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Safety of High Speed Guided Ground Transportation Systems

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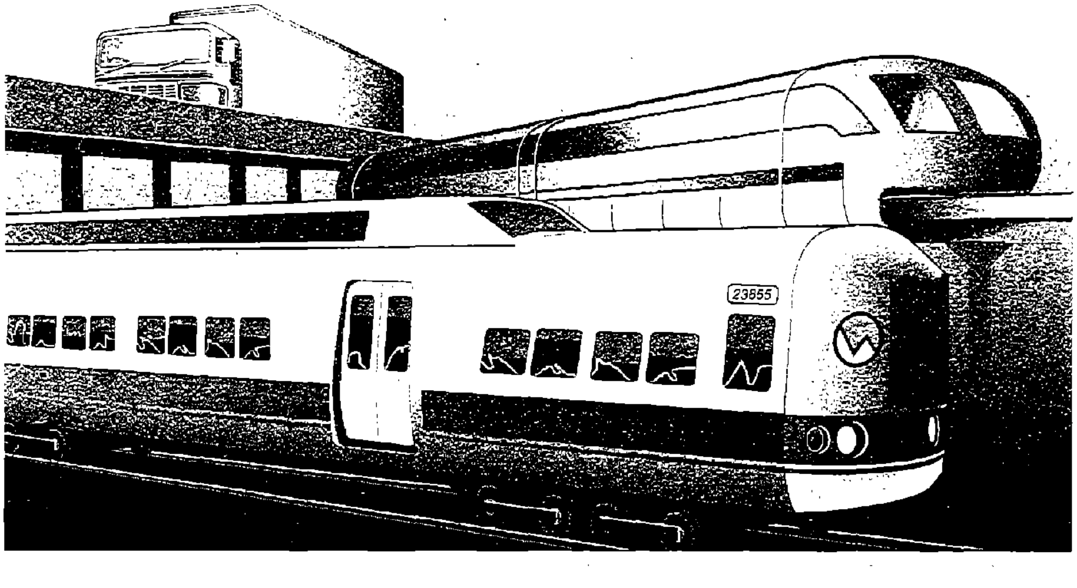

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**Final Report
August 1993**

NOTICE

In places, this report discusses whether various aspects of the technology that is the subject of this report comply with Federal safety laws and regulations. Those discussions, which reflect the seasoned judgement of commentators qualified in their fields, do not constitute rulings by the Federal Railroad Administration's Office of Safety or its Office of Chief Counsel concerning compliance with the law.

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13. ABSTRACT (Maximum 200 words)

The safety of magnetically levitated (maglev) and high speed rail (HSR) passenger trains proposed for application in the United States is the responsibility of the Federal Railroad Administration (FRA). Plans for near future US applications include maglev projects (e.g. in Orlando, FL and Pittsburgh, PA) and high speed rail (the French Train a Grande Vitesse (TGV) in the Texas Triangle).

Concerns exist regarding the potential safety, environmental and health effects on the public and on transportation workers due to electrification along new or existing rail corridors, and to proposed maglev and high speed rail operations. Therefore, the characterization of electric and magnetic fields (EMF) produced by both steady (dc) and alternating currents (ac) at power frequency (50 Hz in Europe and 60 Hz in the U.S.) and above, in the Extreme Low Frequency (ELF) range (3-3000 Hz) is of interest.

This report summarizes and compares the results of a survey of EMF characteristics (spatial, temporal and frequency bands) for representative conventional railroad and transit and advanced high-speed systems including: the German TR-07 maglev system; the Amtrak Northeast Corridor (NEC) and North Jersey Transit (NJT) trains; the Washington, DC Metrorail (WMATA) and the Boston, MA (MBTA) transit systems; and the French TGV-A high speed rail system.

This comprehensive comparative EMF survey produced both detailed data and statistical summaries of EMF profiles, and their variability in time and space, characterizing a range of electrotechnologies. EMF data represent a range of train or transit system operating conditions and locations (in vehicles, stations and waysides), as well as in traffic control and electrical power supply facilities.

EMF ELF levels for WMATA are also compared to those produced by common environmental sources at home, work, and under power lines, but have specific frequency signatures.

14. SUBJECT TERMS
Electric and Magnetic Fields (EMF); Static (dc) Magnetic Field; Alternating (ac) Field; Extra Low Frequency (ELF); Passenger Trains; Maglev; Rapid Transit Rail; Transit; Electrified Rail; Catenary; Third Rail; Electric Locomotive; Traffic Control Center; Passenger Stations; Power Substations; Autotransformer; Power Frequency (PF); Harmonics; Transients; Fourier Analysis; Personal Magnetic Field Exposure Monitor; Digital Audio Tape (DAT) Recorder; MultiWave Magnetic Field Recording System.

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SYSTÈME INTERNATIONAL (SI) UNIT DEFINITIONS AND CONVERSIONS USED IN THIS REPORT

DISTANCE (ENGLISH-TO-SI CONVERSION):

1 inch (in) = 2.54 centimeters (cm) = 0.025 meters (m)
1 foot (ft) = 30.5 centimeters (cm) = 0.305 meters (m)
1 yard (yd) = 91.4 centimeters (cm) = 0.914 meters (m)
1 mile (mi) = 1.61 kilometers (km) = 1,610 meters (m)

ELECTRICAL QUANTITIES:

Electric Fields

1 volt/meter (V/m) = 0.01 volts/centimeter (V/cm)
1 kilovolt/meter (kV/m) = 1000 volts/meter (V/m)
1 kilovolt/meter (kV/m) = 10 volts/centimeter (V/cm)

Magnetic Flux Densities (English-to-SI Conversion)

10,000 gauss (G) = 1 tesla (T)
10 milligauss (mG) = 1 microtesla (μT)
1 milligauss (mG) = .1 microtesla (μT)
0.01 milligauss (mG) = 1 nanotesla (nT)

Electromagnetic Frequency Bands

1 cycle per second = 1 hertz (Hz)
1,000 cycles per second = 1 kilohertz (kHz)

Ultra Low Frequency (ULF) Band = 0 Hz to 3 Hz
Extreme Low Frequency (ELF) Band = 3 Hz to 3 kHz
Very Low Frequency (VLF) Band = 3 kHz to 30 kHz
Low Frequency (LF) Band = 30 kHz to 300 kHz

PREFACE

The Federal Railroad Administration (FRA) has undertaken a series of studies to facilitate the introduction of advanced high speed guided ground transportation (HSGGT) technologies to the United States, including both magnetic levitation (maglev), such as the German Transrapid TR07, and steel-wheel-on-rail high-speed alternatives, such as the French Train à Grande Vitesse (TGV), the Swedish Tilt Train (X2000), and the German Intercity Express (ICE). HSGGT technology options can be expected to undergo detailed public scrutiny and environmental assessment in order to convincingly establish their safety.

Timely development of technical information required for rulemaking initiatives is needed to ensure the public safety. An emerging concern related to environmental, workers', and public health and safety is that of potentially adverse health effects of Extremely Low Frequency (ELF) electric and magnetic fields (EMF). EMF is common in the environment, being produced by power transmission and distribution lines, home and office electric appliances, industrial and laboratory equipment, and by electrically-powered transportation systems.

Magnetic fields are of greater concern than electric fields, because they are pervasive, penetrate biological tissues without attenuation, and are more difficult to shield. Although no federal standards and guidelines on EMF exposure of workers and the public currently exist, international, state, and professional associations have issued interim guidelines.

To enable informed assessments and comparisons to be made among emerging and existing HSGGT technologies, a thorough EMF characterization (frequency, intensity, spatial and temporal variability, source analysis) of all representative existing and advanced electrified transportation systems is needed. This report is the final summary and overview of a comprehensive series of studies addressing the EMF engineering and related safety issues for candidate HSGGT technologies and systems.

Electric Research and Management, Inc. (ERM) was engaged to measure, characterize and analyze the EMF for representative existing and advanced electrified ground transportation systems, under contract to the Federal Railroad Administration (FRA), as monitored by the John A. Volpe National Transportation Systems Center. This report summarizes data for ac electric fields and data on both static (dc) and alternating (ac) magnetic fields, obtained from measurements conducted for several electrified transportation systems. These systems include: the Amtrak Northeast Corrider (NEC) and North Jersey Transit (NJT) trains on the 60 Hz ac power segment of the North Jersey Coast Line (Long Branch) section; the Washington, DC Metrorail (WMATA) and the Boston, MA (MBTA) transit systems; the German TR07 maglev system; and the French TGV-A high speed rail system. A comparison of magnetic fields strengths and frequency characteristics is made for this diverse set of electro-technologies, relative to existing EMF guidelines.

This report was prepared by a team of Electric Research and Management, Inc. (ERM) personnel, led by Fred M. Dietrich, Program Manager and William E. Feero, President. Arne Bang, Senior Manager of Special Programs for the Office of Research and Development, the Federal Railroad Administration (FRA) sponsor for this work, is thanked for overall direction and oversight. The technical monitor for the entire series of reports, characterizing Extreme Low Frequency (ELF) electric and magnetic fields (EMF) for several transportation electro-technologies, was Dr. Aviva Brecher of the DOT/RSPA John A. Volpe National Transportation Systems Center (Volpe Center), Manager of the FRA EMF Research Program. Guidance and program support was provided by Robert Dorer, the High Speed Guided Ground Transportation (HSGGT Safety Program Manager at the Volpe Center. Professor Ross Holmstrom of the University of Massachusetts and the Volpe Center, assisted both in planning the measurements and review of analysis results. Stephanie Markos of the Volpe Center provided valuable editorial guidance, and assistance with report production.

Ronald D. Kangas and Jeffrey G. Mora, both of the Federal Transit Administration Office of Technical Assistance and Safety, provided technical advice and review comments for transit system EMF tests. Valuable assistance with the measurements and logistics, as well as review on the system reports was provided by technical representatives of the operators for each transportation system, as indicated in each detailed system EMF report.

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1. EXECUTIVE SUMMARY

1.1 ELECTRIFIED TRANSPORTATION SYSTEMS STUDIED

A series of studies was conducted to gather comprehensive magnetic and electric field (EMF) data on a variety of electrified transportation systems. With such data, emerging technologies could be adequately and equitably compared to existing technologies and other sources of magnetic and electric fields. This was done to determine if significant changes in public exposure to electric and magnetic fields would result from the introduction of the new maglev technology.

The systems studied include: the German TR07 maglev system [1]; the Amtrak Northeast Corridor (NEC) [2] and North Jersey Transit (NJT) trains, on the 60 Hz ac power segment of the North Jersey Coast Line (Long Branch) section [2], Washington, DC Metrorail (WMATA) [4] and the Boston, MA (MBTA) [5] transit systems; and the French TGV-A high speed rail system [3]. Figure 1-1 depicts the sequence of reports containing the results of the studies on various transportation systems. Pertinent information about the location of the tests and power delivery technology employed in each system is shown as well. Technical characteristics of these systems and their impact on field characteristics are discussed in more detail in Section 2 of this report.

1.2 FINDINGS

The magnitude of the magnetic fields found during the TR07 measurements taken at the Emsland, Germany test track did not demonstrate a significant difference from other environmental magnetic fields from power lines and electrical equipment [1]. However, the frequency characteristics of the magnetic fields produced by the TR07 system were different from those reported for other common magnetic field sources. Specifically, magnetic fields produced by common sources like transmission lines and most other power delivery and utilization equipment are predominantly single-frequency fields at the established power frequency of 60 Hz in North America or 50 Hz in Europe. The TR07 data was more complex because it contained a broad low frequency spectrum. The initial report on the TR07 maglev compared the magnetic fields to the single frequency magnetic field reported in close proximity to transmission and distribution lines and near appliances. However, a cautionary note pointed out that the comparison was not valid if any parameter but magnitude was important. Figure 1-2 gives a graphical perspective of how the magnetic fields measured on the TR07 would compare to magnetic fields near transmission lines, distribution lines, and household appliances [6]. It was plotted as a function of frequency bands which were used to characterize

