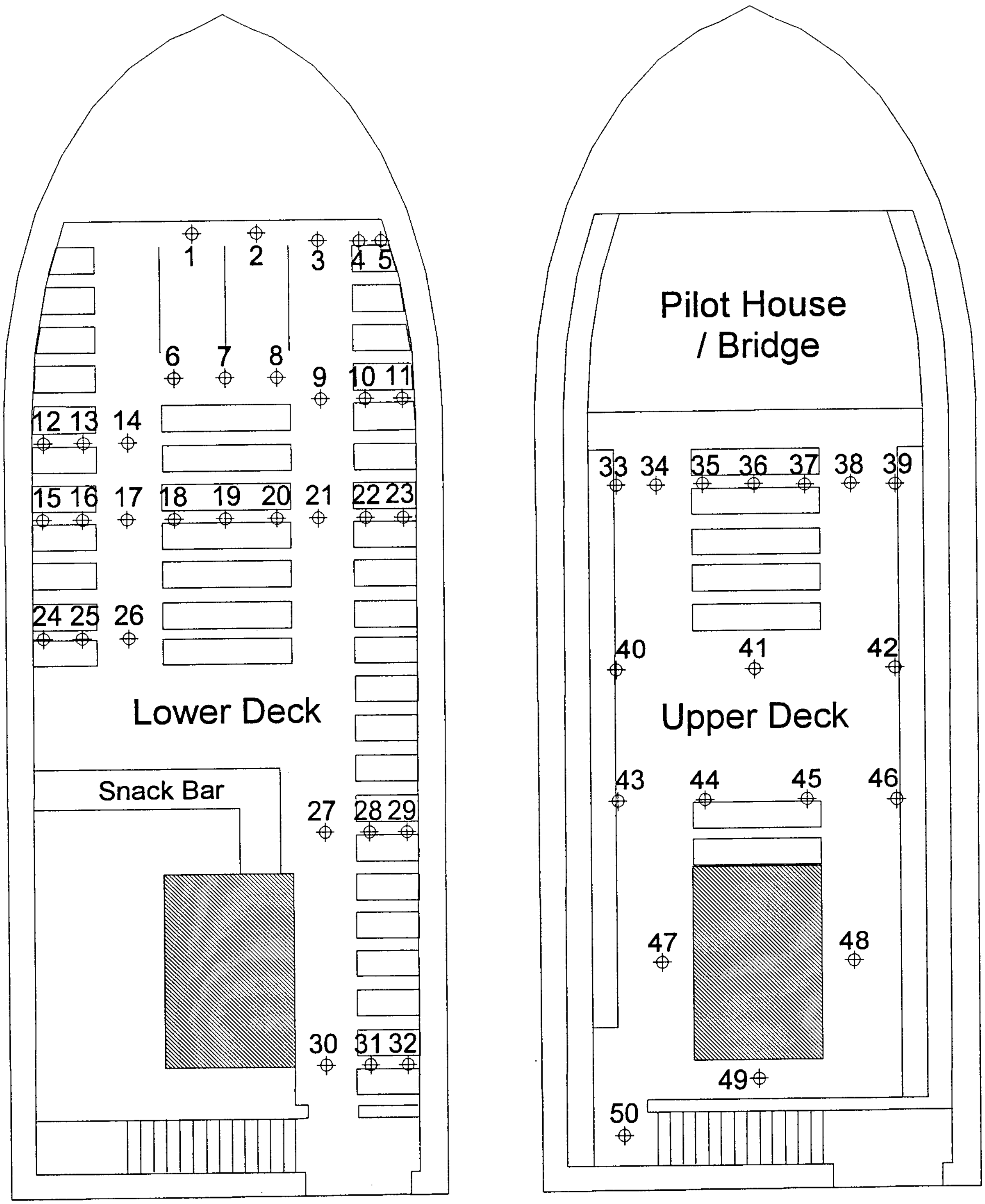


Figure 8-1 Sketch of the Lower and Upper Decks of the Ferry Boat Showing Locations Where Magnetic Field Measurements Were Made.

Three-axis magnetic field waveform measurements were made at heights of 1 foot, 3 feet, and 5 feet above the deck at the 50 locations identified in Figure 8-1. All of the measurements were made while the boat was clear of the docks and underway crossing the river. Three crossings were required to complete the measurements. Only single measurements were made at each location because significant temporal variability was not anticipated when the boat was underway. Overhead lights were on in the lower deck cabin and in the covered portion of the upper deck, but the snack bar was closed and none of the food service appliances were operating except for refrigeration equipment.

8.3 Magnetic Field Characteristics

8.3.1 Temporal Variability

As mentioned in the preceding section, no significant temporal variability was anticipated in the magnetic field characteristics of the ferry boat while operating in open water. No attempt was made to assess temporal variability while approaching and leaving the docks because of likely confounding by magnetic field sources on shore which are not inherent parts of the transportation system.

Although no repeated measurements were made at a fixed location to assess the validity of the assumption that fields are temporally stable, many of the measurements were in close proximity to one another (e.g. Locations 15 to 23 on the lower deck and 33-39 on the upper deck). The consistency of nearby measurements was examined for variability not attributable to position relative to possible field sources. Such variability would be indicative of temporal instability of fields. Excessive variability was not found. Hence, the assumption that the magnetic fields on the ferry boat are stable over time appears valid.

8.3.2 Spatial Variability

Three-axis magnetic field waveform measurements were made at 1 foot, 3 feet, and 5 feet above the deck of the ferry boat at the 50 locations indicated on Figure 8-1 while the boat was crossing the Hudson River. One additional measurement was made at the same heights above the ground at the dock on the Manhattan side of the river while the ferry was not present. The results of the measurements are summarized by frequency band in Table 8-1. Full spectral data are available from the RAPID EMF data base [5].

Table 8-1
Magnetic Field Levels in Milligauss (mG) at Various Heights Above the Deck
at the Indicated Measurement Locations on the Ferry Boat

Location in Boat Keyed to Fig. 8-1	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz			Total Harmonic Distortion of the 60 Hz Field		
	5 ft	3 ft	1 ft	5 ft	3 ft	1 ft	5 ft	3 ft	1 ft	5 ft	3 ft	1 ft	5 ft	3 ft	1 ft	5 ft	3 ft	1 ft	5 ft	3 ft	1 ft
Dock	529	601	225	0.2	0.2	0.2	0.0	0.0	0.0	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.1	14%	14%	16%
1	588	565	564	0.6	0.3	0.3	0.3	0.1	0.1	0.5	0.3	0.2	0.2	0.1	0.1	0.1	0.0	0.1	42%	32%	29%
2	590	570	553	1.0	0.3	0.2	0.2	0.0	0.1	1.0	0.2	0.2	0.3	0.1	0.1	0.1	0.0	0.1	19%	28%	32%
3	528	550	525	1.7	0.6	0.3	0.4	0.1	0.1	1.6	0.5	0.3	0.6	0.2	0.1	0.2	0.1	0.1	35%	40%	38%
4	493	530	540	1.3	0.5	0.2	0.7	0.2	0.1	1.1	0.4	0.2	0.4	0.2	0.1	0.1	0.1	0.1	29%	38%	33%
5	533	539	551	0.6	0.2	0.2	0.3	0.1	0.0	0.4	0.2	0.1	0.2	0.1	0.1	0.1	0.0	0.1	32%	37%	31%
6	599	557	553	0.8	0.3	0.2	0.2	0.1	0.1	0.7	0.2	0.2	0.3	0.1	0.1	0.1	0.1	0.1	28%	48%	43%
7	574	544	548	0.9	0.3	0.2	0.4	0.1	0.0	0.7	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.1	37%	49%	50%
8	520	536	540	1.8	0.5	0.2	0.3	0.1	0.0	1.6	0.5	0.2	0.6	0.2	0.1	0.2	0.1	0.1	30%	38%	43%
9	577	570	559	3.3	0.7	0.2	0.6	0.1	0.0	3.0	0.7	0.2	1.2	0.3	0.1	0.3	0.1	0.1	35%	36%	42%
10	595	580	571	1.2	0.4	0.1	0.6	0.1	0.0	1.0	0.4	0.1	0.3	0.2	0.0	0.1	0.0	0.1	28%	34%	26%
11	579	567	565	0.6	0.2	0.1	0.5	0.1	0.0	0.3	0.2	0.1	0.1	0.1	0.0	0.1	0.0	0.1	33%	37%	37%
12	453	511	496	1.3	0.3	0.3	0.2	0.1	0.0	1.2	0.3	0.2	0.5	0.1	0.1	0.1	0.0	0.1	36%	34%	28%
13	465	522	504	0.4	0.3	0.2	0.2	0.0	0.0	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.0	0.1	33%	30%	20%
14	458	534	532	0.6	0.3	0.2	0.5	0.1	0.0	0.3	0.3	0.1	0.2	0.1	0.0	0.1	0.0	0.1	33%	30%	21%
15	553	547	569	0.5	0.6	0.3	0.3	0.1	0.1	0.4	0.5	0.3	0.1	0.2	0.1	0.1	0.1	0.1	32%	34%	24%
16	558	529	543	0.5	0.6	0.3	0.3	0.1	0.0	0.3	0.5	0.3	0.1	0.2	0.1	0.1	0.1	0.1	31%	33%	23%
17	547	535	541	1.2	0.4	0.6	0.4	0.1	0.1	1.0	0.4	0.5	0.4	0.2	0.2	0.2	0.1	0.1	39%	39%	37%
18	590	541	541	1.6	0.6	0.3	0.3	0.1	0.2	1.5	0.6	0.2	0.4	0.2	0.1	0.1	0.1	0.1	19%	30%	27%
19	614	548	569	1.2	0.7	0.2	0.3	0.1	0.1	1.0	0.6	0.2	0.5	0.2	0.1	0.1	0.1	0.1	45%	34%	28%
20	587	541	549	1.4	0.6	0.4	0.6	0.1	0.1	1.2	0.6	0.3	0.4	0.2	0.1	0.1	0.1	0.1	14%	30%	30%
21	572	538	541	2.7	0.7	0.6	0.4	0.1	0.1	2.5	0.7	0.5	1.1	0.3	0.2	0.3	0.1	0.1	38%	37%	39%
22	470	510	528	0.7	0.6	0.3	0.1	0.1	0.1	0.7	0.6	0.3	0.3	0.2	0.1	0.1	0.1	0.1	37%	36%	23%
23	382	528	550	0.7	0.6	0.3	0.2	0.1	0.1	0.6	0.6	0.3	0.3	0.2	0.1	0.1	0.1	0.1	38%	38%	24%
24	527	524	570	0.5	0.4	0.3	0.1	0.1	0.1	0.4	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	36%	37%	20%
25	553	537	564	0.8	0.5	0.4	0.6	0.1	0.1	0.6	0.5	0.3	0.2	0.2	0.1	0.1	0.1	0.1	37%	37%	24%
26	561	552	593	1.2	0.5	0.4	0.5	0.2	0.1	1.0	0.4	0.4	0.4	0.2	0.1	0.1	0.1	0.1	38%	35%	31%
27	480	500	577	0.6	0.5	0.3	0.3	0.1	0.1	0.5	0.4	0.2	0.2	0.2	0.1	0.1	0.1	0.1	37%	38%	24%
28	487	488	584	0.8	0.6	0.3	0.5	0.1	0.1	0.6	0.5	0.3	0.3	0.2	0.1	0.1	0.1	0.1	37%	39%	27%
29	500	476	556	0.5	0.3	0.3	0.1	0.1	0.2	0.5	0.3	0.2	0.2	0.1	0.1	0.1	0.0	0.1	42%	41%	38%
30	533	522	534	3.3	0.9	0.5	0.5	0.3	0.1	3.1	0.8	0.4	1.2	0.3	0.2	0.3	0.1	0.1	33%	32%	32%
31	560	519	542	0.9	0.5	0.1	0.3	0.1	0.0	0.8	0.5	0.1	0.3	0.2	0.0	0.1	0.1	0.1	34%	35%	20%
32	550	541	563	0.4	0.3	0.1	0.2	0.1	0.0	0.3	0.3	0.1	0.2	0.1	0.0	0.1	0.0	0.1	35%	34%	28%
33	560	543	578	0.7	0.1	0.1	0.7	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1	47%	40%	80%
34	556	565	552	1.1	0.5	0.7	1.0	0.5	0.4	0.2	0.1	0.5	0.3	0.1	0.2	0.2	0.1	0.1	44%	36%	12%
35	534	521	502	0.1	0.1	0.2	0.1	0.1	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	63%	28%	13%
36	533	516	511	0.1	0.1	0.6	0.1	0.1	0.1	0.0	0.1	0.6	0.0	0.0	0.2	0.0	0.0	0.1	46%	15%	9%
37	538	517	523	0.3	0.1	0.2	0.3	0.1	0.1	0.0	0.0	0.2	0.1	0.0	0.1	0.1	0.0	0.1	46%	29%	16%
38	549	572	629	0.5	0.2	0.3	0.5	0.2	0.2	0.0	0.0	0.3	0.1	0.0	0.1	0.1	0.0	0.1	50%	22%	13%
39	579	579	627	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	77%	29%	25%
40	595	554	592	0.7	0.2	0.1	0.5	0.2	0.1	0.1	0.0	0.0	0.5	0.0	0.0	0.2	0.0	0.1	77%	62%	81%
41	583	593	584	0.3	0.1	0.4	0.3	0.1	0.2	0.0	0.0	0.4	0.0	0.0	0.1	0.0	0.0	0.1	49%	31%	10%
42	586	561	600	0.3	0.1	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.1	146%	29%	76%
43	564	561	596	0.4	0.3	0.3	0.4	0.3	0.3	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.1	49%	50%	56%
44	564	556	553	0.6	0.2	0.4	0.5	0.1	0.1	0.1	0.1	0.3	0.1	0.0	0.1	0.1	0.0	0.1	34%	13%	9%
45	549	526	506	0.8	0.2	0.5	0.7	0.1	0.1	0.1	0.1	0.5	0.1	0.1	0.1	0.0	0.0	0.1	21%	14%	13%
46	578	578	614	0.5	0.1	0.1	0.3	0.1	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.1	0.0	0.1	128%	53%	69%
47	610	561	576	1.1	0.1	0.3	1.0	0.1	0.1	0.2	0.0	0.3	0.3	0.0	0.1	0.2	0.0	0.1	41%	51%	12%
48	639	679	760	0.5	0.2	0.3	0.4	0.2	0.2	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	48%	43%	19%
49	584	578	543	0.7	0.2	0.2	0.7	0.2	0.1	0.1	0.0	0.1	0.2	0.0	0.0	0.1	0.0	0.1	44%	51%	31%
50	564	526	510	0.3	0.2	0.2	0.3	0.2	0.2	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1	38%	36%	39%
Summary of Field Levels on the Lower Deck (Locations 1-32)																					
Minimum	382	476	496	0.4	0.2	0.1	0.1	0.0	0.0	0.3	0.2	0.1	0.1	0.1	0.0	0.1	0.0	0.1	14%	28%	20%
Maximum	614	580	593	3.3	0.9	0.6	0.7	0.3	0.2	3.1	0.8	0.5	1.2	0.3	0.2	0.3	0.1	0.1	45%	49%	50%
Median	552	538	551	0.9	0.5	0.3	0.3	0.1	0.1	0.7	0.4	0.2	0.3	0.2	0.1	0.1	0.1	0.1	35%	36%	29%
Average	537	536	550	1.1	0.5	0.3	0.3	0.1	0.1	1.0	0.4	0.2	0.4	0.2	0.1	0.1	0.1	0.1	33%	36%	30%
Std. Dev.	53	23	20	0.8	0.2	0.1	0.2	0.0	0.0	0.7	0.1	0.1	0.3	0.1	0.0	0.1	0.0	0.0	7%	4%	8%
Summary of Field Levels on the Upper Deck (Locations 33-50)																					
Minimum	533	516	502	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	21%	13%	9%
Maximum	639	679	760	1.1	0.5	0.7	1.0	0.5	0.4	0.2	0.1	0.6	0.5	0.1	0.2	0.2	0.1	0.1	146%	62%	81%
Median	564	561	577	0.5	0.2	0.2	0.4	0.1	0.1	0.1	0.0	0.2	0.1	0.0	0.1	0.1	0.0	0.1	47%	34%	17%
Average	570	560	575	0.5	0.2	0.3	0.5	0.2	0.1	0.1	0.0	0.2	0.1	0.0	0.1	0.1	0.0	0.1	58%	35%	32%
Std. Dev.	27	37	61	0.3	0.1	0.2	0.3	0.1	0.1	0.1	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	31%	14%	26%
Summary of Field Levels in Both Throughout the Ferry Boat (Locations 1-50)																					
Minimum	382	476	496	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	14%	13%	9%
Maximum	639	679	760	3.3	0.9	0.7	1.0	0.5	0.4	3.1	0.8	0.6	1.2	0.3	0.2	0.3	0.1	0.1	146%	62%	81%
Median	559	541	553	0.7	0.3	0.3	0.3	0.1	0.1	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.0	0.1	37%	36%	28%
Average	549	545	559	0.9	0.4	0.3	0.4	0.1	0.1	0.6	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.1	42%	36%	31%
Std. Dev.	48	31	42	0.7	0.2	0.1	0.2	0.1	0.1	0.7	0.2	0.1	0.3	0.1	0.0	0.1	0.0	0.0	23%	9%	17%

Static magnetic field levels on the ferry boat averaged 551 mG (Std Dev 41 mG) and ranged from 382 mG to 760 mG. The average static field was slightly higher on the partially open upper deck (569 mG) than on the enclosed lower deck (541 mG). The magnitude of the static field, its uniformity throughout the boat and its slightly higher average strength on the upper deck suggests that this component of the magnetic field is essentially all natural geomagnetic field with only moderate perturbation by structural steel in the boat. There is no evidence in the data that the ferry boat produced static magnetic fields by its operation.

Extreme low frequency (ELF) time-varying magnetic fields were produced by the ferry boat and ranged from less than 0.1 mG to 3.3 mG. Average ELF magnetic field level throughout the boat was slightly above 0.5 mG. The field tended to be larger on the lower deck (0.6 mG average) than on the upper deck (0.3 mG average). On the lower deck, there was a large variation in average ELF magnetic field level with height above the deck ranging from 0.3 mG at a height of 1 foot to 1.1 mG at a height of 5 feet above the deck. The relationship between height and field level was less pronounced and less consistent on the upper deck but the highest average fields were still at the 5 foot height (0.5 mG average).

Individual field measurements 5 feet above the deck at the 50 measurement sites on the boat were used to construct the contour plots of ELF magnetic field levels shown in Figure 8-2. Distribution of the ELF magnetic field levels by position in the boat and height above the deck suggest that the principal field sources are the overhead lights and perhaps the wiring to those lights.

8.3.3 Frequency Characteristics

Spectral analysis of the magnetic fields measured on the ferry boat indicates that the principal frequency component of the magnetic field is nominally 60 Hz; the power frequency generated on board to operate lights and electrical equipment since the electric power is produced by diesel-operated generators, its frequency precision and stability is less precise than that of the interconnected commercial electric power system. On the ferry, the power frequency averaged about 61 Hz.

The magnetic fields measured throughout the boat were generally rich in harmonics of the power frequency. The 3rd harmonic was the dominant harmonic at most locations, but the 5th, 7th, and 9th harmonics were also evident. The magnitude of the 3rd harmonic is indicated on Table 8-1 in the "Power Harmonics" column. The 5th and higher harmonics fall into the "High ELF" frequency band on Table 8-1. (The 5th harmonic of the power frequency

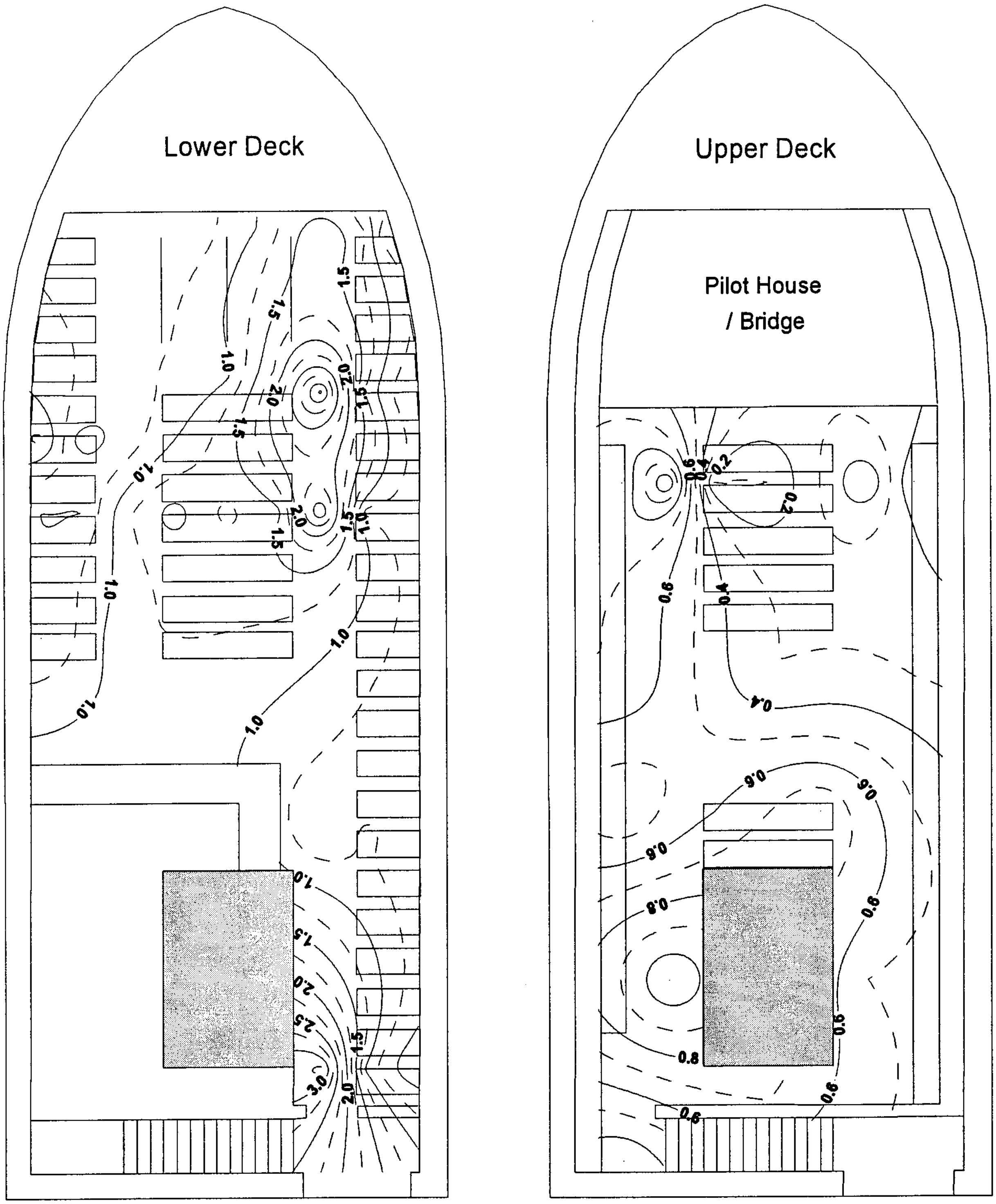


Figure 8-2 Contour Plots of ELF Magnetic Field Level 5 Feet Above the Deck.

would normally fall within the "Power Harmonics Band" which extends to 300 Hz, but because the locally generated power was at a higher frequency, the 5th harmonic was 305 Hz which moved into the "High ELF" band.) The total harmonic distortion of the magnetic field (the ratio of the field strengths of the harmonic components divided by the field strength of the power frequency component) is also tabulated on Table 8-1 and is a concise indicator of the intensity of the harmonic fields compared to the power frequency field.

Some very low frequency components, typically less than about 15 Hz are caused by movement in the geomagnetic field. Since the test engineer held the measurement staff with field sensors, the sensors mimicked the movement of his body in response to the very mild rocking and pitching of the boat. Hence, the observed low-frequency components would be present in the body of a passenger as well.

At Locations 40, 42, 43, and 46 on the upper deck (see Figure 8-1), the principal frequency component of the magnetic field 5 feet in the air was 160 Hz. The origin of that 0.1 to 0.5 mG field is unknown but the source was probably on or near the edge of the roof above because the intensity of that unique frequency component attenuated quickly with distance down or to the sides.

9.0 PEOPLE-MOVERS AND TRAVEL-RELATED DEVICES

Magnetic field measurements were made on and near electric-powered people-movers including an airport shuttle tram, escalators, and moving walkways. Magnetic field characteristics were also examined near airport metal detectors, hand baggage x-ray equipment and a baggage carousel.

All of the measurements reported in this section were made at the Greater Pittsburgh International Airport Terminal Complex. That facility was built within the last decade so all of the people-mover systems, and other systems, are of contemporary design.

9.1 Airport Shuttle Tram

Two electric-powered shuttle trams operate through underground tunnels between the land side and air side portions of the terminal. These automated, two-car, rubber-tired vehicles were built by AEG/Westinghouse Transportation Systems and are similar to shuttle trams in many domestic airports. Sixty-hertz electric power is supplied to the vehicles by contacts which follow an energized "third rail" which runs the length of the tramway. Traction motors are on the drive wheels beneath the coaches. Most of the power-control equipment is installed beneath the coach floor. Some control equipment is located in cabinets at the extreme ends of the coaches. These cabinets also serve as the only seats within the coaches. The vehicle travels from the land side terminal to the air side terminal in just over 3 minutes. After a pause of approximately 2 minutes to unload and load passengers, the tram returns to the land side terminal by traveling the opposite direction through the same tunnel. This cycle is repeated continually. The second shuttle-tram operates in a parallel tunnel on the opposite schedule such that the two vehicles pass one another in the parallel tunnels midway between terminals.

Repetitive three-axis magnetic field waveform measurements were made at 1, 3, and 5 ft above the floor of the tram at four locations:

1. Front right of leading coach;
2. Front left of leading coach;
3. Center of trailing coach; and
4. Between front doors of leading coach.