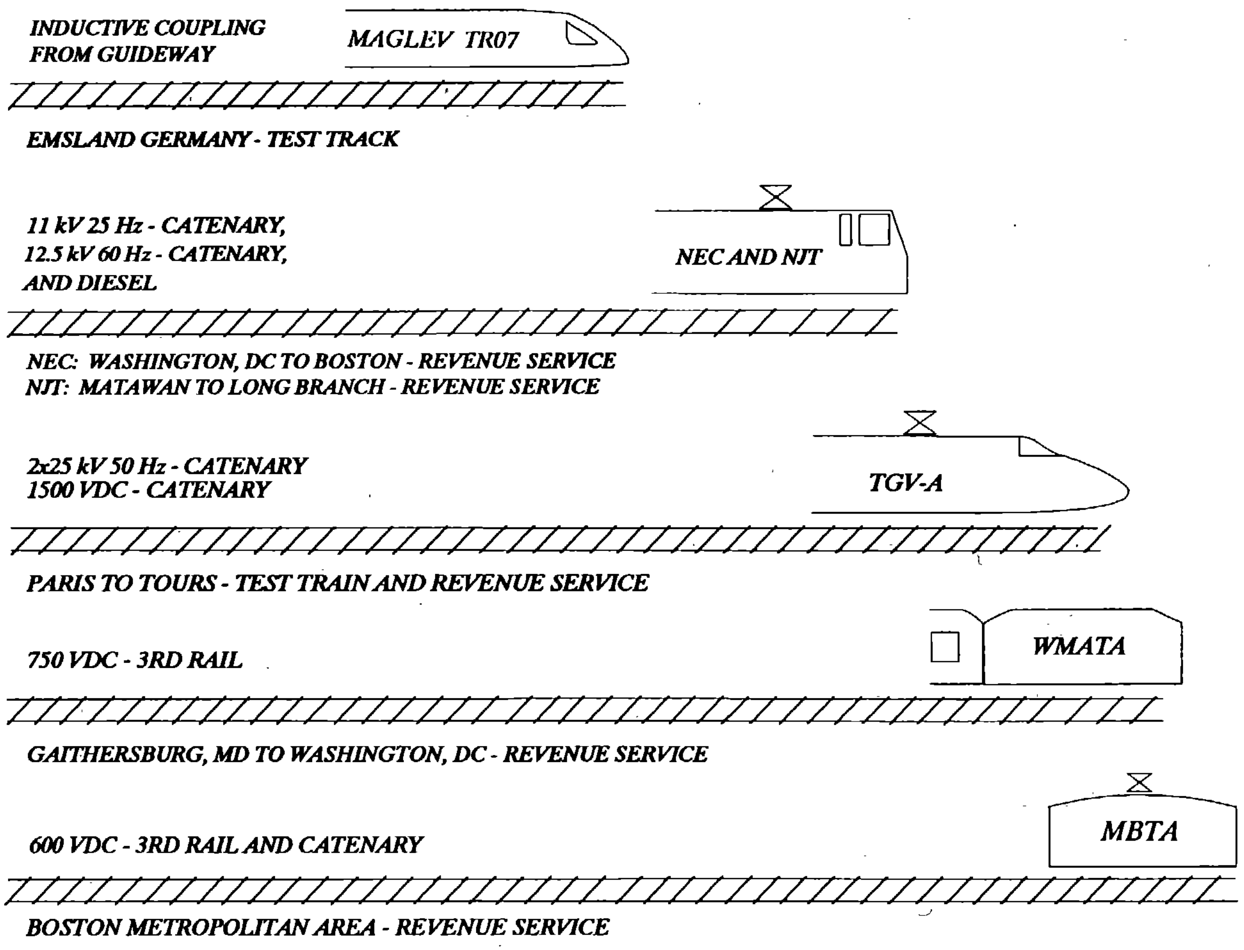


FIGURE 1-1. ELECTRIFIED TRANSPORTATION SYSTEMS ON WHICH LOW FREQUENCY ELECTRIC AND MAGNETIC FIELDS WERE MEASURED

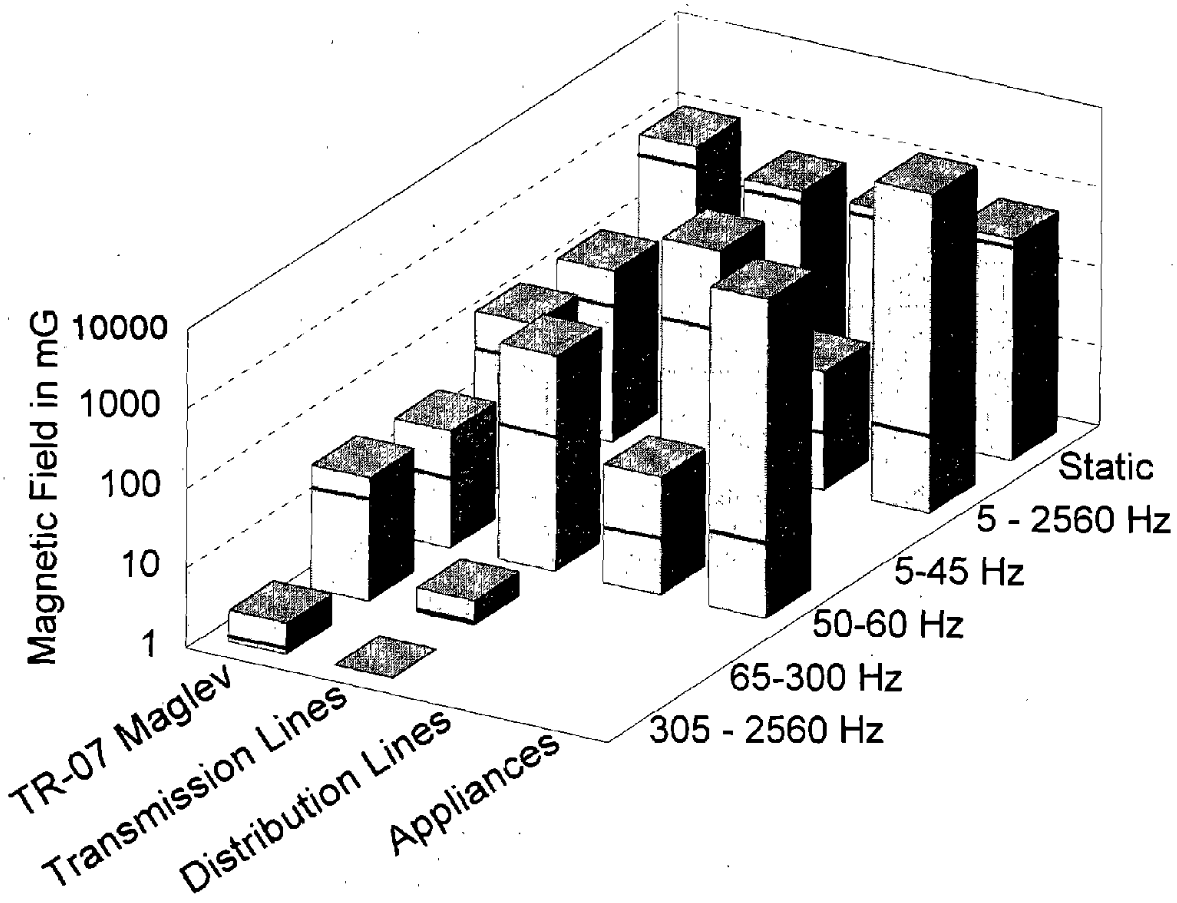


FIGURE 1-2. MAGNETIC FIELDS, AS A FUNCTION OF LOW FREQUENCY SUB-BANDS, IN THE PASSENGER COMPARTMENTS OF THE TRANSRAPID TR07 AS COMPARED WITH REPORTED MAGNETIC FIELDS NEAR TRANSMISSION AND DISTRIBUTION LINES AND HOME APPLIANCES

the TR07 measurements. Transmission line currents contain less than one percent of harmonics and therefore are well characterized as generating principally 50 or 60 Hz fields. With the recent emergence of the widespread use of solid state control devices, distribution lines and household appliances now may generate more than just 50 or 60 Hz magnetic fields. To fairly compare the magnetic field data of the yet to be commercially used TR07 with distribution line and appliance magnetic field data, the "blanks" in Figure 1-2 indicate that little magnetic field data has been recorded in these frequency sub-bands for these recently introduced electrotechnologies [7].

In fact, it can safely be assumed that attractive Electro Magnetic Suspension (EMS) maglev systems of the Transrapid TR07 design do not present any unique magnetic field environment that is not already encountered in a number of different electrified transportation systems within the United States. Note that other design concepts for achieving magnetic levitation, such as the repulsive superconducting Electro Dynamic Suspension (EDS) concepts, may produce significantly higher magnetic fields and have not been addressed in this study.

The subsequent studies of other electrified transportation systems [2-5] were an attempt to collect EMF data which at least permitted comparison within a specific technology. By using a version of the same high quality instrumentation (enhanced for portability) that was used for maglev measurements, multiple frequency magnetic fields that existed in other rail technologies were recorded. This report examines the data sets together to demonstrate how the Transrapid TR07 magnetic field characteristics, both onboard and adjacent to the maglev operating facilities compare to similar measurement on all the other electrified transportation technologies studied.

The following sections in this report present a concise but detailed discussion of relevant data. The data will be cross-compared for surveyed electrotechnologies at key locations (in the passenger sections, in the operator's compartments, at the wayside, on the passenger platforms, near the substations supplying power to the trains, and in the operator control rooms), and for representative operating conditions. The datasets collected in the passenger compartments of the different electrified transportation systems give an overview of the general findings of these studies.

Figure 1-3 (top graphic) is a depiction of the maximum magnetic fields measured on the inter-city trains studied. The magnetic field is presented on a log scale which makes it possible to see both the low-level fields and the higher-level fields. Figure 1-3 (bottom graphic) is a similar plot for the urban transit systems that were monitored. As can be seen from this figure, the magnitudes of the Transrapid TR07 magnetic fields are reasonably typical of magnetic fields found on electrified transportation systems. Their frequency characteristics are not greatly different from the frequency characteristics found when looking at electrified trans-

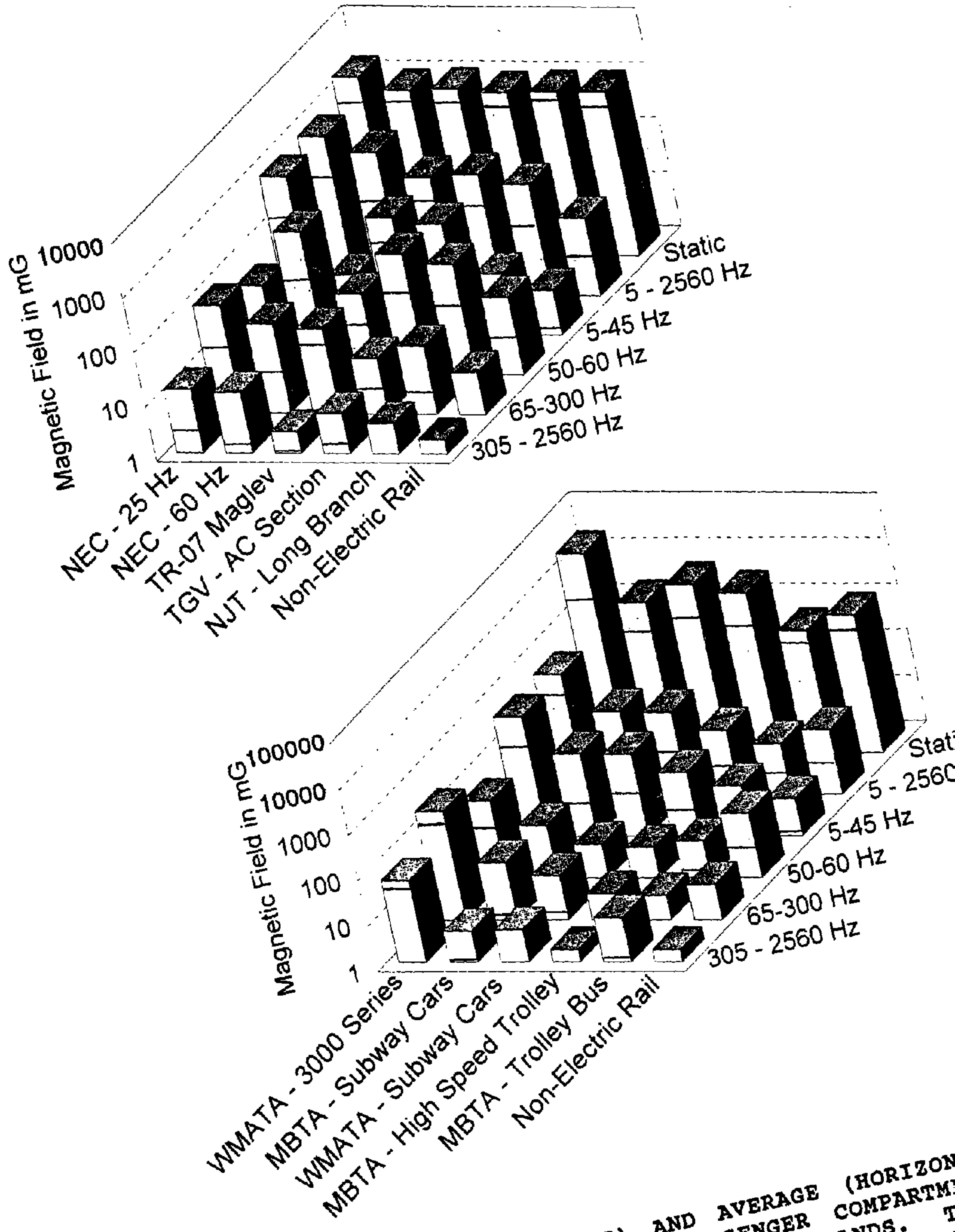


FIGURE 1-3. MAXIMUM (BAR TOP) AND AVERAGE (HORIZON
MAGNETIC FIELDS IN PASSENGER COMPARTM
FUNCTION OF LOW FREQUENCY SUB-BANDS. T
CITY ELECTRIFIED SYSTEMS. BOTTOM:
TRANSIT

portation technology as a whole. In fact, it can be inferred from this figure, and the report, that the Transrapid TR07 maglev system does not represent a unique electro-magnetic environment and that is comparable to EMF characteristics measurable in a number of different electrified transportation systems within the United States.

As shown in Figure 1-4, none of the magnetic fields measured in or near any of the electrified transportation systems surveyed exceed the threshold limit value (TLV) of any existing standard or guidelines for occupational or public exposure. This figure shows with bar graphs the maximum magnetic fields found at the height of the torso of adult humans, seated .6 m (2 ft) or standing 1.6 m (5.3 ft). The American Conference of Governmental Industrial Hygienists (ACGIH) [9] guidelines has a caveat restriction that may require further review. ACGIH suggests a further lowering of the TLV by a factor of 10 to ensure non-interference with medical devices, in particu-lar cardiac pacemakers. Figure 1-4 suggests that the reduced TLV may be exceeded at a small localized area in the center of WMATA 3000 series cars. However, compliance cannot be determined because the guideline fails to address treatment of spatially non-uniform fields, highly variable in time (transients), and fields with multiple frequency components. Magnetic fields at other locations and in other transportation systems are well below the reduced TLV recommended for pacemaker wearers. In no case were magnetic fields measured in or near the Transrapid TR07 maglev systems found to be within an order of magnitude of the most restrictive interpretation of any of these standards.

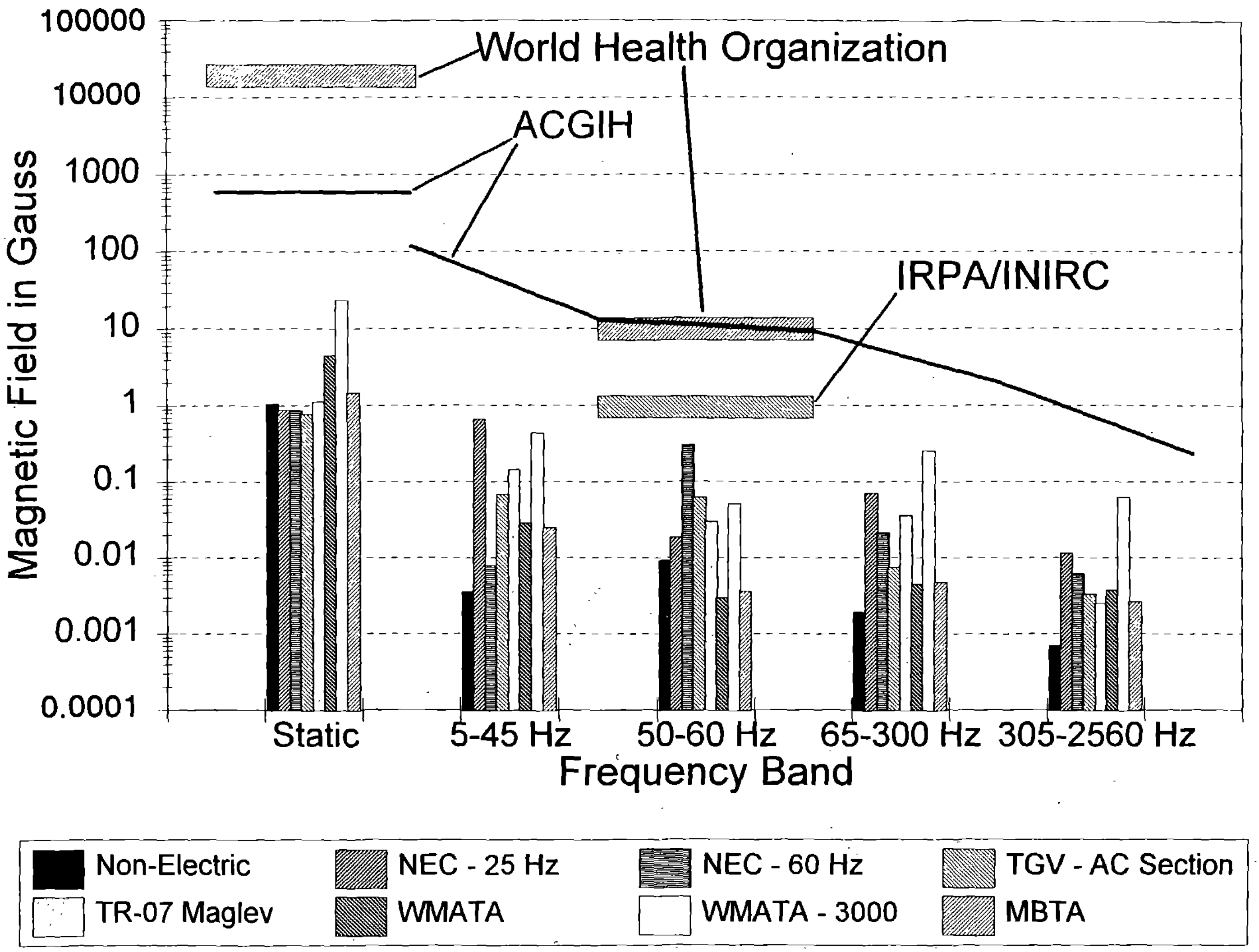


FIGURE 1-4. ELECTRIFIED RAIL MAXIMUM MAGNETIC FIELD LEVELS WITHIN LOW FREQUENCY SUB-BANDS COMPARED TO MINIMUM THRESHOLD LIMIT VALUES OF KNOWN GUIDELINES

2. FIELD CHARACTERISTICS

Electric and magnetic fields (EMF) produced by the electrified transportation systems examined in a series of surveys [1-5] differ not only in intensity from one system to another, but in a number of other specific and potentially important ways. Field characteristics analyzed include the frequency spectra, temporal variability, and spatial variability of the fields in addition to the field magnitude. The individual reports on each set of measurements [1-5] document these field parameters in detail.

This report draws on the specific findings of these individual studies to assess the uniqueness and commonalities of Transrapid TR07 maglev magnetic fields. This chapter discusses the technological characteristics of each surveyed transportation system which significantly affect the electric and magnetic field characteristics. Quantitative comparisons of electric and magnetic field levels associated with the systems examined can be found in following sections.

2.1 TERMINOLOGY

Several terms are often used to refer to the frequency and temporal characteristics of electric and magnetic fields. Throughout this report, as in the preceding individual transportation system reports [1-5], electric and magnetic fields with no temporal variability or with variability substantially slower than the frequency resolution of the measurements reported herein (1 Hz) are referred to as static electric or magnetic fields. Conversely, those portions of the electric and magnetic fields which can be resolved by Fourier Transformation into components with frequencies of 1 Hz or greater are referred to as time varying fields. Contemporary technical literature often uses the term alternating current (ac) fields when describing sinusoidally time varying fields. Since the source of magnetic field time variance was not always related to sinusoidal source currents during electrified rail measurements, the more inclusive term of time varying fields is used in this and the preceding reports. Similarly, the term static fields was chosen over the frequently-used term direct current (dc) field, in that the earth's geomagnetic field was in many cases more significant than fields created by currents in dc circuits.

Time varying fields are subdivided into a number of frequency bands by various conventions. The band definitions accepted by the American National Standards Institute [8] which are relevant to measurements made throughout this program are the extreme low frequency (ELF) band from 3 Hz to 3 kHz and the ultra low frequency (ULF) band lower than 3 Hz.

Electric and magnetic field data measured on electrified ground transportation systems focused on the ELF and ULF bands. Since the static component of the field was in all cases the dominant component of the ULF band, ULF fields and static fields are numerically equivalent in the data reported herein. Although the extreme low frequency fields were resolved into 5 Hz increments of frequency (center frequency ± 2.5 Hz), those very narrow bands were aggregated into five larger bands: 5-2560 Hz; 5-45 Hz; 50-60 Hz; 65-300 Hz; and 305-2560 Hz. The 5-2560 Hz band of frequencies represents the ELF field because none of the systems had appreciable fields between 2560 Hz and the 3000 Hz upper limit of the ELF band. These aggregations are intended to facilitate comparisons of field levels in segments of the ELF band where most of the data on electric power system magnetic fields have been reported.

2.2 TEST PROTOCOL AND INSTRUMENTATION

The majority of the magnetic and electric field measurements were made with a portable version of the *MultiWave*™ monitoring system (hereafter referred to as the waveform capture system). The waveform capture system was augmented with a digital audio tape (DAT) recorder and EMDEX-II personal exposure recorders (hereafter referred to as rms recorders). The DAT recorder was used to obtain a continuous record of magnetic field levels at one location. The rms recorders were used to document the significance of personnel movement through the train or its environs.

The waveform capture system recorded the actual waveform of the three orthogonal components of the magnetic field at multiple measurement locations. This was accomplished by sampling those waveforms at a high rate and storing the values digitally on computer disk or computer tape. The sensors themselves were arrayed on a staff at 0.5 m (1.6 ft) intervals, starting at 0.1 m (.3 ft) from the base, in other words at 0.1, 0.6, 1.1 and 1.6 m (.3, 2, 3.6, and 5.2 ft). The staff, set in an upright position, corresponds to the torso of a standing person. The 0.6 m (2 ft) readings correspond to the midpoint of a seated person. Held in a horizontal position, the staff can be used to capture a field profile, measuring spatial attenuation of the various frequency components, independently. Electric fields were also measured by the waveform capture system using a sensor mounted on the top of the staff 1.7 m (5.6 ft) above the vehicle floor.

The measurement protocol used sensors on this staff to record the spatial variability of the field. The waveform sampling technique characterized the frequency components of the field. Longer-term temporal variability of the field was documented by performing repetitive waveform recordings every ten seconds.

Data was collected at representative system locations: in passenger areas, in wayside areas adjacent to the electrified transporation systems, and in working areas of employees. Figure 2-1 indicates the general position of staff probe and the reference sensor for the various areas where measurements were made: in passenger compartments, inside operator's cabs or locomotives, on passenger platforms, along waysides, inside dispatch or control rooms, outside transformer stations or electric substations, and both inside and outside traction power supply stations.

2.3 FIELD SOURCES

Electric and magnetic fields in the vicinity of any electrified transportation system would occur both from sources associated with the transportation system, and from unrelated sources. These sources include nearby commercial electric power facilities and the background geomagnetic field of the earth. Since electric and magnetic field measurements at any point in space can only quantify the total field regardless of the sources, field data may include field contributions from sources unrelated to the transportation facility. To clearly identify fields from the transportation system, measurements were made at locations onboard or near the transportation vehicles or facilities. These measurements maximized the possibility of detecting fields from the transportation system and its subsystems. Through careful analysis of the resulting data, it has been possible to identify contributory sources. It was also possible to accurately discriminate which portion of the electric and magnetic field environment is attributable to the transportation system. Table 2-1 presents a brief summary and comparison of certain electro-technological characteristics of the surveyed transportation systems, which have bearing on the electric and magnetic characteristics of those systems, and on their sources.

2.3.1 Magnetic Field Sources

In inter-city electrified rail systems using overhead catenaries, electric current flows through the catenaries to meet the traction power requirements of the locomotives and then returns to the substations or autotransformers via the running rails. This current is the most significant source of magnetic fields measured on or near conventional and advanced electrified railroads such as the Northeast Corridor, the NJT North Jersey Coast Line and the TGV-Atlantique. The same situation is expected to occur on all electrified railroads using overhead catenaries to supply alternating current (ac) electric power to locomotives or self-powered cars via a pantograph. A similar situation occurs with urban mass transit systems, which usually receive direct current (dc) power from a third rail. However, current in the third rail and running rails is a less effective magnetic field source, because the supply rail and return rails are in close proximity to each other.

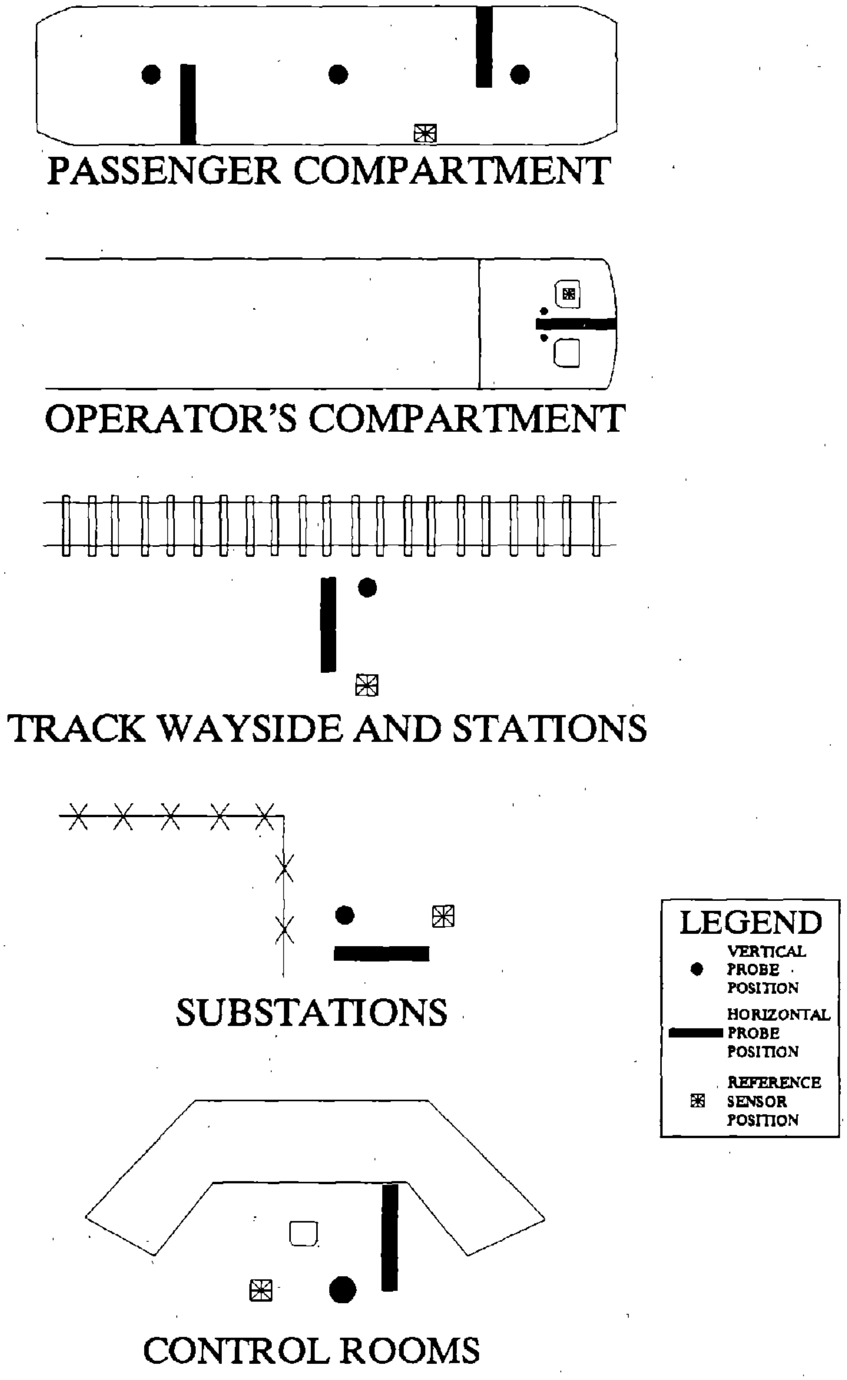


FIGURE 2-1. DEPICTION OF TYPICAL PROBE PLACEMENTS

TABLE 2-1.

SUMMARY OF SYSTEM CHARACTERISTICS WHICH SIGNIFICANTLY IMPACT ELECTRIC AND MAGNETIC FIELDS ASSOCIATED WITH GROUND TRANSPORTATION SYSTEMS

SYSTEM AND LOCATION	TRACTION POWER DELIVERY, VOLTAGE AND FREQUENCY	ONBOARD TRACTION POWER CONTROL	ELECTRICAL BRAKING	LOCATION OF TRACTION POWER EQUIPMENT
TRANSRAPID TR07 EMSLAND, GERMANY	ACTIVE GUIDEWAY LSM, 55-215 Hz	CONTROLLED B1 GUIDEWAY POWER FREQUENCY	DYNAMIC-RESISTORS AT THE INVERTER STATION	GUIDEWAY
NEC-WASHINGTON TO NEW YORK	DOUBLE FED CATENARY, 11 kV, 25 Hz	CONTROLLED RECTIFIERS AND DC MOTORS	DYNAMIC-RESISTORS ABOVE LOCOMOTIVE	IN LOCOMOTIVE
NEC-NEW YORK TO NEW HAVEN	AUTOTRANSFORMER FED CATENARY, 12.5 kV, 60 Hz	CONTROLLED RECTIFIERS AND DC MOTORS	"	"
NEC-NEW HAVEN TO BOSTON	NOT ELECTRIFIED	DIESEL-ELECTRIC; 105 Hz ALTERNATOR, RECTIFIERS AND DC MOTORS	"	"
NJT-MATAWAN TO LONG BRANCH	SINGLE FED CATENARY 12.5 kV, 60 Hz	CONTROLLED RECTIFIERS AND DC MOTORS	"	"
TGV-A-PARIS TO TOURS, FRANCE	AUTOTRANSFORMER FED CATENARY 25 kV, 50 Hz OR 1.5 kV DC CATENARY	VARIABLE FREQ INVERTER WITH AC MOTORS	REGENERATIVE-HI SPEED DYNAMIC-LO SPEED	"
WMATA-1000 AND 2000 SERIES WASHINGTON, DC AREA	THIRD RAIL, 750 V DC	CAM CONTROL WITH DC MOTORS	DYNAMIC-RESISTORS UNDER VEHICLE	BENEATH EACH VEHICLE
WMATA 3000 SERIES WASHINGTON, DC AREA	THIRD RAIL, 750 V DC	273 Hz CHOPPER WITH DC MOTORS	REGENERATIVE-HI SPEED DYNAMIC-LO SPEED	"
MBTA-RED LINE - BOSTON AREA	THIRD RAIL, 600 V DC	CAM CONTROL WITH DC MOTORS	DYNAMIC-RESISTORS UNDER CAR	"
MBTA-BLUE LINE - BOSTON AREA	THIRD RAIL AND CATENARY, 600 V DC	CAM CONTROL WITH DC MOTORS	"	"
MBTA-ORANGE LINE - BOSTON AREA	THIRD RAIL, 600 V DC	CAM CONTROL WITH DC MOTORS	"	"
MBTA-GREEN LINE - BOSTON AREA	CATENARY, 600 V DC	218 Hz CHOPPER WITH DC MOTORS	"	"
MBTA-TROLLEY - ASHMONT TO MATTAPAN	CATENARY, 600 V DC	CAM CONTROL WITH DC MOTORS	"	"
MBTA-TROLLEY BUS - NORTH CAMBRIDGE AREA	DOUBLE CATENARY, 600 V DC	CAM CONTROL WITH DC MOTORS	"	"

In the Transrapid TR07 maglev system, traction power is produced by a "moving" magnetic field in the longstator of the guideway. The frequency of the magnetic field produced by the guideway varies linearly with the speed of the vehicle. Hence, the active guideway represents a significant source of magnetic fields, which may differ from those found in conventional transportation systems. The guideways of some prototype "people mover" systems, which make use of linear synchronous or linear induction motors, may produce magnetic fields having characteristics analogous to those produced by the TR07 guideway. However, none were tested in these studies.

The Transrapid TR07 system is also unique among the other systems surveyed in that it uses magnetic fields for vehicle levitation and guidance. The levitation and guidance fields are nominally static fields and they require dynamic control to maintain the gap equilibrium. As a result, those fields have a significant time varying component. Magnetic fields directly from the levitation and/or guidance magnets, or from current in the cables beneath the vehicle floor which provide power to those magnets, are clearly present within the maglev vehicle. They are also detected briefly along the guideway, or at the station, as the vehicle passes by or stops.

For transportation systems other than the Transrapid TR07 maglev, traction equipment and the associated onboard wiring are generally not dominant magnetic field sources. However, their contributions to the magnetic environment are detectable at specific locations, or at times when fields from other sources are relatively low. There are two clear exceptions to that trend. One is the TGV-A, where a power cable from the pantograph on the locomotive at the rear end of the train travels along the coach tops to the front locomotive. The influence of that cable is discussed along with the discussion of magnetic fields from other systems' catenaries later in this section. The other example of a large, dominant field arising from a piece of traction power equipment is the magnetic field produced by a large reactor beneath the floor of the 3000 (and arriving 4000) series WMATA cars.

Modest magnetic fields are also produced within transportation vehicles by the appliances and associated electric cables for "hotel" services. These include such services as heating, lighting, air conditioning, food service, etc. Fields from these sources are often similar to those near appliances and wiring in homes and offices.

Power supply and conditioning substations, rectifier stations, etc., represent potential sources of magnetic field exposure for workers. They did not produce significant magnetic fields beyond station property lines where the general public may be found.

Magnetic fields were also measured in train/transit control and dispatch areas. They were found not to contain any uncommon magnetic field sources. Within dispatch areas, the principal field sources were video display terminals and general electric wiring within the floor, ceiling, and walls of the room. Hence, the magnetic field environment was like many other office areas. Electric power equipment rooms containing backup power capabilities adjunct to control rooms contain a concentration of electric power circuits and equipment, which produce significant [2] magnetic fields within that room. These conditions are not unique to transportation facilities. Comparable field conditions are reported for electric utility rooms and vaults [10] in any major commercial building.

2.3.2 Electric Field Sources

The only two electric field sources of significance were the high voltage (of order 12 or 25 kV) overhead catenaries (and catenary feeder conductors in autotransformer-fed systems) on the electrified portion of the Northeast Corridor (NEC) section [2], on the electrified portion of the North Jersey Transit (NJT) section [2], on the French TGV-A [3], and the transmission lines supplying power to substations along the electrified railroad lines [2,3]. Third-rail and catenary circuits of the urban mass transit systems were not significant electric field sources in areas routinely accessible to workers or the general public. The voltage on the third rail or catenary was relatively low, in the 600 to 750 volt range. Power delivery to traction power substations feeding urban mass transit systems was typically at distribution voltages. Therefore, the electric fields associated with those systems were no larger than those found near commercial electric power distribution lines commonly found along residential streets. The electric field was not measured near the power supply facilities associated with the Transrapid TR07 system. It is likely that the 110 kV transmission line supplying power to the facility [1] produced electric fields in its immediate vicinity similar to those produced by other high voltage transmission lines.

2.4 MAGNETIC FIELD CHARACTERISTICS

Magnetic fields are produced by electric current flowing in wires or equipment. Consequently, the frequency of the magnetic field is determined by the frequency of the electric current. In most constant voltage electric circuits the rms magnitude of the electric current varies in proportion to the amount of power required by the load. Magnetic fields produced by current in the catenary-track circuit, third rail-track circuit, or onboard traction power circuits and equipment vary in intensity over time depending on the traction power needs of the transportation vehicle. Magnetic fields caused by current in "hotel service" circuits and equipment onboard the vehicle have temporal variabilities unrelated to traction power needs of the system.

2.4.1 Catenary and Third Rail Systems

Electric power is supplied to locomotives or powered passenger vehicles in most electrified systems via overhead catenaries or third rails. Electric current flows from nearby substations or autotransformer stations along the wayside to the vehicle along the catenary or third rail. It then returns through the running rails to complete the electrical circuit. This "loop" circuit represents an efficient magnetic field source. In many cases it is the principal source of magnetic fields onboard or near such transportation systems. Passengers and crew onboard vehicles operating from catenaries are inside the current consisting loop of the catenary and running rail return currents. In vehicles operating from third rails, passengers and crew are not directly in the current loop consisting of the third rail supply and running rails return, so they experience lower magnetic fields. Since larger loops produce larger fields at nearby locations than do smaller loops, catenary systems which are 5 to 8 m (16 to 26 ft) above the rails produce larger magnetic fields at the station platform or wayside than the third rail systems. For the third rail system, the power rail is within a meter (3.3 ft) of the running rails, assuming all other factors are equal.

The magnitude of the magnetic field is proportional to the magnitude of the current in the loop. Consequently, the magnetic field fluctuates according to the power needs of the locomotive or powered cars. Additionally, current flowing past the point in question to provide power to other trains in the same power block between substations, or autotransformer stations, creates additional magnetic fields which add to those produced by the train in question. As a result, magnetic fields produced by the loop circuit source are highly variable over time, both on the train and along the wayside. Figure 2-2 shows a typical example of the temporal variability in magnetic field onboard an Amtrak train. More detailed data on the magnetic field from current in the catenaries or third rails and running rails for the electric field transportation systems monitored are found in the individual system reports [2-5].