At all locations, measurements were made at 5 second intervals throughout the time of travel producing approximately 50 field waveform samples at each height above the floor at each measurement location. Magnetic field levels are summarized in Table 9-1 by frequency band for each location and height. Summary statistics are

Table 9-1
Magnetic Field Levels on a Shuttle Tram at Various Heights Above the Floor
Summary Data for Four Locations and for the Pooled Measurements

Frequency Band	Location on Tram	Minimum Field (mG)				Maximum Field (mG)				Median Field (mG)				Average Field (mG)				Standard Deviation (mG)			
		1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All
Static 0 Hz	1	369	258	272	258	625	646	685	685	574	533	526	533	547	502	499	509	74	92	98	93
	2	376	380	363	363	835	734	739	835	564	503	478	510	569	505	475	516	82	68	74	85
	3	139	300	296	139	480	634	646	646	281	458	449	427	290	472	455	407	74	68	68	107
	4	328	243	156	156	597	493	424	597	521	435	345	424	504	421	332	419	77	73	81	104
	All 4	139	243	156	139	835	734	739	835	514	493	457	485	463	486	462	470	148	80	92	109
All ELF Frequencies 5-3000 Hz	1	12.9	1.9	2.4	1.9	32.1	31.4	72.6	72.6	20.3	15.4	17.4	16.3	21.1	13.8	20.1	17.7	5.4	6.9	14.6	11.1
	2	1.6	1.2	1.4	1.2	33.4	26.6	52.6	52.6	9.4	9.4	13.1	9.7	10.9	9.1	13.8	11.3	6.7	5.5	9.0	7.5
	3	3.1	1.8	3.2	1.8	90.4	33.4	35.0	90.4	12.9	6.8	9.3	10.2	18.0	8.5	11.6	12.7	16.6	6.7	8.4	12.0
	4	6.1	1.7	1.6	1.6	67.4	25.0	60.6	67.4	16.4	9.7	11.9	12.3	21.2	10.1	15.8	15.7	15.2	5.8	14.7	13.5
	All 4	1.6	1.2	1.4	1.2	90.4	33.4	72.6	90.4	13.2	9.6	13.4	12.0	16.1	10.4	15.0	13.7	12.8	6.7	11.7	10.9
Low Frequencies 5-55 Hz	1	0.8	0.7	2.0	0.7	17.7	30.7	71.1	71.1	9.4	7.9	12.4	10.3	9.3	9.1	15.9	11.9	5.1	6.5	15.0	11.2
	2	0.3	0.3	0.5	0.3	32.7	25.8	51.8	51.8	6.2	6.4	11.5	7.3	8.6	7.3	11.6	9.2	7.0	5.5	9.8	7.9
	3	0.1	0.1	0.2	0.1	88.5	32.5	33.9	88.5	7.8	5.3	8.5	7.5	13.9	7.1	10.1	10.4	17.7	7.1	9.1	12.5
	4	0.4	0.1	0.1	0.1	65.3	24.3	59.5	65.3	14.0	8.8	11.5	10.6	17.5	8.8	15.1	13.8	16.1	6.4	14.8	13.7
	All 4	0.1	0.1	0.1	0.1	88.5	32.5	71.1	88.5	7.8	6.5	11.3	8.3	11.6	7.9	12.7	10.7	13.1	6.4	12.0	11.0
Power Frequency 60 Hz	1	9.3	0.6	0.9	0.6	29.0	22.3	27.0	29.0	15.9	3.5	4.3	8.7	16.9	7.0	7.7	9.2	6.1	6.9	7.4	7.9
	2	0.4	0.9	1.0	0.4	13.6	13.6	11.6	13.6	4.2	2.7	5.0	4.2	4.2	3.7	4.9	4.3	3.1	3.0	1.9	2.8
	3	1.6	0.5	2.3	0.5	14.8	6.0	4.6	14.8	6.3	2.5	3.1	3.2	7.0	2.8	3.1	4.3	2.8	1.1	0.4	2.6
	4	4.1	1.6	1.4	1.4	13.9	6.2	3.5	13.9	6.9	2.9	2.1	3.4	7.6	3.1	2.3	4.3	2.8	1.3	0.6	2.9
	All 4	0.4	0.5	0.9	0.4	29.0	22.3	27.0	29.0	6.1	2.6	3.3	3.7	7.5	4.3	4.9	5.5	5.6	4.5	4.5	5.0
Power Harmonic Frequencies 65-300 Hz	1	2.4	0.4	0.5	0.4	11.2	7.7	12.7	12.7	3.4	2.7	3.1	2.9	5.0	2.9	3.7	3.6	3.0	1.9	2.7	2.6
	2	0.1	0.2	0.5	0.1	8.9	6.7	7.5	8.9	2.4	2.1	2.5	2.4	2.8	2.1	2.6	2.5	1.7	1.3	1.5	1.5
	3	0.2	0.2	1.1	0.2	13.5	6.2	6.3	13.5	3.6	2.0	2.0	2.3	4.6	2.2	2.2	3.0	3.4	1.4	1.1	2.5
	4	0.6	0.4	0.7	0.4	14.4	4.7	9.9	14.4	5.1	2.1	2.1	2.5	5.6	2.2	2.6	3.5	3.1	1.0	2.2	2.7
	All 4	0.1	0.2	0.5	0.1	14.4	7.7	12.7	14.4	3.4	2.2	2.3	2.5	4.1	2.4	2.8	3.0	3.0	1.5	2.0	2.3
High ELF Frequencies 305 to 3000 Hz	1	1.3	0.2	0.1	0.1	3.1	3.3	6.6	6.6	2.1	1.4	1.7	1.7	2.0	1.5	1.9	1.7	0.4	0.8	1.4	1.0
	2	0.1	0.0	0.1	0.0	2.6	2.3	3.5	3.5	1.0	0.9	1.1	1.1	1.0	0.9	1.1	1.0	0.6	0.6	0.7	0.7
	3	0.1	0.0	0.1	0.0	6.5	2.7	3.3	6.5	0.8	0.5	0.8	0.7	1.3	0.7	0.8	0.9	1.5	0.6	0.7	1.0
	4	0.2	0.1	0.1	0.1	7.0	2.2	5.0	7.0	0.8	0.7	1.0	0.9	1.5	0.8	1.2	1.2	1.8	0.6	1.2	1.3
	All 4	0.1	0.0	0.1	0.0	7.0	3.3	6.6	7.0	1.1	0.9	1.1	1.0	1.3	1.0	1.2	1.2	1.2	0.7	1.1	1.0

also tabulated for all samples at a given height, all samples at a given location and all samples in the tram regardless of height or location.

Magnetic field characteristics are shown graphically in Figure 9-1 at five ft above the floor at the first measurement location. Temporal characteristics of the field are similar at other locations. The upper frame is plotted with the static component of the field intact. This component of the field is apparently geomagnetic in origin. (If it had arisen from the electric traction power system, it would show some temporal correlation with traction power). Shielding by structural steel in the tunnel apparently causes significant variation in the geomagnetic field strength along the route of travel. To better show the characteristics of the time-varying field components, the static component is suppressed and the data are replotted in the lower frame at more appropriate frequency and amplitude scales. The principal time-varying field component is at the 60 Hz electric power frequency. That component of the field is small for the first ten seconds of the record while the tram is stationary. The 60 Hz field increases markedly as the tram accelerates for about 40 to 50 seconds before decreasing to a low ambient value as the tram coasts toward its stop. This obvious correlation with traction power indicates that the 60 Hz field arises from the power delivery system to the tram and its onboard electric traction and control equipment. Fields are also present at odd and even harmonics of the 60 Hz power frequency as a result of waveform distortion of the 60 Hz electric traction current.

A small 30 Hz field is present at approximately constant amplitude throughout the data record. The origin and purpose of this field is not known to the authors but could be related to signaling.

Temporally variable, low-frequency components having approximately exponentially decaying amplitude with increasing frequency are also prominent in Figure 9-1. These time-varying components arise from moving through the inhomogeneous geomagnetic field around steel structures in the tramway tunnel. The larger of these is visible in the upper frame of Figure 9-1 and their correlation with aberrant geomagnetic field conditions is obvious. These components disappear when the tram is stopped as in the first and last few records of the data sample.

Spatial variability of the magnetic field within the shuttle tram is indicated in the pattern of field values in Table 9-1. Power-frequency and harmonic fields are most intense at floor level at the front right corner of the car (Location 1), but floor level fields at those frequencies are also elevated at locations more toward the centers of the cars (Locations 3 and 4). Those fields undoubtedly arise from traction power equipment beneath the coach floor. At other locations, the 60 Hz field is more homogeneous and probably results from power delivered to the vehicle from the "third rail" system.

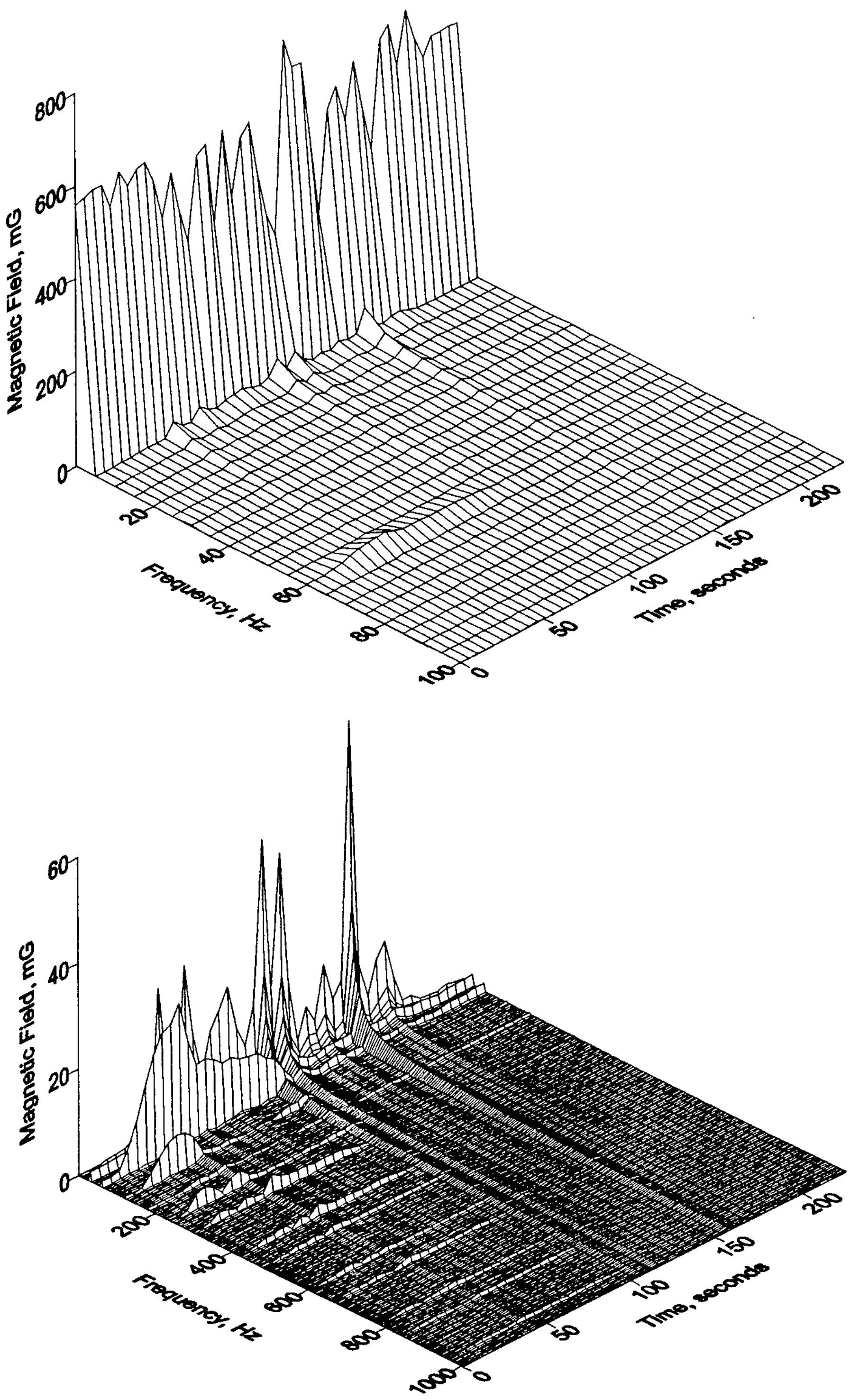


Figure 9-1 Static (Upper Frame) and Time-Varying (Lower Frame) Magnetic Fields as a Function of Frequency and Time Measured 5 ft Above the Floor at the Front Right (Location 1) in the Airport Shuttle Tram.

Low frequency fields at the 3 ft height tend to be lower than those nearer the floor or ceiling where there is less static field perturbation by the coach body. At the other locations having more complex shielding interactions between the coach body and tunnel structural steel, temporal variation in the geomagnetic field within the moving tram is more rapid and more extreme thereby giving rise to larger, low-frequency fields.

Overall, the average ELF field level in the tram was consistent among measurement locations (11-18 mG, average 13.7 mG). The low frequency field components were the predominant frequency components (average 10.7 mG) and varied with height as described above. Power-frequency and harmonic frequency fields (5.5 mG and 3.0 mG average levels, respectively) were present throughout the tram but generally more intense near the floor.

9.2 Shuttle Tram Stations

Magnetic fields were also characterized in the tram stations close to the doors to the tram where passengers wait and enter or exit the tram. The measurement method was the same as that employed in the tram. The three locations examined were:

1. Land Side Station, second of four doors*;
2. Land Side Station, first of four doors*;and
3. Air Side Station, first of four doors*.

*Doors are numbered with Door 1 being the front of the tram at departure.