The magnetic fields produced by current in the catenary or third rail and return current in the running rails have the same frequency characteristics as the current. As mentioned previously, the electric utility fundamental power frequencies are 50 Hz in Europe and 60 Hz in North America. Some older systems such as the Amtrak Northeast Corridor south of New York City use non-standard frequencies like 25 Hz (see Figure 2-3). Some electrified rail systems in Europe still use 16.67 Hz. This supply frequency uniqueness was utilized to help analyze likely sources for measured fields. The electronic control circuits within locomotives and powered cars distort the current waveform. They create current components at frequencies which are integer multiples of the base power frequency. These higher frequency components of the

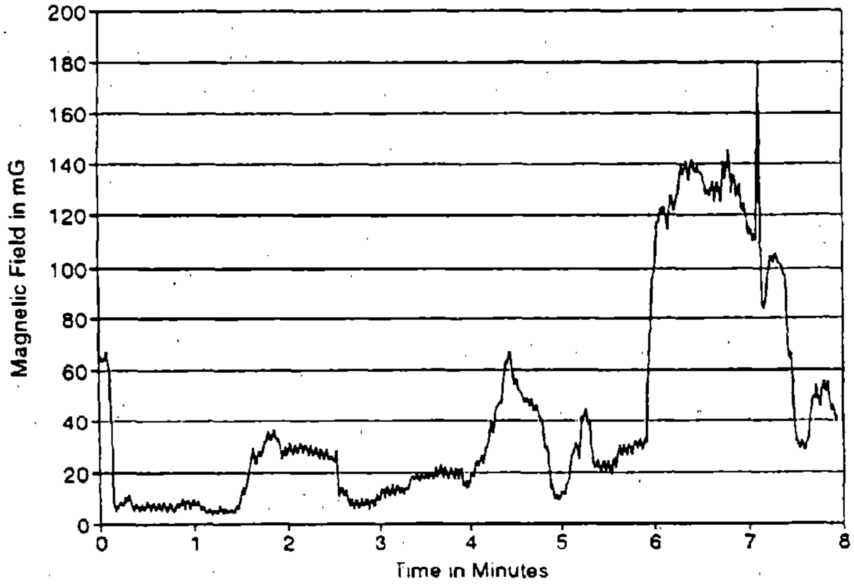


FIGURE 2-2. TYPICAL EXAMPLE OF THE VARIABILITY OF MAGNETIC FIELDS CAUSED BY CATENARY CURRENT OVER TIME IN AN AMTRAK TRAIN

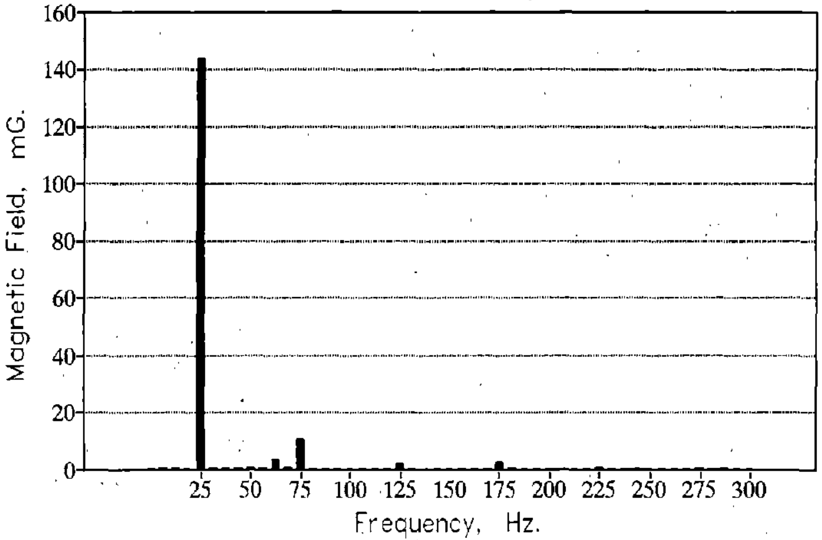


FIGURE 2-3. TYPICAL FREQUENCY SPECTRUM OF MAGNETIC FIELDS CAUSED BY CATENARY CURRENT OVER TIME IN AN AMTRAK TRAIN ON THE 25 Hz PORTION OF THE NORTHEAST CORRIDOR

alternating (ac) current are called harmonics and they produce corresponding harmonic components in the magnetic field. Figure 2-3 shows a typical graph of the frequency characteristics of the magnetic field in an Amtrak train on the 25 Hz portion of the Northeast Corridor. It should be noted that that the largest magnetic field component is at the fundamental frequency of 25 Hz, but smaller field components are also present at 75 Hz, 125 Hz, 175 Hz, etc. (A small component of "hotel" 60 Hz power frequency magnetic field is also detectable on this figure.) Those magnetic field components are called the third harmonic, fifth harmonic, seventh harmonic, etc., of the 25 Hz fundamental field component because their frequencies are 3 times, 5 times, 7 times, etc., the base frequency. It should be noted that on this system, with the exception of the ubiquitous 60 Hz power grid frequency, which is detectable, there are no significant field components at frequencies other than the fundamental and the harmonics. Corresponding frequency spectra were found in the magnetic fields from catenary currents on 60 Hz sections of the Northeast Corridor [2], on the New Jersey Transit North Jersey Coast Line [2] and the French TGV-A high speed line [3]. The fundamental frequencies were 60 Hz or 50 Hz, respectively, and the harmonics are odd integer multiples of 60 Hz or 50 Hz. If the current supplied to vehicles is switched on and off at a "control frequency," that frequency and its harmonics will also be found in magnetic field spectra.

Urban mass transit systems usually use direct current in their catenaries or third rails. The French TGV-A system also uses dc-powered catenaries in low speed urban areas, in order to achieve compatibility with existing infrastructure. The direct current dc in such catenaries or third rails, and running rails return circuits produce predominantly static magnetic fields [3-5]. However, smaller time varying components are found in the field due to changes in the dc current [3-5], rectifier ripple current [4,5], and ripple current from semiconductor "chopper" power control equipment onboard newer vehicles [4,5].

For catenary-powered transportation systems, the passengers and crew onboard the train are within the current "loop" created by the overhead catenary current supply line and the running rails return circuit. Consequently, the magnetic field is spatially rather uniform throughout the entire train. Conversely, on third rail systems where the current loop is at ground level beneath the vehicle, the magnetic field tends to be higher near the floor of the vehicle and lower near the ceiling [4,5]. The spatial variability is more complicated in the TGV-A, where a high voltage cable across the roofs of the coaches carries power from the pantograph on the rear locomotive to the front locomotive. The proximity of that conductor to the passenger compartment causes the magnetic fields to be higher near the ceilings of the coaches than near the floor [3].

Another important observation regarding the magnetic fields from current in the catenary or third rail and running rails is the relationship between magnetic field intensity, catenary or third rail voltage, and motive power needs. Operating on a system of any established third rail or catenary voltage, larger trains requiring greater motive power will draw more current and produce larger magnetic fields than smaller, lighter, or lower-speed trains. It does not matter significantly if that increased motive power is drawn by larger locomotives or multiple locomotives. For a given supply line voltage, larger system current is needed to supply the greater power and the magnetic fields increase accordingly [2]. But, since the power delivered to the locomotives or to powered vehicles is the product of catenary (or third rail) voltage and current, trains of equal motive power needs would require less current on higher voltage supply systems. This would result in correspondingly lower magnetic fields. For example, the same train operating from a 25 kV catenary system would produce approximately half the current and magnetic field from the track and catenary system, than if it was operating on a 12.5 kV system.

Current in the catenary or third rail and running rails produces magnetic fields along the wayside, as well as in the train [2-5]. These wayside fields have the same frequency characteristics as those found inside the train and generally the same temporal variability, as long as the train is within the same power block between substations or autotransformer stations [2,3]. Magnetic fields along the wayside drop significantly once the train passes the next substation or autotransformer station beyond the wayside point of interest [2,3].

The intensity of the magnetic field attenuates rapidly with increased distance from the tracks, as shown quantitatively in Section 3.2 of this report.

2.4.2 Active Maglev Guideways

The active guideway linear synchronous motor propulsion system of the Transrapid TR07 maglev system was unique among the transportation systems examined in this project. The guideway structure is equipped with a long series of coils powered by a variable frequency inverter at a central location [11]. This produces a magnetic field which appears to move along the guideway at a speed proportional to the frequency of coil current. This "moving" magnetic field provides the motive force, which pulls the maglev vehicle along the guideway. It also provides the source of inductive power coupling to the vehicle required to meet onboard power needs.

2.4.3 Maglev Levitation and Guidance Magnets

Interacting with the guideway fields are the ferromagnetic coils (with magnetic cores) of the vehicle's levitation electromagnets, and the magnetic fields produced by the onboard levitation coils, guidance coils, and their associated wiring. These sources act collectively to produce a magnetic field environment within the vehicle with a pronounced spatial gradient from high fields near the floor to weaker fields near the ceiling. The frequency components of this field are many. There is a significant static field component from both the earth's natural field and the dc component of the current in the levitation and guidance magnet systems. Time varying (ac) components originate from the guideway which are proportional to vehicle speed, while others originate from dynamic control of the levitation and guidance magnets. Since the frequency signature of the magnetic fields in the TR07 vehicle are constantly changing, attempts to show a "typical" frequency spectrum would misrepresent the full range of frequency characteristics [1]. Instead, Figure 2-4 shows a graph of the magnetic field frequency spectrum and how it changes over a ten-minute interval. During this time, the vehicle operated over a range of speeds from 175 to 400 km/h. The static field is not plotted on this graph in order to more accurately show the time varying ac components. It is immediately apparent that the frequency structure of the magnetic fields on the TR07 is considerably more complicated than that of conventional catenary or third rail systems, such as depicted in Figure 2-3.

The temporal variability of the magnetic field onboard the TR07 vehicle can also be seen in Figure 2-4 by focusing on the variability of field intensity over the ten-minute period depicted. Like in the conventional systems, the field intensity is highly variable over time. The component of the static field produced by the vehicle shown in the inset on Figure 2-4 has temporal characteristics somewhat similar to those shown for the time varying fields. But, since the static field from the magnet system is comparable in magnitude to the geomagnetic field of the earth, the total static field in the vehicle appears less variable over time than the time varying fields.

Magnetic fields near the Transrapid TR07 guideway or at the station have similar frequency characteristics to those in the vehicle [1]. However, these fields exist for only a very brief period of time while the vehicle passes by. The sections of guideway not occupied by the vehicle are not energized, and therefore produce no significant fields. Since the magnetic fields attenuate rapidly with distance from the guideway, magnetic fields at likely areas of public access along the guideway or at stations are significantly less than at passenger locations onboard the vehicle.

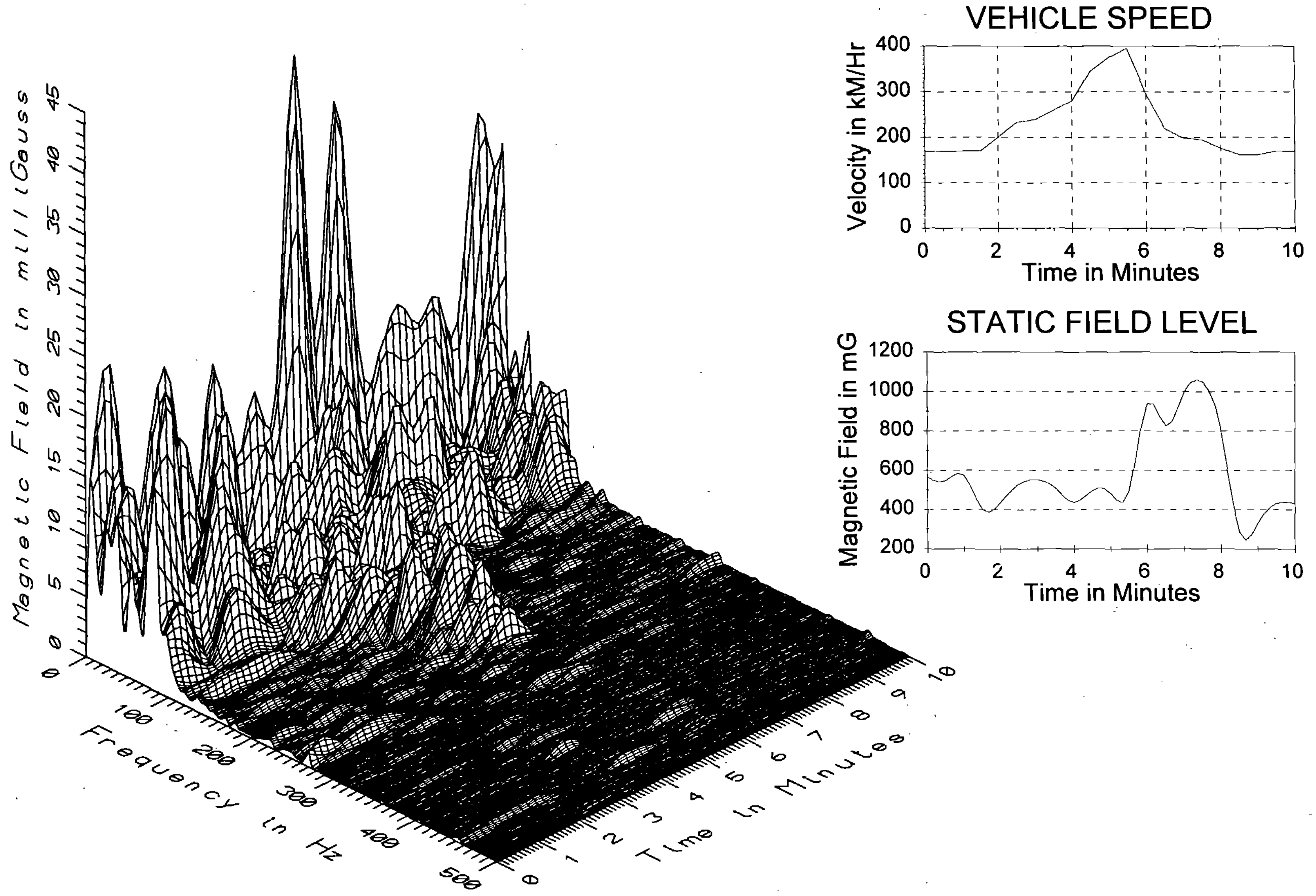


FIGURE 2-4. TYPICAL FREQUENCY CHARACTERISTICS AND TEMPORAL VARIABILITY OF THE TIME VARYING MAGNETIC FIELD IN A TRANSRAPID TR07 MAGLEV VEHICLE. VEHICLE SPEED AND STATIC MAGNETIC FIELD LEVEL ARE SHOWN IN THE INSETS

2.4.4 Traction Power Equipment

Measurements on all of the electrified transportation systems addressed in these EMF survey studies included efforts to identify magnetic fields at passenger or crew locations arising from traction power equipment, such as pantographs, transformers, motors, resistor banks, control cabinets, etc. Although many of those components undoubtedly have significant fields very close to them, most did not contribute significantly to the overall magnetic field environment of passenger, or operator compartments.

Magnetic fields from equipment within Amtrak, NJT, and TGV-A electric locomotives could be detected within the locomotive cabs. Those fields were significantly less than the magnetic fields from the catenary and track circuit current. The weaker fields from onboard traction power and control equipment were detectable by virtue of their unique frequency, temporal variability, or spatial variability characteristics. The specific characteristics of the fields from these secondary sources are detailed in the previous task reports [2,3]. The locomotive onboard power and control equipment was the principal source of magnetic field in the operator's cab of the Amtrak diesel-electric locomotive operating on a non-electrified portion of the Northeast Corridor. Without the stronger field from catenary and track current, the modest 2 mG average magnetic field from the diesel-electric locomotive's equipment [2] was clearly the dominant magnetic field.

Measurements in urban mass transit vehicles near the operator's controls, above the traction motors, and elsewhere in the cars generally failed to show areas of high magnetic field implicating a specific piece of equipment as the source. In most cases, there was a weak attenuation in field levels with increasing height above the vehicle floor. This indicated that there were perhaps a number of modest and well-distributed sources among the many components installed beneath the vehicle floors [3,4]. A salient exception was the intense and highly localized magnetic field in the center of the newer WMATA 3000 series cars (which are similar to the newest 4000 series cars being phased in). These cars, which use semiconductor "choppers" to efficiently control power delivery to the traction motors, have a large reactor coil directly under the center of the car. This "smoothing" reactor is part of a filter circuit intended to minimize the amount of 273 Hz and harmonics current flowing in the third rail and running rails from the onboard control system.

The magnetic field produced by the reactor beneath the WMATA 3000 series cars has a large static component and time varying field components primarily at the 273 Hz chopper frequency and harmonics thereof. The intensity of the field is highly variable over time, and is correlated with both vehicle traction power needs and vehicle regenerative braking. Since these magnetic fields originate from a specific piece of hardware beneath the floor in the central area of the vehicle, the field exhibits a highly localized spatial characteristic, attenuating rapidly with increased distance from the reactor. Figure 2-5 shows the attenuation of both the static and time varying magnetic field components with increasing height above the floor at the location of maximum field directly above the reactor. Since the field gradient is so steep, an average of field levels at various heights above the floor provides a misleading estimate of field levels at the torso of a passenger. Consequently, quantitative comparisons of magnetic field levels in Section 3 provide a comparison of field levels at 60 cm height above the floor at this location to average field levels measured elsewhere, where fields were of lower intensity and more spatially uniform.

The Transrapid TR07 vehicle also exhibited its maximum magnetic field closest to the floor, since the guideway and vehicle magnets were the principal field source. A plot of the magnetic field attenuation above the floor illustrated in Figure 2-6 shows a curve similar in shape to that of Figure 2-5, but with considerably lower maximum values. It should also be noted that the principal components of the time varying magnetic field are found in the frequency band below 45 Hz. The principal components of the time varying magnetic field shown in Figure 2-4 are found in the 65 Hz to 2560 Hz ELF frequency band.

2.5 ELECTRIC FIELD CHARACTERISTICS

Electric fields are produced by electrical power grid and equipment components energized at high voltage. The strength of the electric field is proportional to the voltage of the component relative to ground. The electric power transmission lines which bring power to traction substations or the high voltage catenaries [2,3] are the principal high voltage component associated with electrified rail systems.

Since the instantaneous electric field strength is proportional to the voltage on catenary and transmission line conductors, the frequency of the electric field is the same as the frequency of the voltage on the catenary or the transmission line. Consequently, the frequency of the electric field near the transmission lines and catenaries on the Northeast Corridor from Washington, DC to a point just north of New York City is 25 Hz [2]. The frequency of electric fields near the same facilities on the portion of the Northeast Corridor from New York to New Haven and the North Jersey Coast Line from Matawan to Long Branch is 60 Hz [2]. The frequency of the electric fields near TGV-A catenaries and transmission lines feeding TGV-A substations in France is 50 Hz [3]. The reason for use of different frequency for electric voltage supplies is a matter of both local practice and history. The standard frequency in North America is 60 Hz, while the standard frequency in Europe is 50 Hz. The section of the Northeast Corridor which presently operates at 25 Hz was electrified at a time before power

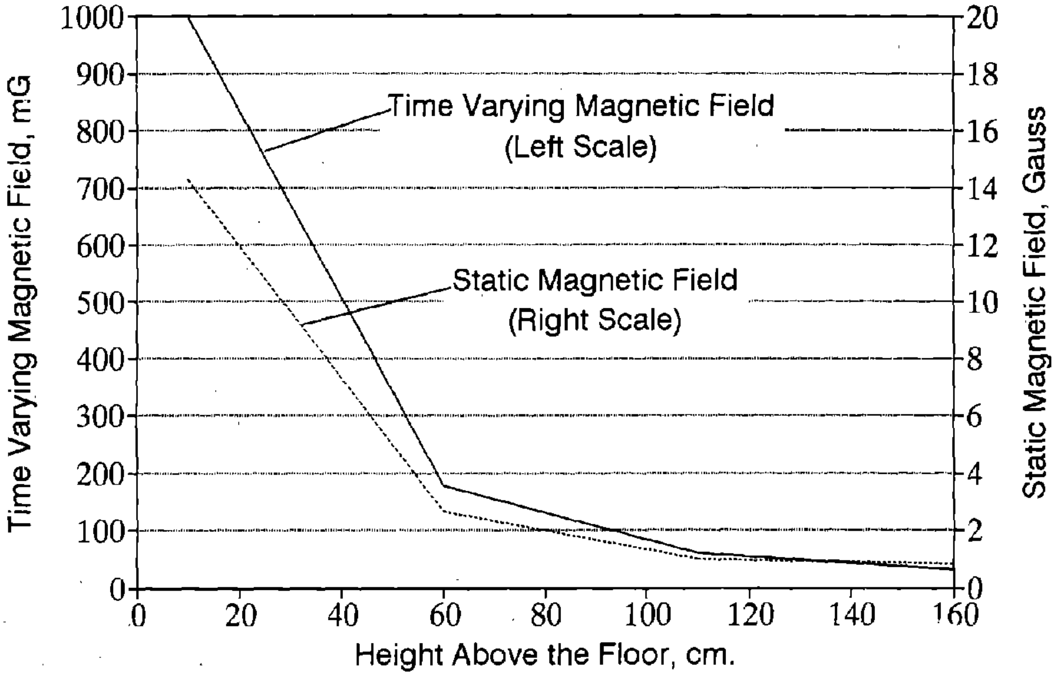


FIGURE 2-5. REPRESENTATIVE DISTRIBUTION OF MAGNETIC FIELD INTENSITY AS A FUNCTION OF HEIGHT ABOVE THE FLOOR AT A POINT DIRECTLY ABOVE THE REACTOR IN A WMATA 3000 SERIES METRORAIL CAR

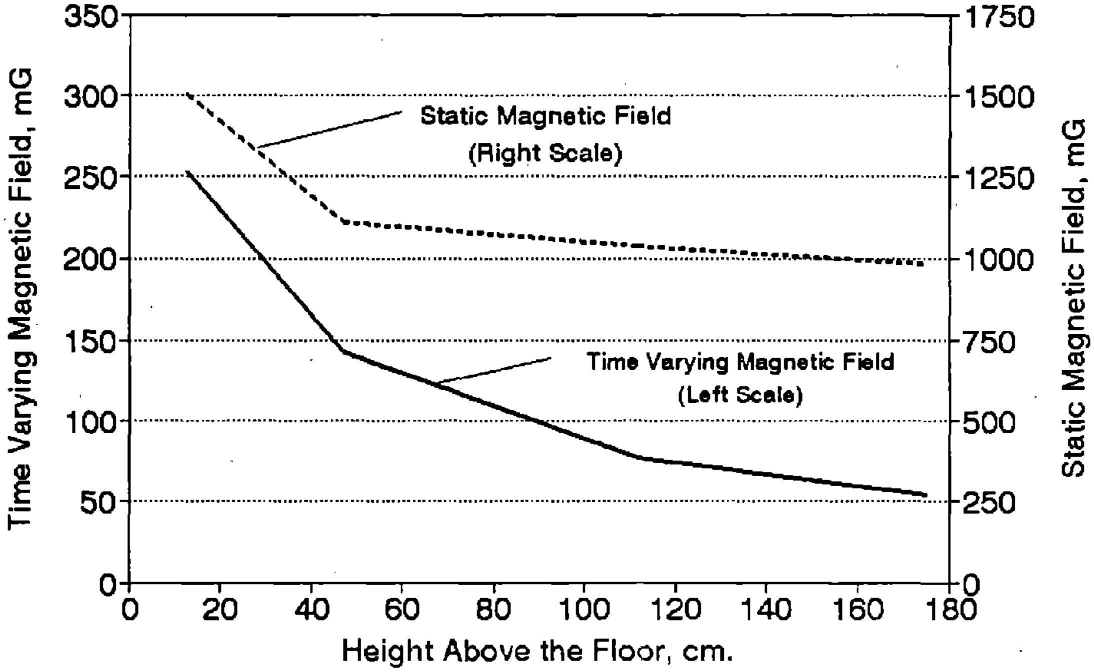


FIGURE 2-6. REPRESENTATIVE DISTRIBUTION OF MAGNETIC FIELD INTENSITY AS A FUNCTION OF HEIGHT ABOVE THE FLOOR OF THE TRANSRAPID TR07 MAGLEV PASSENGER COMPARTMENTS

frequencies were standardized at 60 Hz. Early frequencies of 16 to 25 Hz were common in the early part of this century for many applications such as electric traction.

Another characteristic of the electric field predicted by the proportionality between line voltage and electric field is that the rms value of the electric field shows little temporal variability [2,3]. Transmission lines and catenaries are energized regardless of the proximity of a train, and the rms voltage is regulated to a nearly constant value.

Electric fields become rapidly weaker with increased distance from the source. Consequently, electric field intensities in excess of 100 V/m generally occur only within approximately 30 m (98.4 ft) of the tracks [2,3] or within 40 m (131.1 ft) of high voltage transmission lines and substations [3].

Electric fields are easily attenuated by conductive material. The electric fields produced by overhead catenaries do not significantly penetrate either the operator's compartment or the passenger compartments of trains [2,3]. Furthermore, metallic structures at stations such as platform light standards, platform overhangs, station buildings, and even vegetation provide varying degrees of electric field shielding and attenuation at passenger locations in station buildings, on the platforms, or at the wayside.

Some urban mass transit systems, such as the MBTA Green Line light rail vehicle (LRV), High Speed Trolley, Trolley Bus, and above ground sections of the Blue Line, use an overhead catenary to supply power to vehicles. In the MBTA system, the catenary voltage is 600 V dc, which produces an estimated static field of 50 V/m or less on station platforms, or at road crossings directly under the catenary. There was no attempt made to measure the static electric field near dc catenaries.

3. QUANTITATIVE DESCRIPTION

This section concentrates on the quantitative aspects of the magnetic fields produced by the representative electrified transportation systems examined in these studies. The discussions, summaries and comparisons are grouped into three areas: passenger areas; public access areas; and work areas.

3.1 PASSENGER AREAS

This subsection presents quantitative results for measurements made in passenger areas, namely the vehicle passenger compartments and passenger platforms.

3.1.1 Passenger Compartments

Measurements conducted in the passenger compartments onboard the transportation vehicles were taken in a variety of locations. This was done in order to identify likely magnetic field sources and collect data representative of the entire passenger seating area. General characteristics of the frequency, temporal, and spatial characteristics of the magnetic fields in various system passenger compartments were discussed in Section 2 above. Systems which produce magnetic fields with similar characteristics are grouped for the following quantitative comparisons of magnetic field levels.

The Amtrak Northeast Corridor (NEC), New Jersey Transit (NJT) North Jersey Coast Line (Long Branch), and French TGV-Atlantique (TGV-A) are inter-city rail systems carrying large passenger loads, over relatively long distances, and at high speeds. Consequently, they operate from high voltage alternating current (ac) catenaries capable of providing the large quantities of electrical power which they require. In all of those systems, the dominant field source is current in the catenary and running rails. Therefore, the fields found in the passenger compartments of all three systems are relatively uniform spatially. Whether running at constant speed or changing speed, they have comparable temporal variability, and they have frequency spectra determined primarily by the frequency of the ac power of the catenary [2,3].

Although the Transrapid TR07 maglev vehicle is different from the inter-city rail systems in its propulsion, guidance and suspension technology, it is useful to compare its magnetic field levels to the other inter-city systems because of the similarity in purpose. Furthermore, there are similarities in field characteristics (spatial uniformity over the length of the vehicle, temporal variability with traction power needs, ac traction power, and significant time varying magnetic fields in the same range of frequencies) which improve the validity of numerical comparisons between those systems.

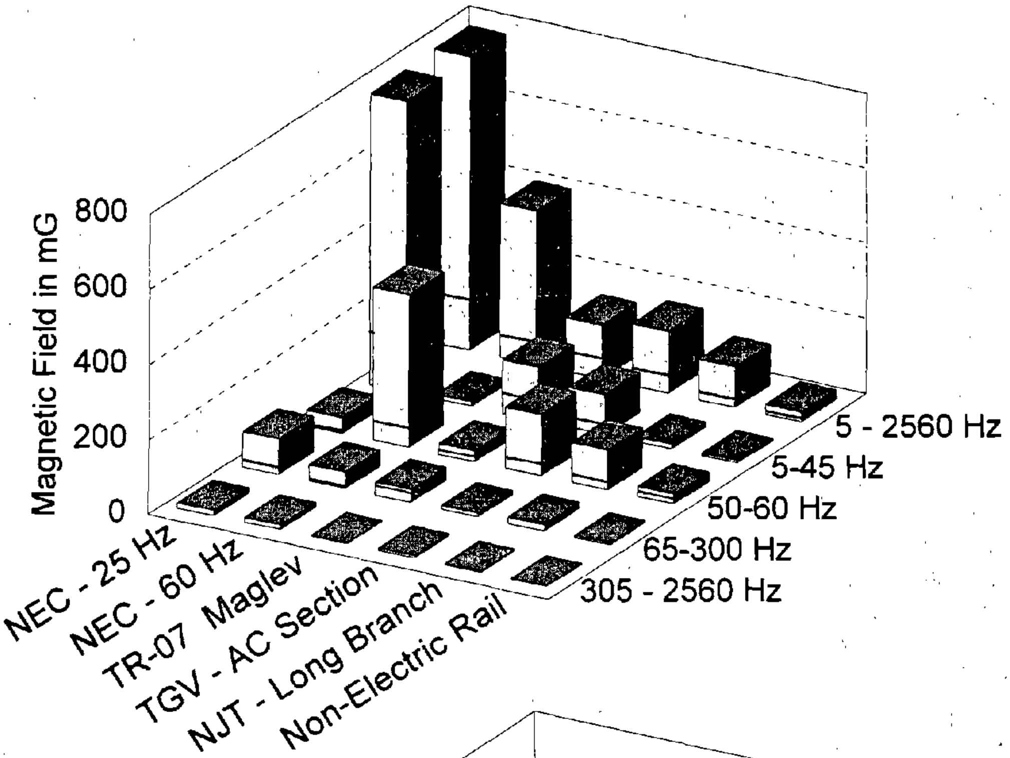
Table 3-1 provides a summary of the average and maximum magnetic field levels measured in the passenger compartments of the inter-city systems. The maximum values are in parentheses. Both static and time varying fields are tabulated, with the time varying fields further subdivided by frequency range. While the tabulated values represent the maximums and averages of all measurements in the rail passenger compartments where the fields were relatively uniform, the field levels reported in Table 3-1 for the TR07 represent only the data measured 50 cm above the floor. Average and maximum values of all data in the TR07 passenger compartments without regard to height above the floor are misleading because of the high field levels near the floor. More complete data on field levels in the TR07 vehicle are found in the report [1] on measurements in that system.

TABLE 3-1.

COMPARISON OF AVERAGE (AND MAXIMUM) MAGNETIC FIELD LEVELS IN MILLIGAUSS MEASURED IN PASSENGER COMPARTMENTS OF INTER-CITY TRANSPORTATION SYSTEMS IN VARIOUS FREQUENCY RANGES

SYSTEM	STATIC	5 - 45 Hz	50 - 60 Hz	65 - 300 Hz	305 -2560 Hz	5 - 2560 Hz
NEC 25 Hz	606 (1763)	132.0 (776.0)	6.0 (41.4)	16.2 (95.2)	2.7 (14.7)	133.8 (782.1)
NEC 60 Hz	630 (1039)	1.4 (12.2)	52.0 (407.0)	5.7 (43.9)	1.4 (12.8)	52.5 (408.4)
NEC NON-ELECTRIC	569 (1033)	1.4 (6.7)	4.8 (26.3)	0.7 (5.9)	0.2 (1.9)	5.2 (26.5)
NJT LONG BRANCH	734 (1016)	1.6 (13.0)	18.2 (107.1)	2.5 (17.7)	0.7 (3.6)	18.6 (108.8)
TGV-A	545 (962)	23.3 (106.2)	30.5 (164.7)	2.7 (10.4)	1.5 (5.4)	43.2 (165.0)
TR07	(1110)	(141.4)	(29.4)	(35.5)	(2.5)	(143.2)

The magnetic field data from Table 3-1 are presented graphically in Figure 3-1. The top frame of the figure graphs the magnitude of the maximum rms time varying field in the frequency range from 5 Hz to 2560 Hz as well as the field in smaller frequency bands as vertical bars for each transportation system. The horizontal line part way up each bar represents the average value of the magnetic field rather than the maximum. The graph in the bottom frame of the figure is similar except that it includes the value of the static field and is plotted on a logarithmic scale.