Measurements were approximately 1 ft from the tram tunnel safety doors and 1 ft, 3 ft, and 5 ft above the floor. Measurements at each location began before the tram arrived, continued while the safety and tram doors opened and closed, and ended after the tram departed the station.

Magnetic field levels measured at the shuttle tram stations are summarized by measurement location and height as well as by various aggregations in Table 9-2. A measurement fault at Location 2 caused the loss of data from the 3 ft high sample location.

Figure 9-2 presents a graphical representation of the field characteristics 5 ft above the floor at the first measurement location. The same field components observed in the tram cars are also present on the platform but of lower magnitude. Static field is of geomagnetic origin and slightly attenuated by the shielding of the tram body when the tram is in the station (from about 30 seconds to 125 seconds on the Figure). As the tram is entering and leaving, the geomagnetic field fluctuates due to

Table 9-2
Magnetic Field Levels Outside the Door to the Shuttle Tram at Various Heights Above the Floor
Summary Data for Three Different Doors and for the Pooled Measurements

Frequency Band	Door to Tram	Minimum Field (mG)				Maximum Field (mG)				Median Field (mG)				Average Field (mG)				Standard Deviation (mG)			
		1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All
Static 0 Hz	1	429	444	487	429	490	486	558	558	470	454	492	485	473	462	501	480	14	16	16	22
	2	584		494	494	629		520	629	596		516	550	603		515	559	13		6	45
	3	369	453	470	369	452	509	504	509	416	499	502	478	414	487	494	465	30	20	12	42
	All 3	369	444	470	369	629	550	558	629	486	464	509	491	512	472	505	501	76	24	14	52
All ELF Frequencies 5-3000 Hz	1	0.2	0.2	0.3	0.2	12.8	2.3	5.5	12.8	1.1	0.7	0.6	0.7	1.3	0.7	0.8	0.9	2.1	0.4	0.9	1.4
	2	0.5		0.7	0.5	9.0		4.9	9.0	1.3		1.2	1.2	1.8		1.4	1.6	1.9		0.9	1.5
	3	0.3	0.3	0.5	0.3	14.0	5.9	2.9	14.0	0.9	0.7	0.8	0.8	2.3	1.5	1.3	1.7	3.6	1.5	0.8	2.3
	All 3	0.2	0.2	0.3	0.2	14.0	5.9	5.5	14.0	1.2	0.7	0.7	0.9	1.7	0.9	1.1	1.3	2.4	1.0	1.0	1.7
Low Frequencies 5-55 Hz	1	0.0	0.0	0.0	0.0	7.6	1.7	2.1	7.6	0.1	0.1	0.1	0.1	0.5	0.2	0.3	0.3	1.3	0.3	0.4	0.8
	2	0.0		0.0	0.0	7.4		2.2	7.4	0.1		0.1	0.1	0.7		0.3	0.5	1.6		0.5	1.2
	3	0.0	0.0	0.1	0.0	13.7	5.6	2.8	13.7	0.4	0.4	0.3	0.4	1.7	1.0	0.7	1.1	3.6	1.6	0.9	2.4
	All 3	0.0	0.0	0.0	0.0	13.7	5.6	2.8	13.7	0.1	0.1	0.1	0.1	0.8	0.4	0.3	0.5	2.0	1.0	0.6	1.4
Power Frequency 60 Hz	1	0.1	0.1	0.2	0.1	8.1	1.4	4.4	8.1	1.0	0.6	0.5	0.6	1.1	0.6	0.6	0.8	1.3	0.3	0.7	0.9
	2	0.4		0.6	0.4	4.4		4.2	4.4	1.2		1.2	1.2	1.3		1.3	1.3	0.9		0.7	0.8
	3	0.2	0.3	0.5	0.2	2.1	1.6	1.6	2.1	0.3	0.4	0.6	0.5	0.9	0.7	0.9	0.8	0.8	0.5	0.4	0.6
	All 3	0.1	0.1	0.2	0.1	8.1	1.6	4.4	8.1	1.1	0.6	0.7	0.7	1.1	0.6	0.9	0.9	1.1	0.4	0.7	0.9
Power Harmonic Frequencies 65-300 Hz	1	0.1	0.1	0.1	0.1	6.1	0.6	2.4	6.1	0.2	0.1	0.2	0.2	0.4	0.2	0.3	0.3	1.0	0.1	0.4	0.7
	2	0.2		0.2	0.2	4.3		2.8	4.3	0.2		0.3	0.3	0.5		0.4	0.5	0.9		0.5	0.7
	3	0.1	0.1	0.2	0.1	2.6	1.1	0.6	2.6	0.1	0.1	0.2	0.2	0.4	0.2	0.3	0.3	0.7	0.3	0.1	0.4
	All 3	0.1	0.1	0.1	0.1	6.1	1.1	2.8	6.1	0.2	0.1	0.2	0.2	0.4	0.2	0.3	0.4	0.9	0.2	0.4	0.6
High ELF Frequencies 305 to 3000 Hz	1	0.1	0.0	0.0	0.0	1.3	0.2	0.5	1.3	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.2	0.0	0.1	0.1
	2	0.1		0.0	0.0	1.1		0.7	1.1	0.1		0.0	0.1	0.1		0.1	0.1	0.2		0.1	0.2
	3	0.0	0.0	0.0	0.0	1.3	0.5	0.2	1.3	0.1	0.0	0.0	0.0	0.2	0.1	0.1	0.1	0.3	0.1	0.1	0.2
	All 3	0.0	0.0	0.0	0.0	1.3	0.5	0.7	1.3	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.2

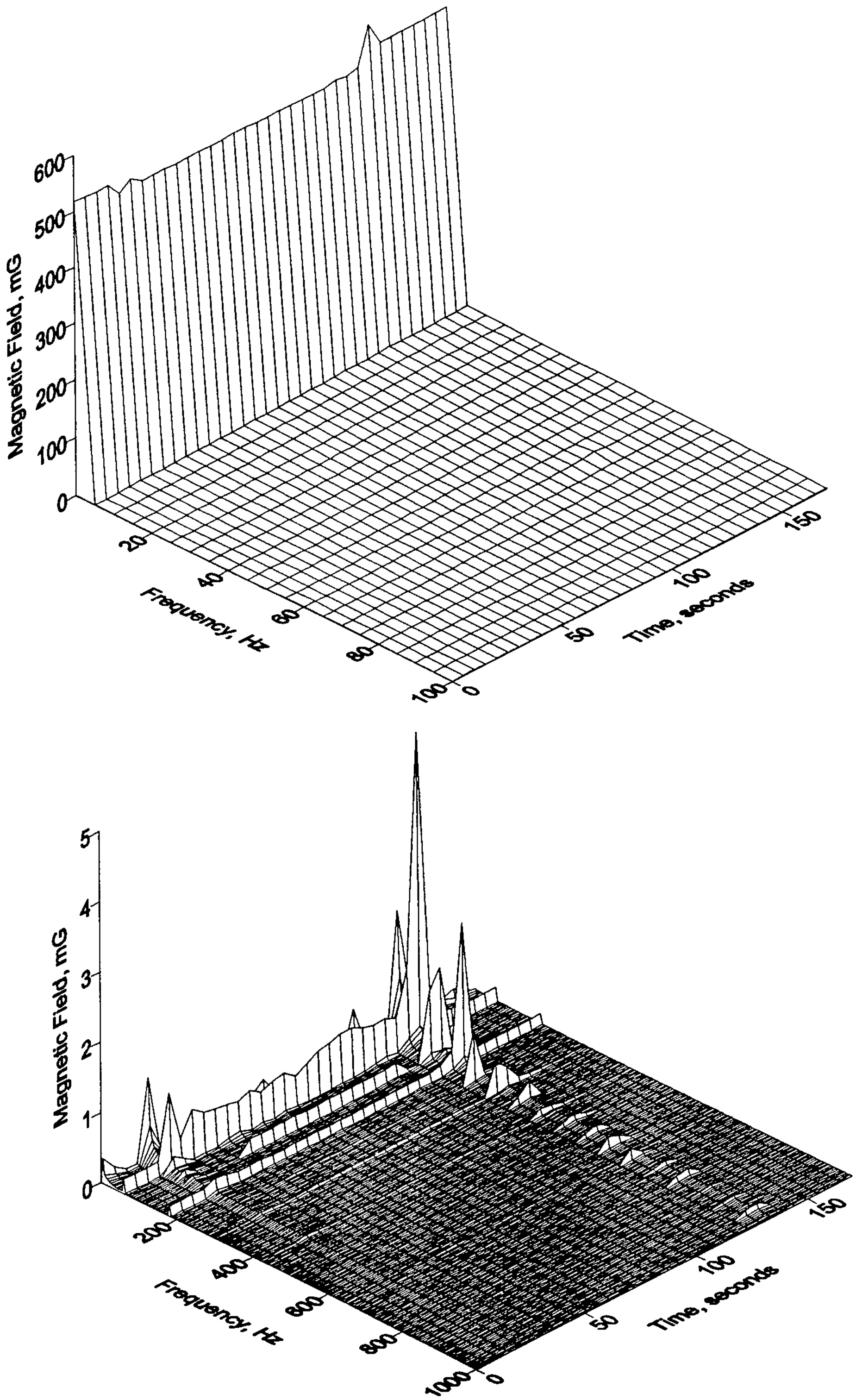


Figure 9-2 Static (Upper Frame) and Time-Varying (Lower Frame) Magnetic Fields as a Function of Frequency and Time Measured on the Shuttle Tram Platform 5 ft Above the Floor and 1 ft from the Doors at the Front of the Tram.

differing shielding by the tram. Sixty-hertz and 180 Hz fields are present at ambient levels before the tram enters and after it leaves the station. While the tram is in the station, the 60 Hz field is elevated indicating that the tram is an additional source of those fields. As the tram departs, 60 Hz and harmonic fields rise abruptly as a result of power in the on-board traction equipment and circuitry, but fall again to ambient levels as those on-board field sources move away from the measurement location. A field of approximately 120 Hz is present from approximately the 40 second and 110 second points on Figure 9-2. This is the interval when the safety and tram doors are open so that field probably comes from the automatic door actuators. During the interval when the tram is entering and leaving the station, the moving steel structure perturbs the geomagnetic field giving rise to low frequency fields which decay exponentially with frequency. The magnitudes of these fields are much smaller than the similar fields seen on-board the tram because the tram is moving slowly in the station and fluctuations in the geomagnetic field are not rapid.

9.3 Escalators

Magnetic fields were measured at 5-second intervals at 1, 3, and 5 ft above the step while riding on five different escalators. Three of the measurements (1 through 3) were while ascending, and 2 (4 and 5) while descending. Table 9-3 summarizes the recorded field levels by frequency band, height, and escalator. Figure 9-3 shows field characteristics 3 ft above the step on two escalators.

Static field levels fluctuate along the escalators due to differing shielding of the geomagnetic field by nearby steel in the escalator and building and due to the presence of magnetized iron components in or near the escalator. This is confirmed by the consistently larger standard deviation in the static field at the lower measurement heights.

Sixty-hertz and harmonic fields are low and relatively constant along the escalators indicative of ambient conditions. Drive motors are 60 Hz and usually located at one end of the escalator. Since elevated 60 Hz fields are not observed at specific locations, the electric drive does not appear to be a meaningful field source.

Low-frequency field components associated with movement through an inhomogeneous static field (and, therefore, time-varying in the frame of reference of the escalator rider) are the major field components and vary markedly from one escalator to another. These are the dominant fields on all five escalators. Escalators 1, 3, and 5 had low-frequency fields of modest amplitude at most measurement time points. Escalators 2 and 4 had high but infrequent low-frequency fields. On escalator 2, moderate fields of 7 to 9 appeared simultaneously at all three measurement heights. The uniformity of those fields at locations a couple feet apart

Table 9-3
Magnetic Field Levels on Escalators at Various Heights Above the Floor
Summary Data for Five Individual Escalators and for the Pooled Measurements

Frequency Band	Esc. Number	Minimum Field (mG)				Maximum Field (mG)				Median Field (mG)				Average Field (mG)				Standard Deviation (mG)			
		1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All
Static 0 Hz	1	221	309	342	221	958	849	786	958	487	570	524	532	545	591	536	556	233	165	146	185
	2	462	539	513	462	761	752	695	761	582	599	576	593	584	619	589	597	83	54	51	66
	3	218	349	347	218	775	709	701	775	459	551	527	504	471	537	523	510	147	113	102	125
	4	274	388	475	274	687	649	677	687	544	553	556	548	515	551	559	542	122	64	51	87
	5	403	431	505	403	742	702	693	742	574	562	576	575	574	576	599	583	118	97	61	96
	All 5	218	309	342	218	958	849	786	958	542	584	558	558	536	576	558	557	157	111	98	125
All ELF Frequencies 5-3000 Hz	1	0.2	0.3	0.3	0.2	4.0	3.3	4.2	4.2	0.7	0.8	1.0	0.8	1.2	1.1	1.5	1.3	1.1	0.9	1.2	1.1
	2	0.4	0.3	0.3	0.3	7.1	8.5	8.7	8.7	1.2	0.9	0.9	1.0	1.7	1.6	1.7	1.7	1.5	1.9	2.0	1.8
	3	0.3	0.3	0.3	0.3	3.2	3.2	3.4	3.4	1.0	0.6	0.6	0.7	1.1	0.9	0.9	1.0	0.7	0.7	0.7	0.7
	4	0.3	0.3	0.3	0.3	5.8	61.4	2.5	61.4	1.1	0.7	0.6	0.7	1.6	4.3	0.8	2.2	1.5	13.5	0.6	8.0
	5	0.3	0.3	0.3	0.3	3.5	3.3	3.6	3.6	1.1	0.6	0.7	0.7	1.3	1.1	0.9	1.1	0.9	1.0	0.9	0.9
	All 5	0.2	0.3	0.3	0.2	7.1	61.4	8.7	61.4	1.0	0.7	0.7	0.8	1.4	1.9	1.2	1.5	1.2	6.6	1.3	3.9
Low Frequencies 5-55 Hz	1	0.1	0.1	0.2	0.1	3.7	3.3	2.9	3.7	0.6	0.7	0.8	0.7	1.1	1.0	1.2	1.1	1.0	0.9	0.9	0.9
	2	0.3	0.1	0.1	0.1	7.0	8.4	8.5	8.5	1.0	0.9	0.8	0.9	1.6	1.5	1.6	1.5	1.5	1.9	2.0	1.8
	3	0.1	0.1	0.2	0.1	3.1	3.1	3.3	3.3	0.9	0.6	0.5	0.6	1.0	0.7	0.8	0.8	0.7	0.7	0.7	0.7
	4	0.3	0.1	0.1	0.1	5.6	60.1	2.4	60.1	0.8	0.5	0.3	0.5	1.4	4.1	0.6	2.0	1.5	13.2	0.6	7.8
	5	0.1	0.1	0.1	0.1	3.3	3.3	3.6	3.6	1.0	0.3	0.2	0.5	1.1	0.9	0.7	0.9	0.9	1.0	1.0	1.0
	All 5	0.1	0.1	0.1	0.1	7.0	60.1	8.5	60.1	0.9	0.6	0.5	0.7	1.3	1.7	1.0	1.3	1.2	6.5	1.2	3.8
Power Frequency 60 Hz	1	0.2	0.2	0.2	0.2	1.3	0.8	3.1	3.1	0.3	0.3	0.4	0.3	0.4	0.4	0.7	0.5	0.4	0.2	0.9	0.6
	2	0.2	0.2	0.2	0.2	1.0	0.5	0.5	1.0	0.3	0.3	0.3	0.3	0.4	0.3	0.3	0.4	0.3	0.1	0.1	0.2
	3	0.1	0.1	0.2	0.1	0.9	0.5	0.7	0.9	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.1	0.1	0.1
	4	0.1	0.2	0.2	0.1	1.0	3.2	0.7	3.2	0.4	0.3	0.3	0.3	0.5	0.5	0.3	0.4	0.3	0.6	0.1	0.4
	5	0.3	0.3	0.2	0.2	0.9	0.5	0.7	0.9	0.3	0.4	0.5	0.4	0.4	0.4	0.5	0.4	0.2	0.1	0.2	0.2
	All 5	0.1	0.1	0.2	0.1	1.3	3.2	3.1	3.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.3	0.5	0.4
Power Harmonic Frequencies 65-300 Hz	1	0.0	0.0	0.0	0.0	0.6	0.6	0.7	0.7	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	2	0.1	0.0	0.1	0.0	1.0	1.1	1.2	1.2	0.2	0.2	0.1	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.3	0.2
	3	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
	4	0.1	0.0	0.0	0.0	1.1	10.5	0.5	10.5	0.1	0.1	0.1	0.1	0.3	0.7	0.1	0.4	0.3	2.3	0.1	1.4
	5	0.1	0.1	0.0	0.0	0.5	0.5	0.4	0.5	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1
	All 5	0.0	0.0	0.0	0.0	1.1	10.5	1.2	10.5	0.2	0.1	0.1	0.1	0.2	0.3	0.2	0.2	0.2	1.1	0.2	0.7
High ELF Frequencies 305 to 3000 Hz	1	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	2	0.1	0.0	0.0	0.0	0.5	0.6	0.6	0.6	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	3	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	4	0.0	0.0	0.0	0.0	0.6	5.5	0.2	5.5	0.1	0.1	0.0	0.1	0.1	0.4	0.1	0.2	0.1	1.2	0.1	0.7
	5	0.1	0.0	0.0	0.0	0.2	0.3	0.2	0.3	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1
	All 5	0.0	0.0	0.0	0.0	0.6	5.5	0.6	5.5	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.6	0.1	0.3

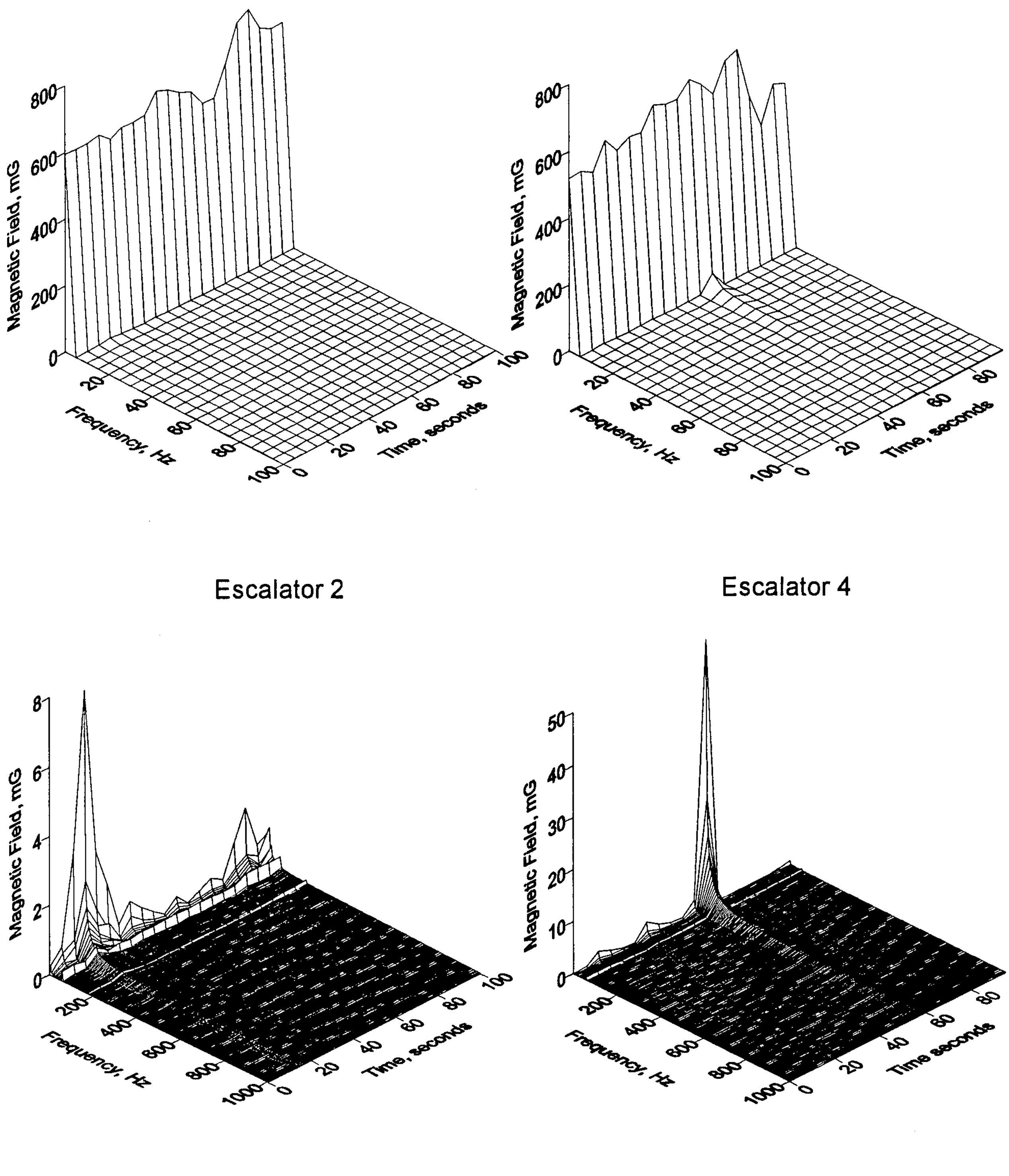


Figure 9-3 **Magnetic Fields as a Function of Frequency and Time Measured 3 ft Above the Step on Two Escalators (Static Field is Suppressed in the Lower Frames).**

indicates that the source is removed several feet from the measurement. In this case, it was geomagnetic field perturbation by a steel member in the wall next to this escalator. But the cause of the high peak field measured on Escalator 4 is quite different. On that escalator, the peak field was much higher at the 3 ft measurement height (61 mG) than at the other heights (5.8 mG at 1 ft and 2.5 mG at 5 ft). The source appeared to be movement through the perturbed static field near a magnetized piece of steel in the escalator handrail support.

9.4 Moving Walkways

Magnetic fields were measured at five-second intervals at three heights (1, 3, and 5 ft) while riding the length of four moving walkways. Walkways 1 and 2 were situated in the center of a concourse adjacent to a moving walkway going the opposite direction. They have glass sides with metal posts which support the handrail. Walkways 3 and 4 were along the walls of a long hall with the opposing walkway well removed along the opposite wall. These walkways have enclosed metal sides. On Walkway 1, the measurements were 6 inches from the right handrail (as far as practical from the nearby parallel opposing moving walkway). The measurement sensors were 6 inches from the left handrail on Walkway 2 to be as near as possible to the parallel walkway. Measurements were made near the left of Walkways 3 and 4.

Measured field levels on the moving walkways are summarized on Table 9-4. Since moving sidewalks are essentially "horizontal escalators", it is not surprising that field characteristics are similar to those seen on the escalators. Figure 9-4 provides a graphical representation of the field characteristics measured 3 ft above the surface on moving Walkways 1 and 2.

As with the escalators, the static fields are primarily geomagnetic in origin but vary along the route due to perturbation by ferromagnetic material in the walkway and the building. Walkway 1 has frequent, but small, low-frequency field components at all measurement heights.

A similar walkway (Walkway 2) has very high peaks of low frequency field which correlate with observable peaks in the static field. On this Walkway, the high peaks in the low-frequency field pattern are highly localized at the 3 ft measurement height. Magnetized components in the handrail support structure appear to be the cause. On Walkways 3 and 4, the largest low-frequency fields were at the 1 ft height apparently due to proximity to ferromagnetic components behind the stainless steel sides of the walkway.

Table 9-4

Magnetic Field Levels on Moving Walkways at Various Heights Above the Floor
Summary Data for Four Individual Walkways and for the Pooled Measurements