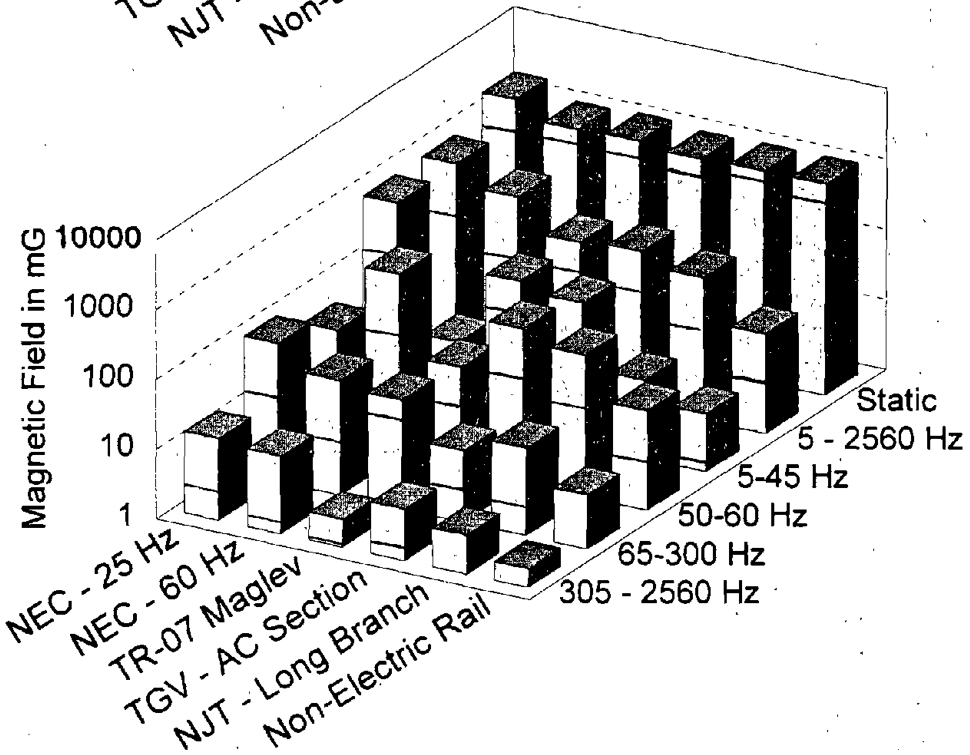


FIGURE 3-1. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS IN PASSENGER COMPARTMENTS ON INTERCITY ELECTRIFIED SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

Figure 3-1 graphically illustrates the relative magnetic field levels in passenger compartments of the various transportation systems as well as the frequency ranges in which they occur. The largest time varying magnetic fields occur in the frequency range containing the catenary power frequency in all catenary-fed systems. The largest time varying fields are found on the 25 Hz section of the NEC. High speed operation over hilly terrain and a relatively low catenary voltage (nominally 11 kV) requires high current from the catenary and running rails circuit. Lower fields are found on the 60 Hz section of the NEC. The terrain was flatter, speeds were lower, and the nominal catenary voltage was 12.5 kV. Even lower time varying magnetic fields are seen in the NJT passenger compartments where passenger load was very light and travel speeds were low between the frequent stops. The TGV-A, which operates with multiple locomotives at high speeds, also requires high power. But, since its catenary voltage (25 kV) is twice that on the American systems examined, it can obtain equal power at half the current level and thereby produce about half the magnetic field. The Transrapid TR07 maglev system, is seen to produce fields in the passenger compartments with amplitudes and frequencies within the range of those found in passenger compartments of steel wheel systems. It is also interesting to note that the average static field in the TR07 maglev vehicle at a height of 50 cm above the floor is insignificantly higher than the average static field in the conventional electrified rail system passenger compartments (Amtrak and NJT) where the only known source is the geomagnetic field.

The 25 Hz portion of the NEC presented a unique opportunity to separate the field generated by the catenary-running rails power circuit (25 Hz) from that of onboard hotel power (60 Hz). Table 3-1 and Figure 3-1 clearly demonstrate that the 25 Hz field (in the 5-45 Hz band) and the harmonic fields (in the 65-300 Hz band) from current in the catenary-running rails circuit significantly exceed the 60 Hz field from onboard "hotel service" appliances and wiring. Also, the non-electrified portion of the NEC provided a test condition where the only magnetic field sources were hotel power and possible external sources. The 60 Hz fields measured there were very similar to the 60 Hz non-traction related fields measured on the 25 Hz section of the NEC.

Urban mass transit systems examined in this study consist of individually-powered vehicles which operate on dc power supplied at either 600 V (MBTA system) or 750 V (WMATA system). Most of the vehicles operate from a third rail; the exceptions are the Mattapan High Speed Trolley, the North Cambridge Trolley Bus, and the Green Line light rail transit cars in the MBTA system, which use overhead catenaries. The MBTA system Blue Line cars operate on third rail when in tunnels and on catenaries when above surface. The magnetic field environment in the Blue Line cars did not change appreciably between catenary and third rail power conditions.

Most of the urban mass transit vehicles investigated in this study use the older "cam" control technology for power control. That system regulates the power supplied to the traction motors by inserting resistors in the motor circuit using electro-mechanical contactors operated from a cam switch at the operator's position. Resistors are also connected via contactors to the motor to serve as a load during dynamic braking. The Green Line cars on the MBTA system and the 3000 series vehicles on the WMATA system use more modern electronic "chopper" circuits (operating at 218 Hz and 273 Hz, respectively) to control power delivered to the traction motors. Semiconductor choppers rapidly turn on and turn off the power to the traction motors at a fixed rate and control the average power delivered to the motors by controlling the percentage of time that the semiconductors are turned on. By chopping the steady direct current from the third rail or catenary into a series of on-off pulses, time varying currents are produced in the control circuit. These currents have fundamental frequencies at the chopper frequency (218 Hz in the Green Line cars [5] and 273 Hz in the WMATA 3000 series cars [4]) and the harmonics thereof. Examination of the magnetic field frequency spectra measured in the chopper controlled cars revealed that fields in the Green Line cars were similar to those in the MBTA cam controlled Orange, Red, and Blue line cars [5]. A similar trend was true for measurements in the front or back of WMATA 3000 series cars, but in the center of the 3000 series cars, the magnetic field was unique in amplitude, frequency spectrum and spatial variability [4].

The rms values of magnetic field measured throughout the passenger compartments of urban mass transit vehicles are summarized in Table 3-2 and Figure 3-2. Magnetic field levels measured in a rail passenger compartment in the non-electrified section of the NEC are also included in Figure 3-2 for purposes of comparison. The data represents the approximate magnetic field levels which arise from "hotel services" unrelated to electric traction power. The magnetic field at the center of the WMATA 3000 series car is strongly dependent on height above the floor as shown in Figure 2-5. Consequently, the average and maximum field values measured at a height of 60 cm above the floor are tabulated and plotted.

The data in Table 3-2 and Figure 3-2 demonstrate that with the exception of the WMATA 3000 series cars, the time varying magnetic fields in the urban mass transit vehicle passenger compartments are smaller than those in the inter-city transportation systems. The time varying magnetic fields in the urban mass transit vehicles are produced by changing levels of dc traction current in power control equipment beneath the floor of the vehicles. There are also changes in current in the third rail or catenary and running rails circuits, causing them to be concentrated in the lowest frequency band. The static field in the passenger compartments of urban mass transit vehicles is slightly elevated over levels attributable to the geomagnetic field (e.g., the non-electrified rail data) due to dc traction current in catenaries, third rails, running rails, and under-car power control equipment.

The static and time varying magnetic fields created by the smoothing reactor beneath the center of the WMATA 3000 series vehicles are substantially greater than the fields found in other urban mass transit vehicles. Furthermore, the average time

TABLE 3-2.

COMPARISON OF AVERAGE (AND MAXIMUM) MAGNETIC FIELD LEVELS IN MILLIGAUSS MEASURED IN URBAN MASS TRANSIT VEHICLES AS A FUNCTION OF FREQUENCY RANGE

SYSTEM	STATIC	5 - 45 Hz	50 - 60 Hz	65 - 300 Hz	305 - 2560 Hz	5 - 2560 Hz
WMATA - CAM CARS	1013 (4714)	9.9 (64.5)	1.0 (5.6)	1.6 (9.3)	0.9 (5.0)	9.4 (64.8)
WMATA - 3000 CARS	2685 (23732)	98.5 (423.9)	12.6 (50.8)	133.5 (248.6)	41.2 (61.6)	177.8 (443.6)
MBTA - LRT CARS	534 (1981)	5.2 (66.0)	1.1 (14.7)	1.4 (18.3)	0.7 (4.7)	5.7 (68.4)
MBTA - TROLLEY	719 (3074)	4.1 (25.6)	0.8 (4.8)	0.7 (3.7)	0.3 (1.8)	4.5 (26.0)
MBTA - TROLLEY BUS	273 (467)	1.7 (12.9)	1.6 (6.5)	0.8 (3.4)	1.3 (9.3)	3.2 (13.2

varying magnetic field produced by the smoothing reactor is at frequencies of 273 Hz and above. Those atypical field conditions are not an inherent characteristic of chopper controlled propulsion systems. This is evidenced by the lack of similar field conditions in the chopper controlled MBTA Green Line cars. But rather, the high magnetic field levels appear to result from the specific design of the smoothing reactors in the WMATA 3000 series vehicles.

For both the MBTA High Speed Trolley and the MBTA Trolley Bus, the highest field maxima occurred closest to the floor in almost all frequency ranges. Again, this indicates that the dominant source is the traction and control equipment under the floor. There are also indications of weaker fields from the overhead catenaries and trolley arms, and some ceiling ventilation fans.

3.1.2 Platforms

Magnetic field measurements were taken on both outdoor and underground station platforms serving all of the transportation systems studied. Measurements on passenger platforms were generally made at the yellow safety line at the edge of the platform, the point nearest to the running rails at which a person can safely stand. Passengers are not permitted on the outdoor platform when Transrapid TR07 vehicles are passing. Therfore, magnetic fields were measured at the station door leading to the platform. For all other systems, measurements were taken at both the arriving and departing ends of the platform as well as at other points near the center of the platform. In addition, measurements were taken on escalators, on mezzanines, and in waiting lounges.

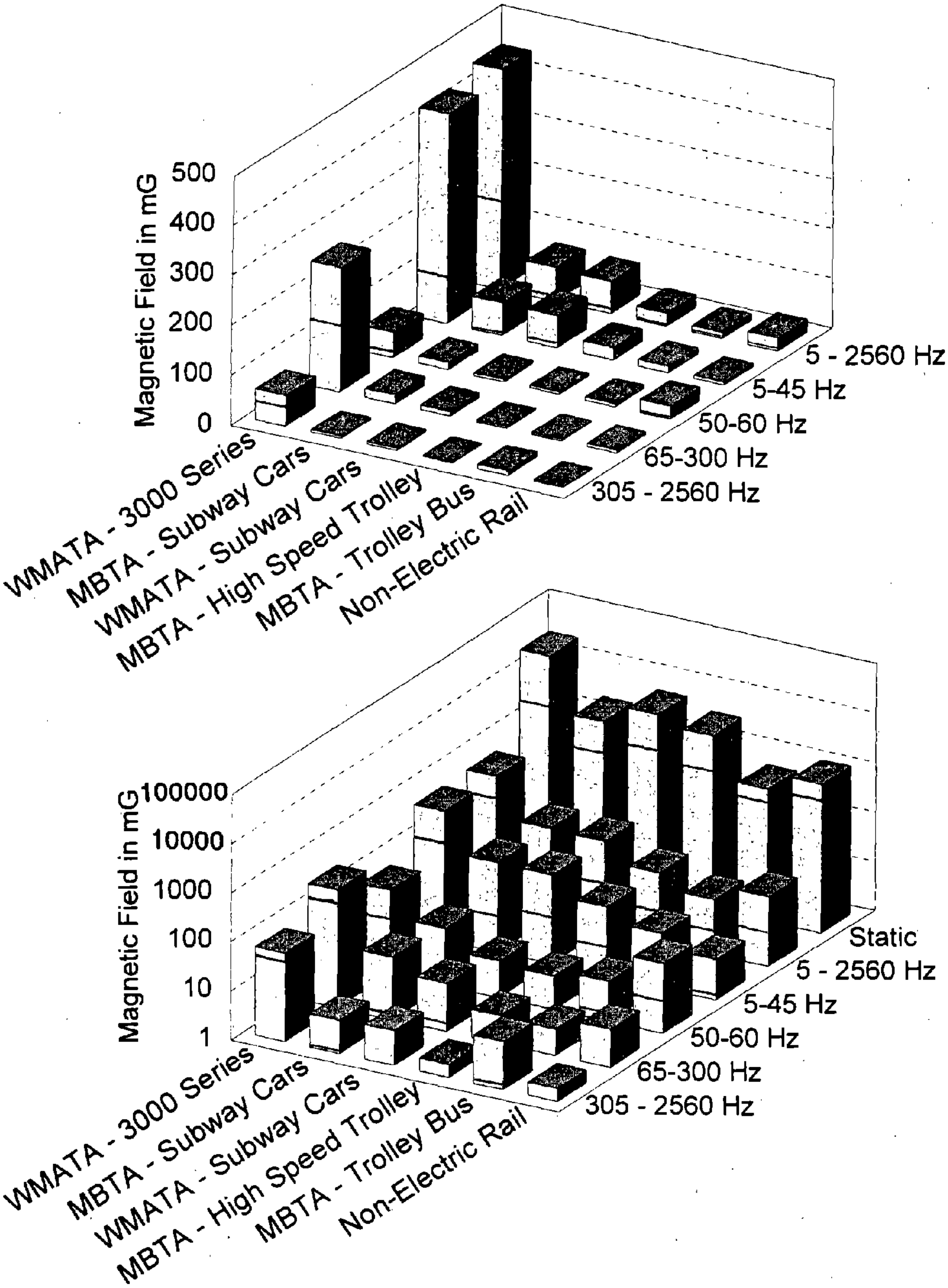


FIGURE 3-2. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS IN PASSENGER COMPARTMENTS ON URBAN MASS TRANSIT SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

The major source of magnetic fields on station platforms is the ac or dc current in the catenary-running rails circuit, third rail-running rails circuit or active maglev guideway. The type of electrification affects both the amplitude of the fields and their frequency spectra. The characteristics are similar to those at locations in the passenger compartments of vehicles which are not near localized magnetic field sources like the reactor in the WMATA 3000 series cars. Secondary sources of magnetic fields on the platforms are current in nearby electric circuits and current in structural members of the platform.

Table 3-3 summarizes the maximum and average values of magnetic fields at passenger platforms and waiting areas for the various transportation systems that were studied. The averages are computed over all locations where measurements were made on each platform. The maximum values are the maximum field measured anywhere on the platform.

The magnetic fields measured at passenger stations can be broadly divided into three categories: passenger waiting lounges; platforms of inter-city rail systems; and platforms of urban mass transit systems.

Figures 3-3 and 3-4 summarize the measured average and maximum magnetic field values on inter-city rail system platforms and urban mass transit system platforms. Magnetic field levels in station waiting lounges are not presented graphically because they are considerably smaller than those on the platforms.

The static magnetic field component is fairly steady on inter-city rail system platforms because it is mainly the result of the earth's magnetic field. On some occasions, when a train is passing, there is a brief perturbation of the geomagnetic field which results in some of the maximum values shown in Figure 3-3. The static field near the platform surface is spatially quite variable, probably from the perturbing effects of structural steel in the platform. The time varying fields on the inter-city rail platforms are predominantly from current in the catenary-running rails circuit. Therefore, the most significant frequency component of the field is at the frequency of the catenary current. Temporal variability of the magnetic field on the station platform is larger than the field variability in the passenger compartments. This is due to little or no magnetic field from the catenary-running rails circuit once the train is beyond the first substation or autotransformer station away from the station.

Time varying magnetic fields are typically smaller on urban transit system station platforms (Figure 3-3) than on platforms of inter-city rail systems (Figure 3-4) because there are no catenaries carrying ac supply current. Low frequency magnetic fields from fluctuating dc traction current are larger at stations with

TABLE 3-3.