Frequency Band	Moving Walkway Number	Minimum Field (mG)				Maximum Field (mG)				Median Field (mG)				Average Field (mG)				Standard Deviation (mG)			
		1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All	1 ft	3 ft	5 ft	All
Static 0 Hz	1	403	522	503	403	762	748	686	762	549	629	590	590	547	630	593	590	82	61	54	75
	2	283	470	500	283	818	708	680	818	607	600	585	592	596	592	591	593	111	64	52	80
	3	259	361	427	259	798	1044	875	1044	449	608	597	560	469	619	620	569	125	142	107	144
	4	154	236	382	154	1035	1218	876	1218	444	575	558	526	477	623	578	559	178	216	119	186
	All 4	154	236	382	154	1035	1218	876	1218	506	608	588	575	514	617	596	576	142	144	94	136
All ELF Frequencies 5-3000 Hz	1	0.6	0.4	0.3	0.3	3.7	1.9	1.7	3.7	0.9	0.8	0.7	0.9	1.2	0.9	0.8	1.0	0.7	0.4	0.4	0.5
	2	0.7	0.6	0.3	0.3	10.4	200.2	2.8	200.2	2.3	1.4	0.8	1.4	2.8	16.0	1.0	6.6	1.8	47.3	0.6	28.2
	3	1.7	1.0	0.8	0.8	127.2	6.7	3.6	127.2	3.7	2.3	1.5	2.4	7.0	2.7	1.6	3.7	18.6	1.1	0.6	11.0
	4	1.6	0.8	0.3	0.3	47.4	12.7	6.8	47.4	3.6	2.3	0.9	2.2	6.5	3.0	1.3	3.6	9.6	2.1	1.2	6.1
	All 4	0.6	0.4	0.3	0.3	127.2	200.2	6.8	200.2	2.9	1.9	1.0	1.7	4.8	5.1	1.2	3.7	11.7	22.4	0.8	14.7
Low Frequencies 5-55 Hz	1	0.1	0.2	0.2	0.1	3.3	1.8	1.6	3.3	0.6	0.5	0.3	0.5	0.7	0.6	0.5	0.6	0.6	0.4	0.3	0.5
	2	0.1	0.3	0.1	0.1	10.0	195.4	2.6	195.4	1.8	1.2	0.4	0.9	2.3	15.4	0.6	6.1	1.9	46.3	0.5	27.5
	3	0.3	0.4	0.1	0.1	124.1	6.1	3.2	124.1	2.3	1.3	0.5	1.3	5.5	1.8	0.6	2.6	18.4	1.3	0.6	10.9
	4	0.8	0.5	0.2	0.2	46.2	12.4	6.6	46.2	3.1	2.2	0.7	1.9	6.1	2.8	1.1	3.3	9.4	2.1	1.2	6.0
	All 4	0.1	0.2	0.1	0.1	124.1	195.4	6.6	195.4	2.0	1.3	0.5	1.0	4.0	4.6	0.7	3.1	11.5	21.9	0.8	14.4
Power Frequency 60 Hz	1	0.5	0.2	0.2	0.2	2.5	1.1	1.5	2.5	0.7	0.4	0.6	0.6	0.9	0.5	0.6	0.7	0.5	0.3	0.3	0.4
	2	0.6	0.4	0.2	0.2	2.2	12.4	1.4	12.4	1.4	0.7	0.7	0.9	1.3	1.5	0.7	1.2	0.3	2.8	0.3	1.7
	3	1.0	0.4	0.4	0.4	9.9	3.1	2.0	9.9	2.6	1.7	1.3	1.8	2.9	1.7	1.3	1.9	1.5	0.6	0.4	1.2
	4	0.5	0.3	0.2	0.2	3.0	1.2	1.1	3.0	1.4	0.6	0.4	0.7	1.4	0.7	0.5	0.9	0.5	0.2	0.2	0.5
	All 4	0.5	0.2	0.2	0.2	9.9	12.4	2.0	12.4	1.5	0.7	0.7	0.9	1.7	1.1	0.8	1.2	1.2	1.4	0.5	1.2
Power Harmonic Frequencies 65-300 Hz	1	0.1	0.0	0.0	0.0	0.6	0.4	0.4	0.6	0.1	0.1	0.2	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1
	2	0.1	0.1	0.0	0.0	1.9	37.2	0.5	37.2	0.3	0.2	0.2	0.2	0.5	3.0	0.2	1.2	0.4	8.8	0.1	5.3
	3	0.4	0.3	0.2	0.2	23.4	1.3	0.9	23.4	0.7	0.5	0.5	0.6	1.3	0.6	0.5	0.8	3.4	0.2	0.2	2.0
	4	0.2	0.2	0.2	0.2	9.2	2.4	1.3	9.2	0.7	0.6	0.3	0.5	1.2	0.7	0.4	0.8	1.9	0.4	0.2	1.2
	All 4	0.1	0.0	0.0	0.0	23.4	37.2	1.3	37.2	0.6	0.4	0.3	0.4	0.9	1.0	0.3	0.7	2.2	4.2	0.2	2.7
High ELF Frequencies 305 to 3000 Hz	1	0.0	0.0	0.0	0.0	0.3	0.2	0.2	0.3	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
	2	0.1	0.0	0.0	0.0	1.0	19.0	0.2	19.0	0.2	0.1	0.1	0.1	0.2	1.5	0.1	0.6	0.2	4.5	0.0	2.7
	3	0.1	0.0	0.0	0.0	12.0	0.6	0.2	12.0	0.2	0.1	0.1	0.1	0.5	0.2	0.1	0.3	1.8	0.1	0.0	1.0
	4	0.1	0.1	0.0	0.0	4.8	1.2	0.6	4.8	0.3	0.2	0.1	0.2	0.6	0.3	0.1	0.3	1.0	0.2	0.1	0.6
	All 4	0.0	0.0	0.0	0.0	12.0	19.0	0.6	19.0	0.2	0.1	0.1	0.1	0.4	0.5	0.1	0.3	1.1	2.1	0.1	1.4

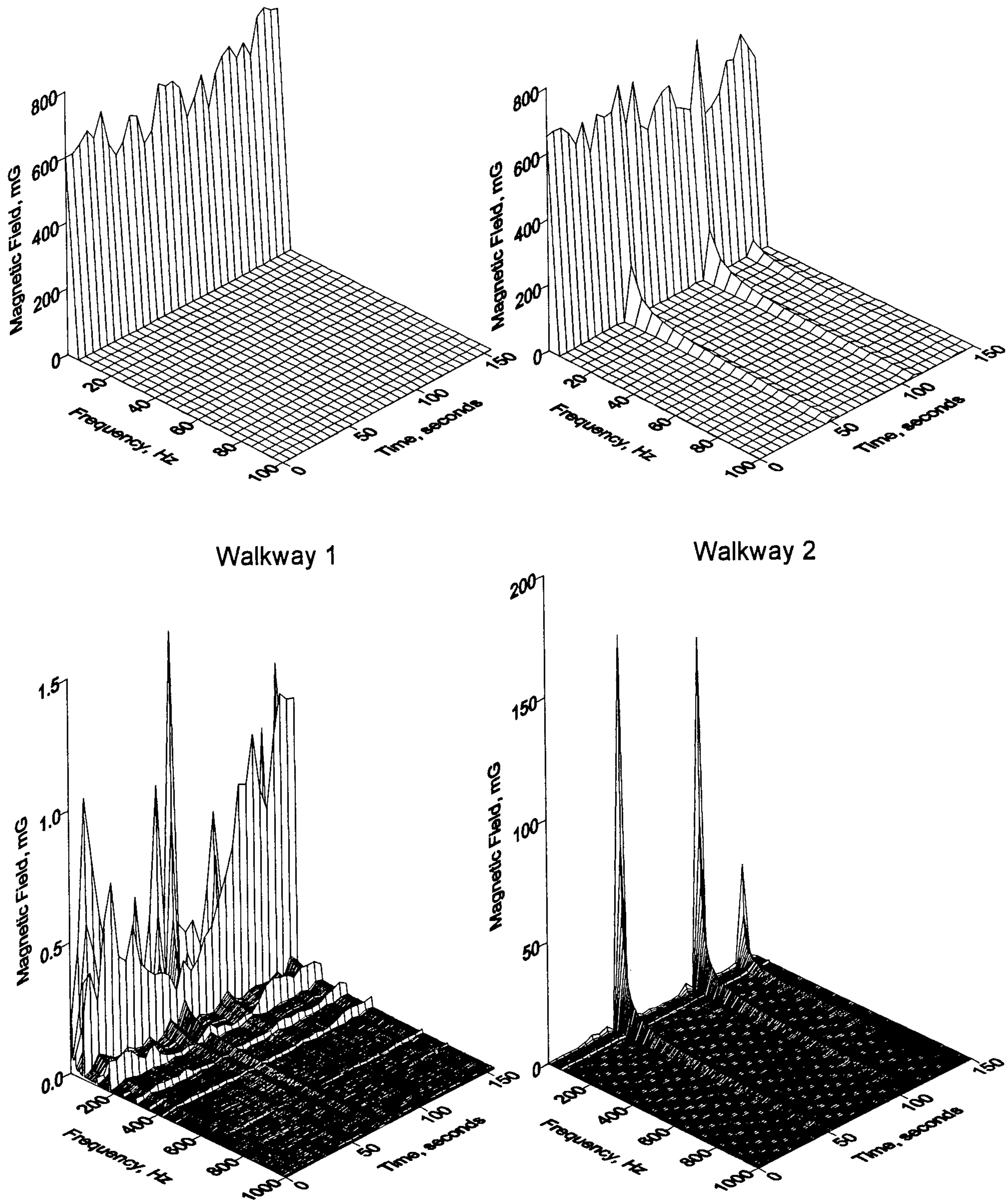


Figure 9-4 Magnetic Fields as a Function of Frequency and Time Measured 3 ft Above the Surface on Two Moving Walkways (Static Field is Suppressed in the Lower Frame).

Power-frequency fields tend to be higher on the walkways than on the escalators and are generally highest at the 1 ft measurement height. But the levels of these fields are not consistent on identical walkways. Hence, the source is more likely power conduits in or beneath the floor than the drive system of the moving walkways.

9.5 Security Equipment

Magnetic field measurements were made in and near a walk-through metal detector and near the carry-on baggage x-ray equipment.

Magnetic field values 1, 3, and 5 ft above the ground in and near the metal detector are given in Table 9-5. The frequency spectrum of the magnetic field in the detector is shown in Figure 9-5. The fundamental frequency of this field is 210 Hz, but it is rich in harmonics which apparently extend well beyond the 3 kHz limit of the measurement equipment employed for this test. Although this field is relatively intense within the detector (51 mG), it attenuates to approximately 11 mG at two ft on either side. The ELF field is less than 2 mG at 6 ft from the center. This field is unusual in that its fundamental and significant harmonic components occur at frequencies above most commonly encountered ELF magnetic fields.

The carry-on baggage x-ray screening equipment is located immediately adjacent to the metal detector. As indicated in Table 9-5 and Figure 9-5, no significant field components attributable to the x-ray equipment (at frequencies other than those unique to the metal detector) were observed along the route by which a passenger would pass the x-ray equipment. An additional measurement was made adjacent to the conveyor belt from the x-ray machine where a traveler might reasonably stand while reaching for his bag. At that point, the 1.4 to 1.9 mG ELF field was principally power frequency (1.1 to 1.4 mG) and harmonics. It did not appear to originate from the x-ray machine or conveyor because the strongest fields were at 5 ft. Fields at the level of the security equipment or beneath were consistently lower. Based on these limited measurements, the baggage screening equipment is not a significant ELF field source in areas accessible to the traveler.

9.6 Baggage Carousel

The airport where these tests were conducted is equipped with large, oval-shaped carousels where the passenger retrieves his luggage. Luggage enters the carousel by way of a slide from a conveyor system above the suspended ceiling. To characterize the fields around this device, spot magnetic field waveform measurements were made at three heights (1, 3, and 5 ft) above the ground at twelve locations equally spaced around the periphery of the carousel. All measurements

Table 9-5
Magnetic Field Levels Passing Through
an Airport Metal Detector

Distance From Detector	Height Above Floor	Static 0 Hz (mG)	ELF Freq. 5-3000 Hz (mG)	Low Freq. 5-55 Hz (mG)	Power Freq. 60 Hz (mG)	Harmonics 65-300 Hz (mG)	High Freq. 305-3000 Hz (mG)
-2 ft	5 ft	528	11.5	0.1	0.5	7.7	8.6
	3 ft	531	11.8	0.1	0.4	7.9	8.8
	1 ft	567	9.9	0.1	0.5	6.7	7.3
	Average	542	11.1	0.1	0.5	7.4	8.2
0 ft	5 ft	515	46.6	0.3	0.6	30.5	35.3
	3 ft	534	55.2	0.2	0.6	36.0	41.8
	1 ft	609	50.2	0.1	0.6	33.3	37.5
	Average	553	50.7	0.2	0.6	33.3	38.2
2 ft	5 ft	508	10.6	0.1	0.6	7.1	7.9
	3 ft	548	11.8	0.1	0.5	7.9	8.7
	1 ft	637	10.6	0.1	0.6	7.2	7.8
	Average	564	11.0	0.1	0.6	7.4	8.1
4 ft	5 ft	506	3.3	0.1	0.5	2.1	2.5
	3 ft	554	3.9	0.1	0.4	2.5	3.0
	1 ft	633	3.3	0.1	0.5	2.1	2.5
	Average	564	3.5	0.1	0.5	2.2	2.6
6 ft	5 ft	505	1.7	0.3	0.5	0.9	1.3
	3 ft	553	1.9	0.3	0.4	1.1	1.5
	1 ft	632	1.6	0.2	0.5	0.9	1.2
	Average	563	1.7	0.3	0.5	1.0	1.3

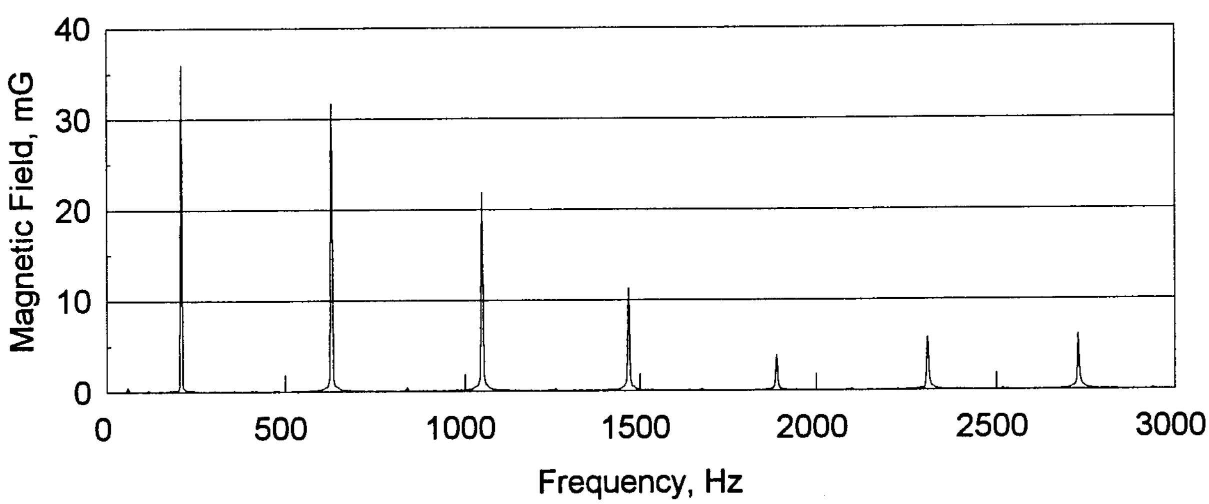


Figure 9-5 Frequency Spectrum of the Magnetic Field in the Metal Detector at a Height of 3 ft above the Floor.

were 1 ft from the edge of the carousel base (the nearest that a traveler would likely stand even while retrieving luggage). Field levels are reported in Table 9-6.