COMPARISON OF AVERAGE (AND MAXIMUM) MAGNETIC FIELD LEVELS MEASURED ON THE STATION PLATFORMS AND IN WAITING LOUNGES OF VARIOUS TRANSPORTATION SYSTEMS IN MILLIGAUSS BY FREQUENCY

SYSTEM AND LOCATION	STATIC	5 - 45 Hz	50 - 60 Hz	65 - 300 Hz	305 - 2560 Hz	5 - 2560 Hz
NEC - 25 Hz PRINCETON JCT. PLATFORM	422 (970)	38.1 (537.0)	1.1 (13.8)	8.8 (121.2)	1.6 (17.1)	39.6 (550.8)
NEC - 60 Hz NEW ROCHELLE PLATFORM	650 (1629)	0.9 (51.5)	59.8 (407.2)	15.6 (101.6)	4.9 (26.6)	62.2 (417.6)
NJT - 60 Hz RED BANK PLATFORM	525 (615)	0.6 (4.8)	28.0 (209.4)	8.0 (50.6)	2.6 (15.7)	28.8 (213.2)
NEC - NON ELECTRIC SOUTH STATION LOUNGE	511 (912)	0.2 (0.7)	0.4 (0.7)	0.1 (0.3)	0.0 (0.1)	0.5 (1.1)
NEC - 25 Hz PENN STATION LOUNGE	573 (1372)	6.0 (13.4)	0.5 (0.9)	1.0 (2.2)	0.1 (0.3)	6.1 (13.6)
TRANSRAPID TR07 PASSENGER LOUNGE	547 (549)	0.1 (12.4)	0.1 (6.3)	0.1 (14.9)	0.0 (1.3)	0.2 (19.5)
TGV-A VENDOME PLATFORM	460 (485)	0.3 (0.9)	7.0 (43.8)	0.6 (1.6)	0.7 (1.5)	9.0 (43.9)
WMATA - OUTDOOR - CHOPPER GROSVENOR PLATFORM	455 (2065)	0.9 (20.4)	1.7 (3.7)	1.5 (57.7)	0.8 (26.0)	3.1 (66.6)
WMATA - OUTDOOR GROSVENOR ESCALATOR	424 (1090)	0.5 (2.4)	1.2 (4.5)	0.4 (0.9)	0.3 (1.5)	1.5 (5.1)
WMATA - UNDERGROUND GALLERY PLACE PLATFORM	385 (953)	1.0 (12.7)	0.3 (1.8)	0.6 (8.4)	0.9 (3.3)	1.5 (15.5)
WMATA - UNDERGROUND GALLERY PLACE MEZZANINE	455 (1004)	0.3 (0.8)	0.3 (0.5)	0.2 (0.5)	0.2 (1.3)	0.5 (1.5)
MBTA - UNDERGROUND SEVERAL PLATFORMS	625 (2411)	2.0 (20.5)	2.6 (9.5)	1.4 (4.1)	0.8 (2.2)	4.0 (23.0)
MBTA - OUTDOOR - CATENARY WOOD ISLAND PLATFORM	612 (1718)	6.5 (81.4)	2.9 (6.4)	1.4 (7.9)	1.4 (3.9)	8.6 (82.0)
MBTA - UNDERGROUND - CHOPPER GOVERNMENT CENTER PLATFORM	515 (912)	2.1 (8.0)	0.9 (3.8)	2.7 (16.2)	1.1 (7.8)	4.0 (17.6)

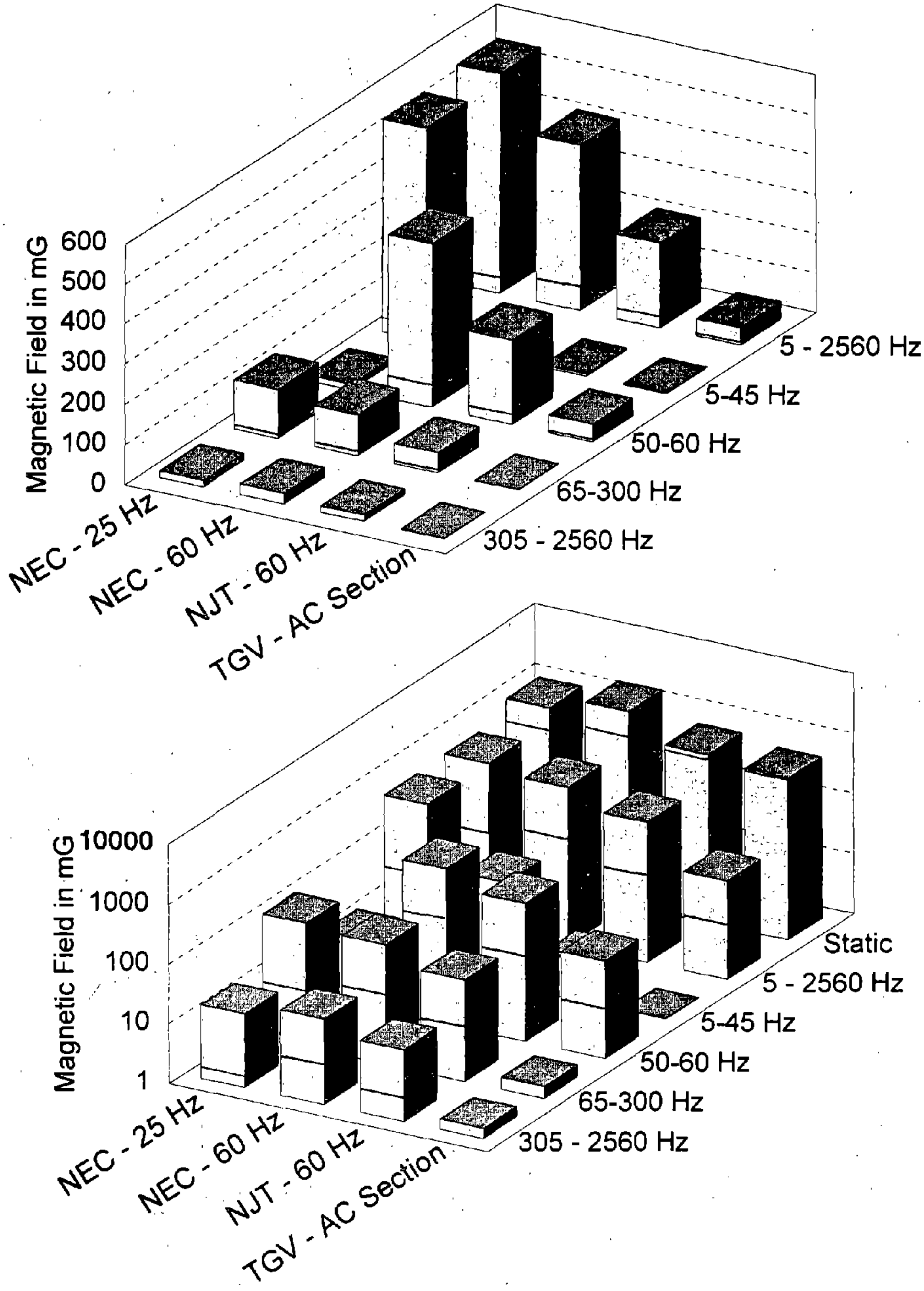


FIGURE 3-3. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS ON PASSENGER PLATFORMS ON INTER-CITY ELECTRIFIED RAIL SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

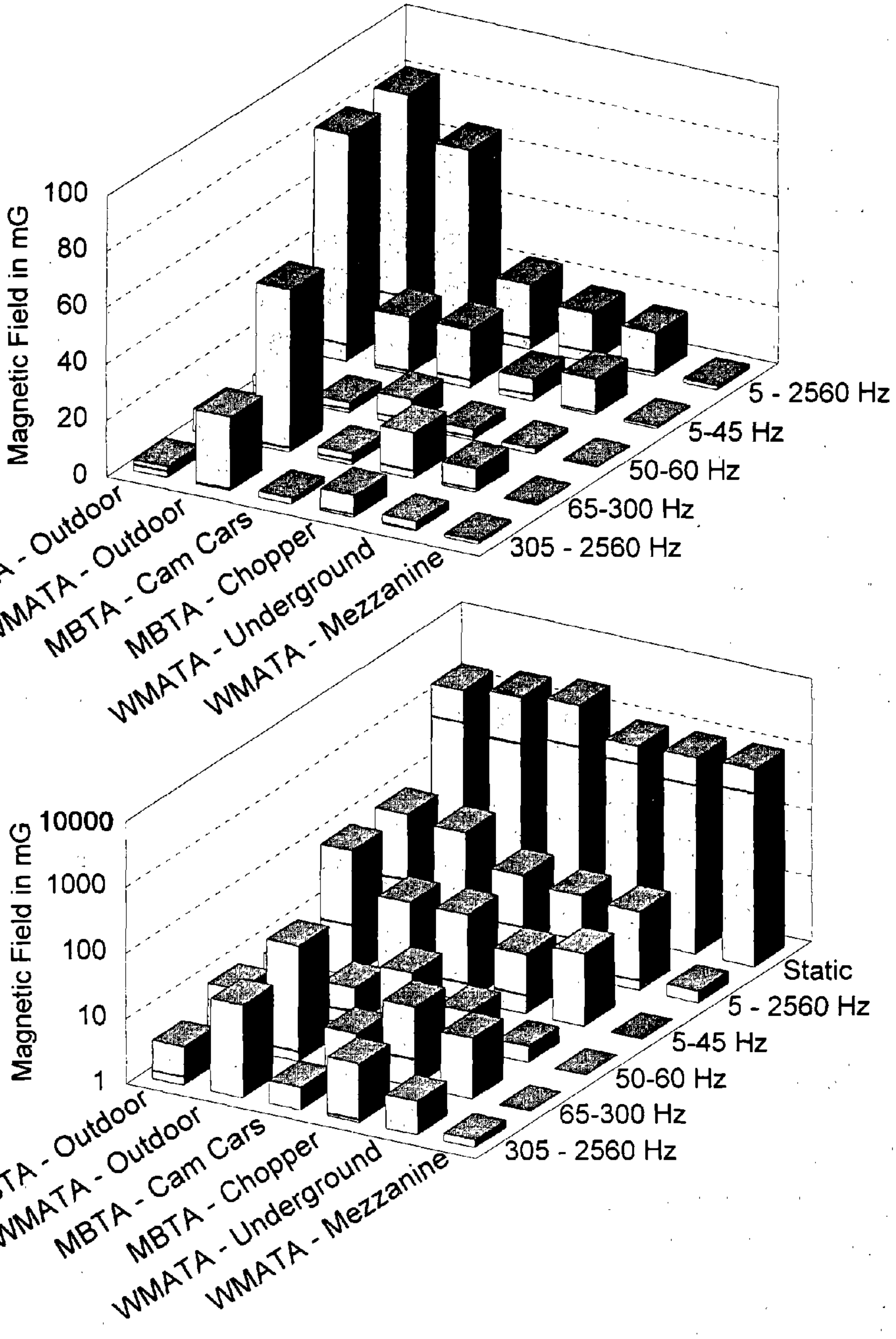


FIGURE 3-4. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS ON PASSENGER PLATFORMS ON URBAN MASS TRANSIT SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

catenaries (MBTA Outdoor) than at stations with third rail power. This is caused by the larger field generated by the large catenary-running rails current loop compared to that of the smaller third rail-running rails current loop. Higher frequency (greater than 60 Hz) magnetic fields are most prevalent at urban mass transit stations served by chopper controlled vehicles (WMATA-Outdoor and MBTA-Chopper in Figure 3-4), due to fields from control circuitry or components on vehicles entering and exiting the stations. There is also evidence that some chopper ripple current flows in the third rails, catenaries, and running rails. This contributes to the higher frequency magnetic fields on station platforms serviced by chopper controlled cars [4,5]. Figure 3-4 also shows the static fields are more variable over time on the urban mass transit system platforms due to the fields resulting from dc current in third rails, catenaries, and running rails. The average static fields are not elevated in any consistent manner.

3.2 PUBLIC ACCESS AREAS

Magnetic fields from electrified transportation systems can be encountered by the general public outside track rights-of-way and outside power supply substations, transformer yards, or rectifier stations. This subsection summarizes the magnetic field levels measured at wayside locations and outside power supply facilities.

3.2.1 Wayside Locations

Wayside measurements were made in several locations, covering most of the electrified transportation systems examined in this project. Measurements were carried out at the sides of the tracks with trains passing in either direction and at highway overpasses and underpasses.

The characteristics of the magnetic fields along the track rights-of-way are very similar to those on the station platforms [1-5] except that there is a strong attenuation in field strength with increasing distance from the tracks or guideway. Measured maximum field data from the system reports [1-5] have been combined with theoretical attenuation rates for fields from catenary and running rails current to produce the summary graph shown in Figure 3-5. Multiple measurements along the 25 Hz and 60 Hz sections of the NEC, the 60 Hz section of NJT's North Jersey Coast Line, and the 50 Hz section of the French TGV-A provided generally consistent time varying magnetic field levels at the wayside. The differences between maximum field levels for the different systems were smaller than the differences from one train pass to another or one wayside location to another on the same system. Consequently, it is not possible to accurately resolve a difference in wayside maximum field levels from one inter-city rail system to another. The range of maximum wayside field levels is plotted as a function of distance from the track in Figure 3-5. The frequency spectrum of the magnetic field at the waysides of the inter-city rail systems

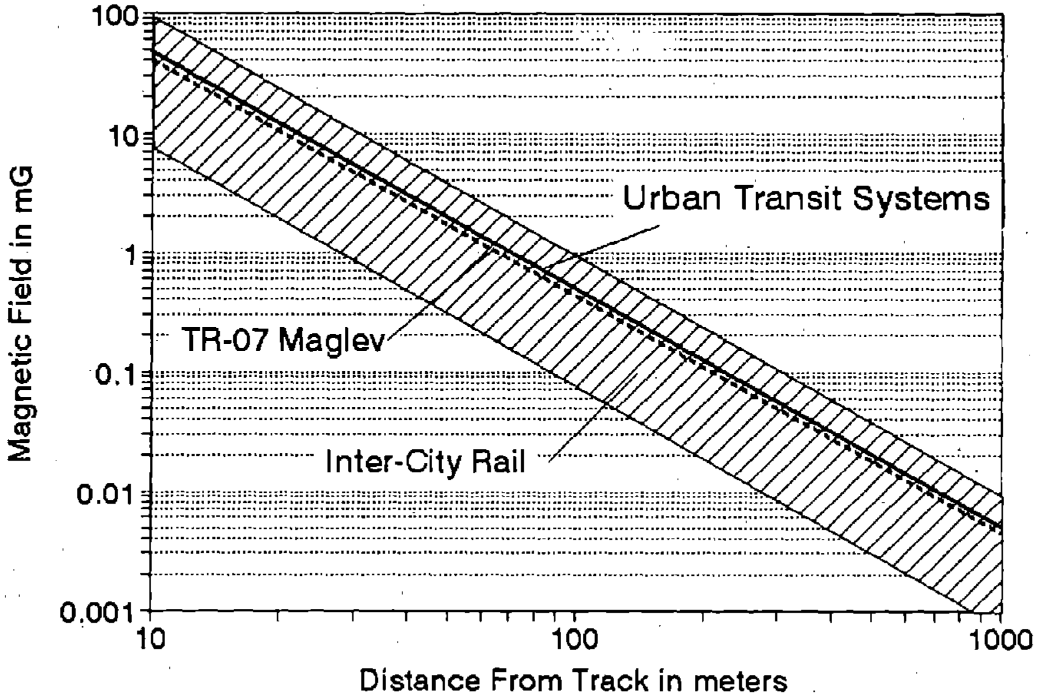


FIGURE 3-5. **MAGNETIC FIELD ATTENUATION AS A FUNCTION OF HORIZONTAL DISTANCE FROM THE TRACKS**

is dominated by the frequency of the catenary current and its harmonics as it was at the station and in the passenger compartments of the vehicles. Average magnetic field level at the wayside is not very meaningful. The level is highly dependent on factors such as rail traffic density, train speed, distance between substations and other factors which could not be controlled from one measurement to another.

Maximum magnetic field levels measured near the Transrapid TR07 guideway have also been converted to attenuation curves and plotted on Figure 3-5. That curve falls within the range of field levels found along intra-city rail lines indicating a similarity in maximum magnetic field strength. However, the magnetic fields along the maglev guideway differ from those along railroad lines in frequency and temporal variability.

The principal magnetic field component produced by dc current in third rails and running rails of urban mass transit systems is the static component which at the wayside is small compared to the geomagnetic field. It could not be reliably measured near third rail systems [4]. However, the larger loop spacing of the catenary-running rails circuit of the above surface section of the MBTA Blue Line produced a measurable static field at the wayside [5]. The maximum static magnetic field at the wayside of the catenary-powered urban mass transit system is shown on Figure 3-5 to be similar to the maximum magnetic field at the wayside of other systems. But, since the maximum field component from the urban mass transit system is the static component and is small compared to the static field of the earth, it does not substantially change the total magnetic field environment at the wayside.

3.2.2 Outside Power Supply Facilities

Measurements were made outside numerous kinds of power facilities associated with the different transportation systems studied. Measurements were carried out at one or more locations outside the facility fence or wall where public access was likely and magnetic fields were expected to be high.

Power facilities associated with inter-city rail systems consist of transformer or autotransformer yards. These yards reduce the voltage of power arriving from incoming power lines to the desired catenary voltage. These yards usually include other equipment such as circuit breakers and switches for protection and control of power routing and buswork for interconnecting the equipment. The magnetic fields produced by these facilities are time varying fields at the power frequency (25, 50, or 60 Hz) and harmonics of the power frequency. Temporal variability of these fields is determined by the power needs of all trains operating on the block or section of track supplied by the station in question.

Power supply stations for urban mass transit systems are often smaller but more complicated than those on inter-city rail systems. In addition to the above-mentioned equipment, the stations must have rectifier banks to convert the incoming ac power to dc power. The ac current entering the station produces power frequency (60 Hz in America) fields. The dc output current from the station, fluctuating in response to the traction power needs of vehicles operating on the associated sections of track, produces static and low frequency time varying fields. Additionally, the rectification process produces new frequency components of the input and output current which create magnetic fields at harmonics of the power frequency.