Static field values vary markedly around the device, especially at the 1 ft height. Similarly, ELF fields at the 1 ft measurement height were also variable around the carousel, ranging from 0.3 to 11.9 mG. At the higher measurement locations, ELF fields averaged ten times less than at 1 ft and were less variable around the carousel.

Power-frequency components are only a minor contributor to the field averaging about 0.3 mG at the 1 ft height and 0.1 mG at the higher measurement positions. Hence, the carousel drive motors and associated wiring are ruled out as significant field sources. The low frequency components which dominate the field appear to arise from the motion of ferromagnetic material in the carousel past the measurement point. The occurrence of the largest low-frequency field at the time and location with the most abhorrent static field level is consistent with this conclusion.

Table 9-6
Magnetic Field Levels in Milligauss (mG) at Twelve Equally Spaced Measurement Locations
Around an Airport Baggage Carrousel (Data at Three Heights Above the Floor)

Location	Static 0 Hz			ELF 3 Hz to 3 kHz			Low ELF 3 Hz to 57 Hz			Power Freq. 60 Hz 3 kHz			Power Harmonics 63 Hz to 300 Hz			High ELF 300 Hz to 3 kHz		
	1 ft	3 ft	5 ft	1 ft	3 ft	5 ft	1 ft	3 ft	5 ft	1 ft	3 ft	5 ft	1 ft	3 ft	5 ft	1 ft	3 ft	5 ft
1	1003	647	617	1.0	0.4	0.2	1.0	0.4	0.2	0.3	0.2	0.2	0.1	0.1	0.0	0.1	0.1	0.0
2	1253	598	563	3.8	0.2	0.2	3.7	0.1	0.1	0.2	0.1	0.1	0.7	0.0	0.0	0.4	0.0	0.0
3	1151	626	548	2.3	0.4	0.2	2.2	0.4	0.2	0.1	0.1	0.1	0.4	0.1	0.0	0.2	0.0	0.0
4	1128	527	419	3.9	0.3	0.2	3.8	0.3	0.2	0.3	0.1	0.1	0.8	0.1	0.0	0.4	0.0	0.0
5	850	702	631	3.9	1.0	0.9	3.8	1.0	0.9	0.3	0.1	0.1	0.7	0.2	0.2	0.4	0.1	0.1
6	761	812	698	2.0	0.4	0.3	2.0	0.4	0.3	0.1	0.1	0.1	0.4	0.1	0.1	0.2	0.0	0.0
7	825	700	648	5.1	0.5	0.9	5.0	0.5	0.9	0.3	0.1	0.1	1.0	0.1	0.1	0.5	0.1	0.1
8	205	585	555	12.2	0.4	0.2	11.9	0.4	0.2	0.8	0.1	0.1	2.3	0.1	0.0	1.2	0.0	0.0
9	681	530	498	3.9	0.2	0.2	3.8	0.1	0.2	0.3	0.1	0.1	0.8	0.0	0.0	0.4	0.0	0.0
10	540	701	634	0.4	0.2	0.3	0.3	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0
11	893	689	625	6.2	0.3	0.3	6.0	0.2	0.2	0.6	0.2	0.2	1.2	0.0	0.0	0.6	0.0	0.0
12	832	691	623	1.8	0.2	0.2	1.8	0.2	0.1	0.2	0.1	0.2	0.3	0.0	0.0	0.2	0.0	0.1
Summary of Field Levels Around the Carrousel																		
Minimum	205	527	419	0.4	0.2	0.2	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0
Maximum	1253	812	698	12.2	1.0	0.9	11.9	1.0	0.9	0.8	0.2	0.2	2.3	0.2	0.2	1.2	0.1	0.1
Median	841	668	620	3.9	0.3	0.2	3.7	0.3	0.2	0.3	0.1	0.1	0.7	0.1	0.0	0.4	0.0	0.0
Average	844	651	588	3.9	0.4	0.3	3.8	0.3	0.3	0.3	0.1	0.1	0.7	0.1	0.1	0.4	0.0	0.0
Std. Dev.	275	79	72	3.0	0.2	0.2	2.9	0.2	0.3	0.2	0.0	0.0	0.6	0.0	0.0	0.3	0.0	0.0

10.0 SUMMARY AND CONCLUSIONS

The preceding sections of this report provide extensive data describing the static and ELF time-varying magnetic field and ELF electric field environments in a variety of widely-varying transportation systems. In each system (and often within different vehicles of the same system), magnetic fields differ in frequency distribution, temporal distribution, and spatial distribution. Hence, looking at summary descriptors of field intensity appears to dismiss other possibly important characteristics of the field. That is not the authors intent in this summary discussion. The following comparisons of field levels are in no way intended to trivialize other aspects of the field discussed more fully in preceding sections.

10.1 Summary of Magnetic Field Levels

Magnetic fields have large spatial variability in all transportation systems and large temporal variability in most. Table 10-1 shows the magnitude of the magnetic field in various frequency bands averaged across a wide range of passenger-relevant locations and a full spectrum of operating conditions. The maximum recorded field level in each transportation system is also tabulated, but placed in parenthesis. These maximum values represent the highest recorded field level at any location and any instant in time. Since thousands of measurements were made in some transportation systems, the maximum field levels represent rare events which may have no particular significance except to identify the wide range of field variability possible in each system. Minimum field levels are not tabulated because, in most cases, they are essentially zero. The reader is encouraged to consult the information contained in the body of this report for more complete system-by-system descriptions of the spatial and temporal variability in magnetic field levels.

Static magnetic fields are comparable in all ten transportation systems which is not unexpected because these fields arise predominantly from the natural magnetism of the earth. There is some suggestion in the data that static magnetic fields are produced at some ankle-level locations in the electric cars, trucks, buses, and commuter train. All of those vehicles make use of direct electric current. Those artificially generated static (direct current) fields do not add appreciably to the average total static field environment of the vehicles but do increase the temporal and spatial variability of the static field. However, the variability of the static fields in those vehicles using dc current is not dramatically inconsistent with the static field variability of other systems which do not use dc current.

To facilitate visualization of the differences in time-varying field levels in the ten transportation systems, the average and maximum time-varying field levels are shown graphically in Figures 10-1 and 10-2, respectively. For each vehicle, a bar indicates

Table 10-1
Average and Maximum (in Parenthesis) Magnetic Field Levels
Measured in Ten Transportation Systems

Transportation System	Static 0 Hz mG	ELF Frequencies 5-3000 Hz mG	Low, Sub-Power Freq. 5-55 Hz mG	Power Frequency 60 Hz mG	Power Harmonics 65-300 Hz mG	High ELF Frequencies 305-3000 Hz mG
Ferry Boat	511 (760)	0.6 (3.3)	0.2 (1.0)	0.4 (3.1)	0.2 (1.2)	0.1 (0.3)
Escalators	557 (958)	1.5 (61.4)	1.3 (60.1)	0.4 (3.2)	0.2 (10.5)	0.1 (0.3)
Moving Walkways	576 (1218)	3.7 (200.0)	3.1 (195.4)	1.2 (12.4)	0.7 (37.2)	0.3 (19.0)
Conventional Cars and Light Trucks	321 (968)	5.7 (124.5)	5.5 (124.2)	0.9 (19.4)	0.8 (13.6)	0.4 (7.8)
Electric Cars and Light Trucks						
FUDS on a Dynamometer	408 (1286)	5.7 (80.8)	3.4 (56.1)	0.9 (12.5)	3.6 (79.9)	1.0 (8.6)
Driving on a Test Track	388 (1041)	5.7 (93.5)	4.8 (92.7)	0.8 (15.3)	1.9 (24.5)	0.7 (6.9)
Jetliner	552 (669)	13.6 (212.5)	0.6 (3.5)	0.0 (0.6)	0.2 (8.1)	13.5 (212.4)
Shuttle Tram (AC Electric)	470 (835)	13.7 (90.4)	10.7 (88.5)	5.5 (29.0)	3.0 (14.4)	1.2 (7.0)
Conventional Transit Bus	401 (1124)	16.8 (145.7)	16.4 (144.2)	0.9 (14.2)	1.9 (21.3)	2.1 (24.8)
Electric Shuttle Bus	381 (808)	20.4 (487.8)	14.7 (486.7)	0.8 (38.8)	8.9 (220.5)	1.6 (10.7)
Commuter Train (AC Electric)	538 (1969)	49.6 (799.3)	18.5 (453.5)	34.2 (738.8)	14.6 (340.3)	5.9 (48.7)

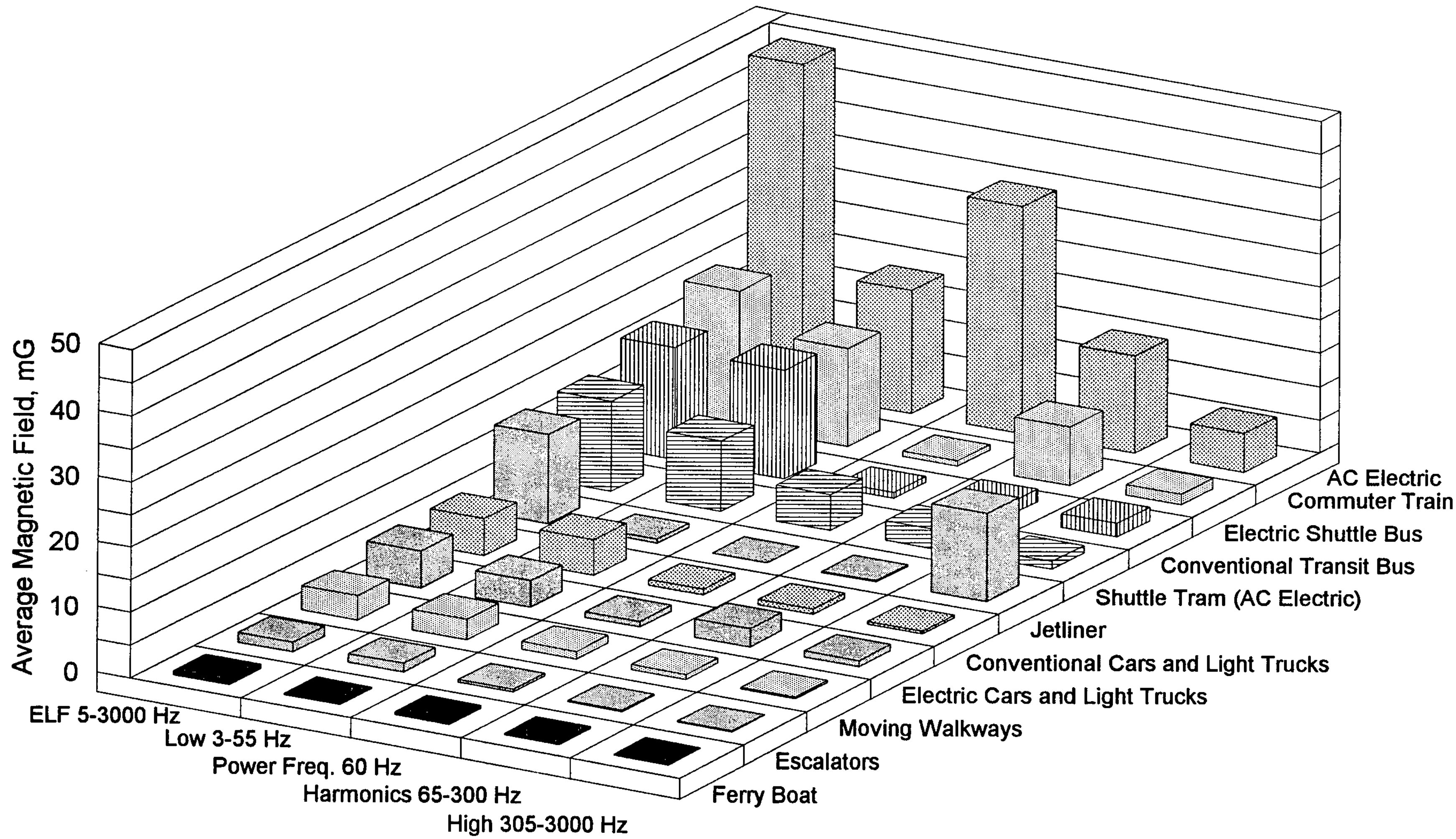


Figure 10-1 Average, Time-Varying Magnetic Field Levels in Ten Transportation Systems for Selected Frequency Bands.

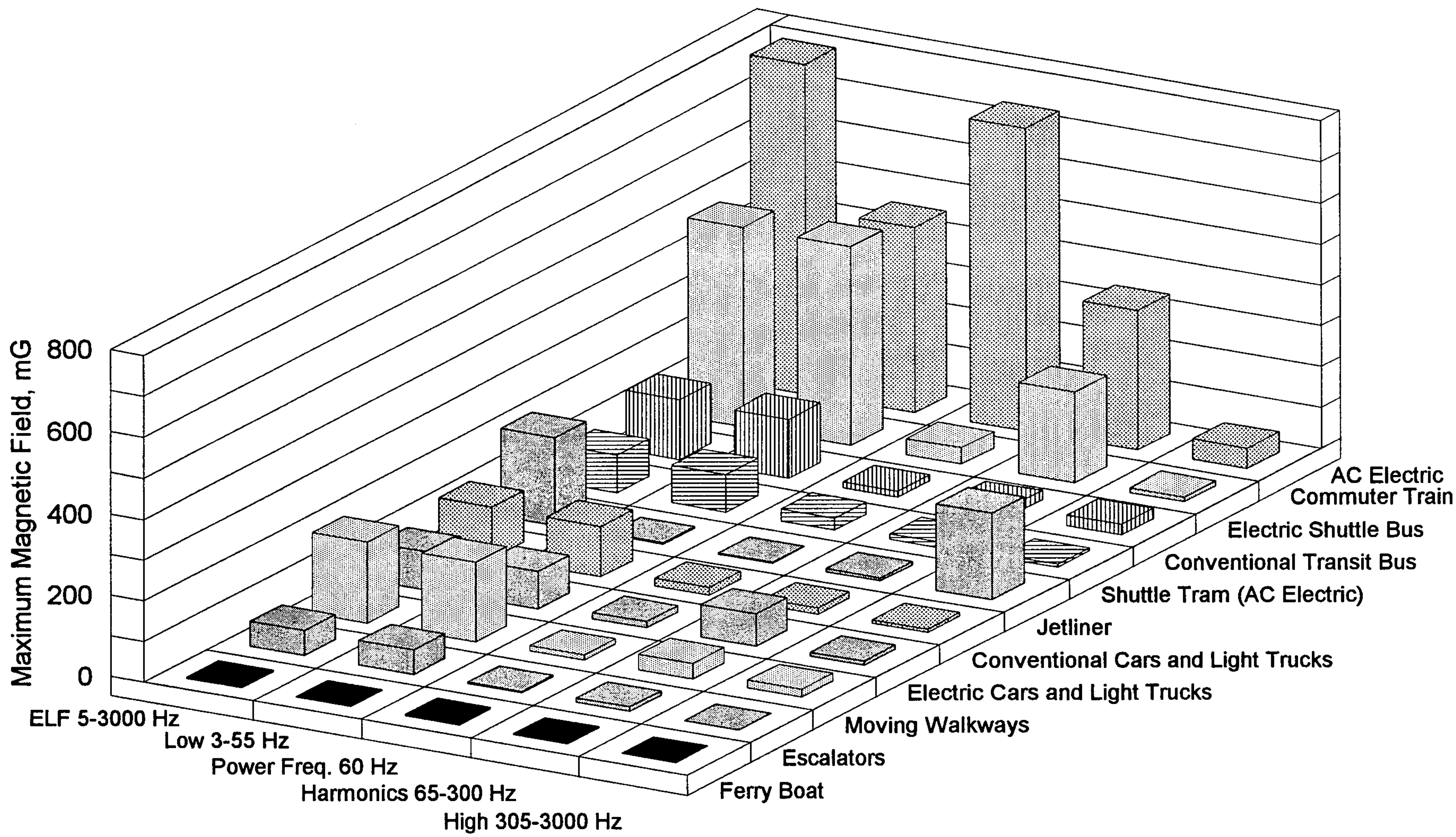


Figure 10-2 Maximum Time-Varying Magnetic Field Levels in Ten Transportation Systems for Selected Frequency Bands.

the total ELF field (5 Hz to 3 kHz) as well as the field level in four sub-bands. In this way, Figures 10-1 and 10-2 not only compare field levels between vehicles, but also provide a rudimentary indication of the frequency distributions of those fields.

In most of the ten transportation systems, the ELF magnetic fields appear primarily in the low range of frequencies below the normal 60 Hz power frequency (the sources and characteristics of those low frequency fields are summarized in the next subsection). Notable exceptions to that trend are the jetliner and the commuter train. The train has low frequency levels comparable to those in other large vehicles. However, they are eclipsed by the larger 60 Hz and harmonic fields.

In the case of the jetliner, the sources of low frequency fields are absent due to the high speed of its engines, the absence of ferromagnetic parts in its engines and airframe, and its operation away from ferromagnetic objects which severely perturb the geomagnetic field. In the jetliner, the major field source is the 400 Hz electric power wiring and electric devices such as lights in the cabin.

Sixty-hertz power frequency fields are only a major component of the magnetic field environment of the airport shuttle tram and the commuter train. Those vehicles are unique among the systems tested in that electric power for the on board propulsion systems is delivered to the vehicle in the form of 60 Hz current from a third rail system and a catenary system, respectively. The 60 Hz magnetic fields arise from both the power delivery system and on board wiring and equipment which utilize the 60 Hz power.

Time-varying magnetic fields in the power harmonics (65-300 Hz) and high ELF frequency (305-3000 Hz) bands are elevated in the vehicles which make use of on board electric propulsion systems, namely the electric cars, trucks and bus, the airport shuttle tram, and the commuter train. Those fields appear to result from power electronic equipment and associated wiring which convert dc electric power from vehicle batteries or 60 Hz electric power from supply circuits to other frequencies need for propulsion and other on board systems.

Electric highway vehicles have ELF field levels similar to their conventional internal combustion counterparts. Low frequency fields from similar sources dominate in both types of vehicles. Although higher frequency (greater than 60 Hz) fields are, on average, only a minor part of the total field environment, those components are markedly higher in some electric vehicles than their conventional counterparts. In those vehicles, the magnetic field sources tend to be localized and usually most intense near the ankles of the traveler.

10.2 Summary of Electric Field Levels

ELF electric fields are essentially nonexistent in most transportation systems. The notable exception is the commuter train which is powered from a high voltage (27 kV) 60 Hz overhead catenary system. Chest-level electric fields in the commuter train were 60 Hz with negligible harmonic distortion. They ranged from near zero to 18 v/m, averaging 4.6 v/m.

The only detectable time-varying electric fields in other vehicles were low frequency fields associated with the movement of passengers or test personnel near the measurement site. Static electric charge on synthetic clothing and other belongings produce a static electric field. When those objects move around the vehicle, there is an associated time-varying component consisting of very low frequency components. Those were detected and found to be typically in the range of 3 to 30 v/m.

10.3 Magnetic Field Sources

Source identification was not an intended component of this effort. Nevertheless, the comprehensive field characterization provided by the magnetic field waveform sampling techniques employed provides valuable insight to significant sources of magnetic fields in transportation systems. The following paragraphs identify the principal sources identified and some salient characteristics of the fields which they generate.

10.3.1 Moving Magnetized Mechanical Components

Nearly all of the transportation systems use ferromagnetic components in their engines and drive trains. Many of those components have some apparently unintentional residual magnetism. When those magnetized components move, they produce time-varying magnetic fields. Periodic magnetic fields were observed from rotating engine and drive train components in both conventional and electric vehicles. A common and significant source is residual magnetism in the steel belts of radial tires on personal highway vehicles (cars and light trucks). The frequency of the fields originating from these sources is proportional to either vehicle or engine speed and most typically in the range of frequencies below 100 Hz. This was the dominant source of magnetic fields in many vehicles.

Linearly moving magnetized components was a dominant time-varying magnetic field source on escalators and moving sidewalks. Components of both the handrail and tread are magnetized and produce time-varying fields as they return the opposite direction beneath the tread.

10.3.2 Movement Through Non-Uniform Static Fields

The geomagnetic field which surrounds all transportation equipment is highly perturbed by ferromagnetic objects such as steel in highway bridges, tunnel reinforcing steel along underground tramways, structural steel in and near escalators and moving sidewalks, or even parked or passing transportation vehicles. Furthermore, any of those ferromagnetic objects can have their own magnetism. As a result, there are frequently large spatial gradients in the static field along the route of travel of a transportation vehicle. There is a significant transient field in the vehicle as it passes through those gradients. The magnitude of the time-varying components in the ELF band is dependant upon the steepness of the gradient and rate of passage through it. However, since the rate of passage is usually rather low compared to frequencies in the ELF band, the largest components of the time-varying magnetic field are almost always in the lowest few frequency bins (5 Hz and 10 Hz) and decrease in intensity rapidly at higher frequencies. Magnetic fields from this source demonstrate large temporal variability, contributing significantly to maximum field levels but having lesser effect on average or median levels.

10.3.3 Anisotropic Shielding by Vehicle Body

In most of the transportation systems examined, the vehicle was constructed using ferromagnetic materials which perturb and generally attenuate the geomagnetic field as it enters the vehicle. The extent of static field perturbation and shielding is highly dependant upon location in the vehicle and orientation of the vehicle with respect to the geomagnetic field vector. If the orientation of the vehicle changes as when negotiating a turn, the magnitude of the static field changes at most locations in the vehicle giving rise to time-varying components with characteristics similar to those described in Section 10.3.2 above. In fact, this anisotropic shielding by the vehicle body typically enhances the low frequency fields generated by traveling through a spatially perturbed magnetic field because, in the area of perturbation, the static field orientation often changes dramatically over short distances.

10.3.4 On Board Electric Propulsion System

Vehicles having an on board electric propulsion system such as electric cars, trucks, buses, airport trams and electric commuter railroad vehicles all contain electric motors and the electric power control circuitry and devices necessary to regulate the traction power needs of the vehicle. Previous measurements

[1] in electric power guided ground transportation systems demonstrated the wide range of field conditions which could be produced by these devices. All of the electric powered transportation vehicles examined in this study used newer power semiconductor technology to control electric power to the traction motors. Some used ac traction motors rather than dc motors as has been done historically making use of newer electronic inverter technology.

Vehicles in this class typically exhibited magnetic fields with a fundamental frequency component in the vicinity of 100 to 200 Hz from the electronic converters but usually had significant harmonic fields throughout much of the ELF range. This accounts for the elevated fields in the power harmonics frequency range (65-300 Hz) and high ELF frequency range (305-3000 Hz) seen for these vehicles in Figures 10-1 and 10-2.

Some vehicles such as the commuter train vehicles use ac traction motors. To control the speed of travel, the electronic traction power control invertors produce ac power at variable frequencies. (The speed of the motor is proportional to the frequency of the applied electric power.) In these vehicles, speed-dependant magnetic fields (in the frequency range from zero to approximately 100 Hz) are observed in some locations.

10.3.5 Stationary Electric Propulsion System

People-movers such as moving walkways, escalators, and elevators typically have stationary electric drive systems which today usually operate from 60 Hz power. Measurements carried out in this project suggest that these stationary power sources are at best very modest field sources creating 60 Hz magnetic fields which are difficult to detect in the presence of ambient 60 Hz fields from other sources.

10.3.6 Power Delivery Circuits

Vehicles such as the airport tram and the electric commuter railroad cars receive electric power from a third rail system or overhead catenary system. Both of the systems tested in this project received ac power at 60 Hz. Other systems use dc power or ac power at other frequencies [1]. To facilitate electric power connections with the moving vehicle while avoiding short circuits, the conductors of the power supply circuits must have reasonable separation. Smaller, three-phase ac systems like the airport tram have a "third rail" system in the center of the guide way with three power conductors separated by approximately 6 inches. Large rail systems have the overhead catenary supply conductor separated approximately 15 feet from the power return circuit. In both cases, the large spacing between the power supply conductors makes them effective magnetic field sources which contribute to the magnetic field within the vehicle. The time-varying magnetic field in the commuter train was principally 60 Hz. That component averaged 32.4 mG which is consistent with that which arose from catenary-track magnetic fields in other 60 Hz electric railroads (52.0 mG Amtrak Northeast Corridor, 18.2 mG New Jersey Transit Long Branch Line [1]).

10.3.7 On Board Accessories

Magnetic fields from on board accessories such as passenger lighting, ventilating fans, and vehicle headlight controllers were seen on many vehicles. In most cases, these fields are highly localized and often have very specific frequency signatures.

10.3.8 External Field Sources

External magnetic fields from sources unrelated to the transportation system contribute to the field environment within the system. The geomagnetic field was the principal source of static fields in all vehicles. Sixty-hertz fields from powerlines along the roadway were the major source of 60 Hz fields in conventional vehicles which were tested on a range of road types. Those tests suggest that an average 60 Hz magnetic field of about 0.9 mG would be found in any highway vehicle from powerlines along the roadway.

11.0 REFERENCE LIST

1. Safety of High Speed Guided Ground Transportation Systems: Comparison of Magnetic and Electric Fields of Conventional and Advanced Electrified Transportation Systems. Fred M. Dietrich, William E. Feero, and William L. Jacobs (Electric Research and Management, Inc.). Prepared for U.S. Department of Transportation, Federal Railroad Administration. DOT-VNTSC-FRA-93-13. DOT/FRA/ORD-93/07. August 1993.

2. National Transportation Statistics. U.S. Department of Transportation, Bureau of Transportation Statistics. Available on the Internet at URL: http://www.bts.gov/btsprod/nts/apxa/auto98.html. 1998.

3. National Transportation Statistics. U.S. Department of Transportation, Bureau of Transportation Statistics. Available on the Internet at URL: http://www.bts.gov/btsprod/nts/apxa/transt98.html. 1998.

4. Survey and Assessment of Electric and Magnetic Field (EMF) Public Exposure in the Transportation Environment - Phase I. Electric Research and Management, Inc. Prepared for the U.S. Department of Transportation, Volpe National Transportation Systems Center. November 1997.

5. EMF Measurement Database. Administered by T. Dan Bracken, Inc. Available on the Internet at URL: http://www.emf-data.org. The NIEHS/DOE RAPID Program URL is: http://www.niehs.nih.gov/emfrapid/.

6. Assessment of Magnetic Fields Produced by Spinning Steel Belted Radial Tires. Electric Research and Management, Inc. Prepared for the U.S. Department of Transportation, Volpe National Transportation Systems Center. May 1998.