The other unique type of power supply station encountered is the inverter station which powers the Transrapid TR07 maglev system. The TR07 inverter station contains all of the components of an inter-city rail power supply station and an urban mass transit power supply station. It also contains inverters which convert the dc from the rectifier banks into a variable frequency ac current which powers the guideway. Consequently, this inverter station can create static and time varying magnetic fields with a wide range of frequencies.

The magnetic field levels measured outside power supply facilities associated with inter-city rail systems, urban mass transit systems, and the Transrapid TR07 maglev system are shown graphically on Figure 3-6. Near inter-city rail system power facilities, only time varying fields are produced. Consequently, the only static field present is the geomagnetic field. The

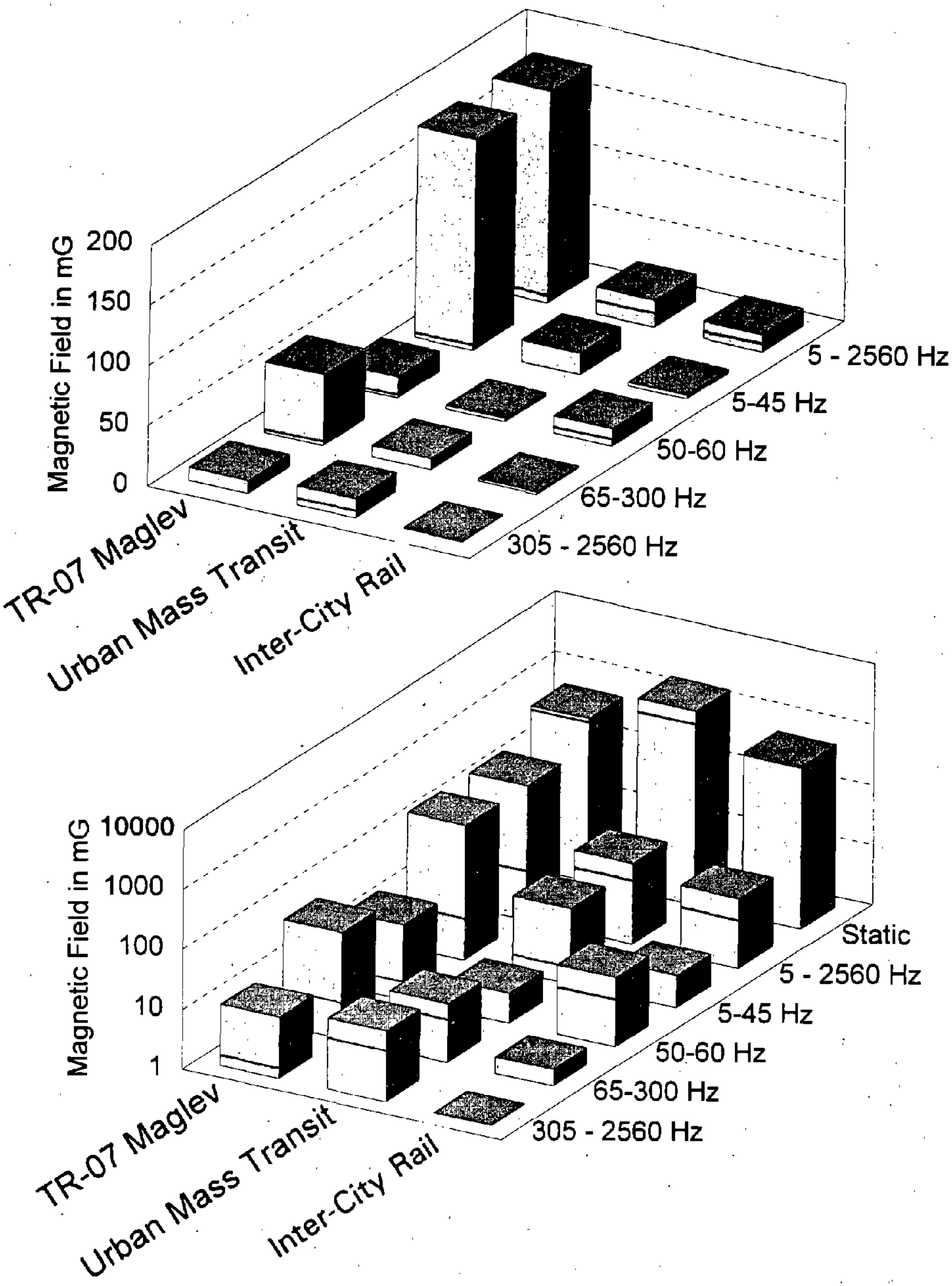


FIGURE 3-6. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS OUTSIDE POWER STATIONS ON ELECTRIFIED RAIL SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

principal component of the time varying field is the power frequency component.

Figure 3-6 shows the presence of a static field near urban mass transit system power facilities that adds to the geomagnetic field. The time varying field contains the low frequency components and the higher frequency harmonic components mentioned above.

The highest time varying magnetic fields were found near the Transrapid TR07 maglev inverter facility where a wide range of frequencies was present. However, it is not known whether the public would be permitted as close to the equipment in a revenue service installation as the location where measurements were made. The magnetic field encountered would be lower if an exclusion fence surrounding a revenue service facility kept the public at a greater distance.

3.3 WORK AREAS

This section of the report provides a quantitative description of the magnetic fields measured in railroad and mass transit system employee work areas. Such areas include: onboard operator's compartments, control and dispatch rooms, and inside power supply stations.

3.3.1 Operator's Compartment

Within the electric locomotive cabs, magnetic fields are produced by current in the catenary and running rails circuit [2,3]. The intensity of these fields vary in proportion to the traction power needs of the locomotives. These fields tend to be large relative to fields from other sources and spatially uniform. Their frequency spectrum consists of a large fundamental component of the catenary current (25 Hz, 50 Hz or 60 Hz) and smaller odd harmonics. There are other sources within the locomotive, most noticeably beneath the floor and in the machinery section of the locomotive. The sources tend to be relatively constant over time and of smaller amplitude than the catenary-running rails fields, but spatially non-uniform. These fields tend to be strongest near the floor and nearer the bulkhead that separates the cab from the locomotive machinery.

The diesel locomotive cab has fields that are produced only by the locomotive's machinery. These fields are lower than those of the electric locomotive, but exhibit a much more complicated frequency spectrum [2]. The fields arise at least in part from the main power alternator or associated circuity which is located at the cab end of the F-40 locomotive.

The operator's compartment in urban mass transit vehicles and the Transrapid TR07 maglev vehicle is a small area set aside within the self powered passenger cars. The operator's compartment fields are therefore quite similar to those found in the passenger compartments.

The predominant magnetic field sources in the powered cars of the WMATA Metrorail system appear to be traction power control equipment beneath the floor of the cars and current in the third rail and the running rails. The smoothing reactors beneath the center of the 3000 series cars are apparently too far from the operator's compartment to contribute significantly to the field in the compartment. The magnetic fields in the operator's compartment are predominantly static with low frequency time varying components resulting from fluctuations in the static field level. The magnetic field levels are similar in magnitude in each of the frequency bands for all three types of vehicles, and are pooled together in the figures and tables that follow.

The magnetic field measurements at operator's seats in the MBTA system vehicles also demonstrated that the fields were similar in all characteristics to those found in the passenger compartments of those vehicles. The subway cars (Red, Orange, Blue and Green lines) exhibited no fundamental differences in frequency distributions and temporal patterns of the magnetic fields measured at the operator's seat. Therefore, the data from all lines and all subway cars was pooled together. Also, the magnetic fields of the High Speed Trolley operator's seat have essentially the same characteristics as elsewhere in the trolley. Finally, the magnetic fields of the Trolley Bus are very low, consisting almost entirely of the earth's magnetic field and a small 60 Hz field from power lines along the streets on which the Trolley Bus operates.

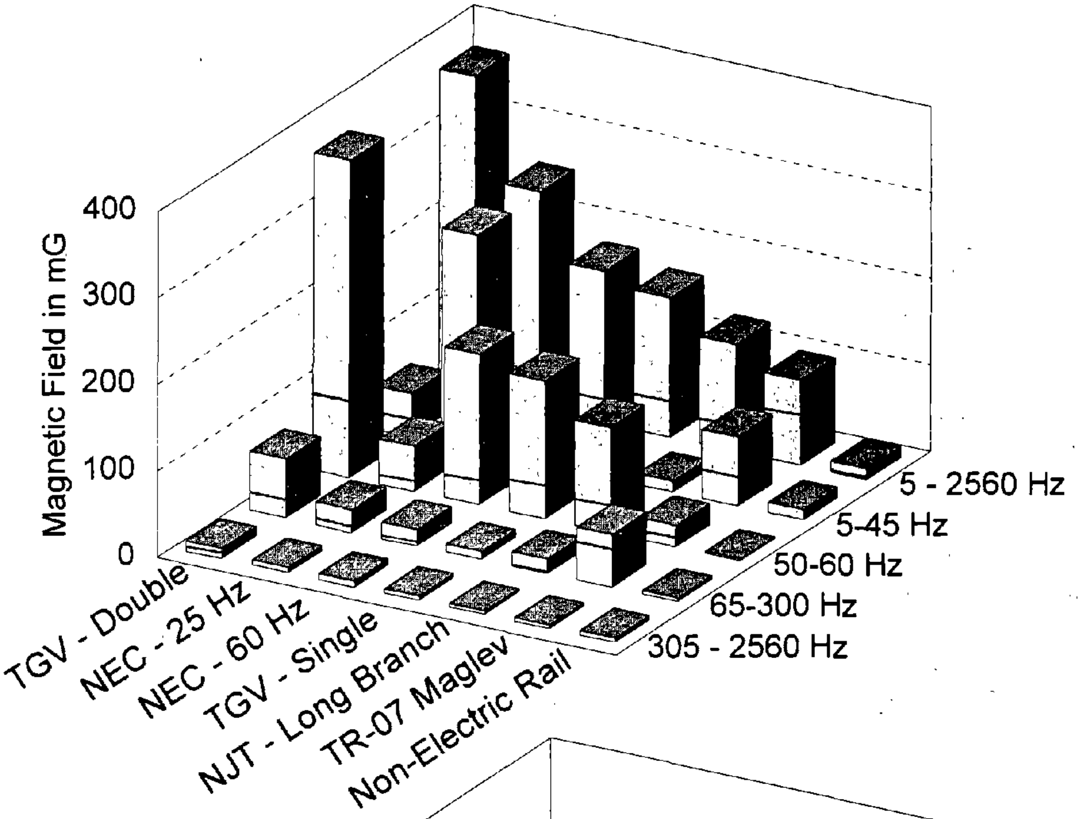
Table 3-4 summarizes the average and maximum (in parenthesis) values of magnetic field measured at the operator's location for the various transportation systems studied. For all systems except the TR07, measurement data taken at a range of heights above the floor are included in the table. Only Transrapid TR07 maglev field data measured 50 cm above the floor are included because of the large variability in field levels with height.

The data of Table 3-4 are presented graphically in Figures 3-7 and 3-8. They are very similar to Figures 3-1 and 3-2 showing magnetic field levels in the passenger compartments because of the similarity between field conditions in passenger compartments and in operator's compartments. Figure 3-7 shows field levels in two TGV-A locomotive cabs. Time varying magnetic fields in the cab of the empty double train set used for the passenger compartment tests are approximately twice those measured in the cab of a single train set in revenue service and loaded with passengers. Apparently passenger load is not an important factor in determining traction power needs and the resulting magnetic fields from the catenary-running rails circuit. The two-to-one difference in field level is well accounted for by the single train set versus double train set without adjusting for the fact that the double train set was empty while the single train set was full. These data imply that the magnetic field levels inside the passenger compartments of a single

TABLE 3-4.

COMPARISON OF AVERAGE (AND MAXIMUM) MAGNETIC FIELD LEVELS IN OPERATOR'S COMPARTMENTS OF VARIOUS TRANSPORTATION VEHICLES IN MILLIGAUSS AS A FUNCTION OF FREQUENCY RANGE

SYSTEM	STATIC	5 - 45 Hz	50 - 60 Hz	65 - 300 Hz	305 - 2560 Hz	5 - 2560 Hz
NEC - 25 Hz	648 (1555)	41.2 (247.4)	11.7 (52.8)	5.5 (26.7)	1.4 (5.9)	46.0 (250.9)
NEC - 60 Hz	435 (992)	2.1 (19.0)	26.8 (174.3)	3.9 (19.5)	1.2 (7.1)	27.4 (174.7)
NEC - NON-ELECTRIC	330 (767)	1.0 (12.1)	0.4 (2.2)	1.0 (3.9)	1.0 (5.3)	1.9 (12.7)
NJT - LONG BRANCH	319 (445)	1.3 (12.5)	31.1 (122.6)	3.8 (17.2)	1.2 (3.8)	31.5 (123.7)
TGV-A - 50 Hz DOUBLE	795 (1149)	18.0 (50.2)	87.3 (366.6)	16.6 (68.3)	4.4 (11.9)	94.2 (367.7)
TGV-A - 50 Hz SINGLE	611 (897)	16.4 (54.5)	37.4 (159.8)	2.6 (9.2)	2.0 (5.2)	43.2 (160.8)
WMATA ALL CARS	745 (3589)	12.7 (47.4)	1.0 (3.6)	1.6 (7.0)	0.9 (9.2)	12.9 (47.9)
MBTA SUBWAY	747 (3078)	4.2 (45.4)	1.4 (9.5)	1.2 (25.2)	0.7 (5.3)	4.8 (52.9)
MBTA TROLLEY	532 (738)	2.5 (11.3)	0.4 (1.1)	0.5 (1.8)	0.3 (0.9)	2.6 (11.5)
MBTA TROLLEY BUS	442 (706)	0.6 (1.4)	1.2 (3.5)	0.2 (0.4)	0.1 (0.3)	1.3 (3.5)
TR07 MAGLEV	791 (1108)	37.3 (80.8)	11.53 (24.7)	45.2 (62.0)	2.0 (4.2)	60.5 (98.4)



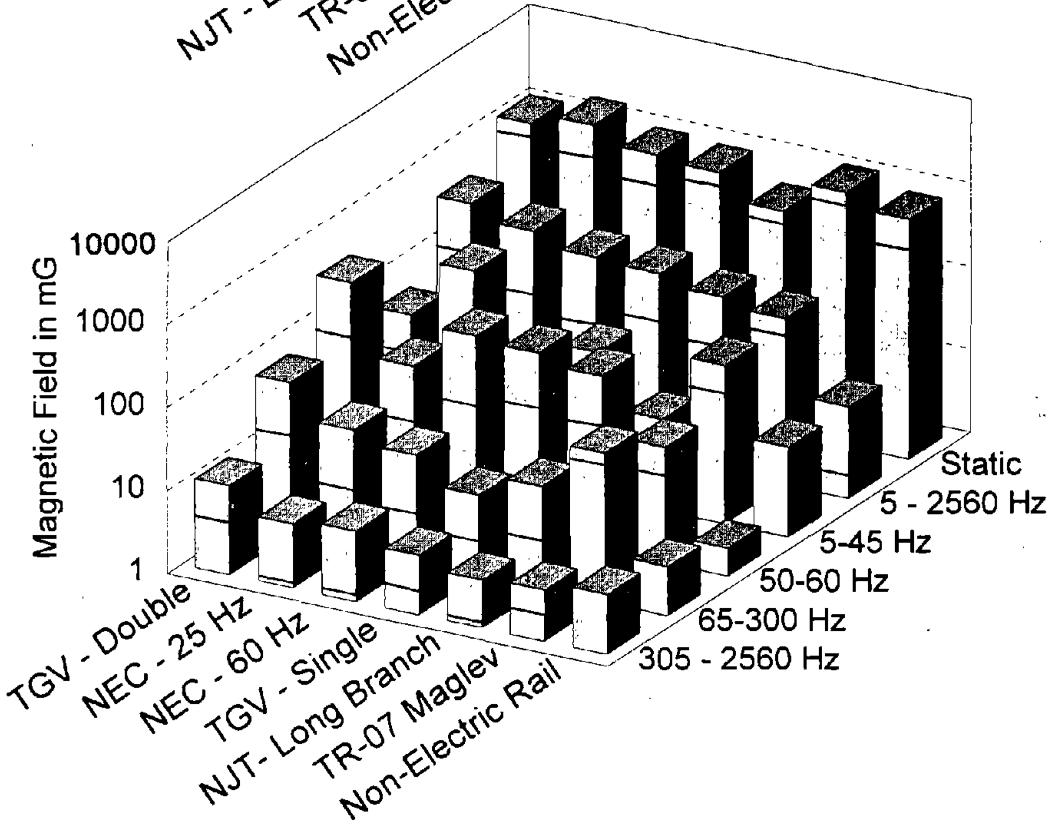


FIGURE 3-7. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS IN OPERATOR'S COMPARTMENT ON INTER-CITY ELECTRIFIED RAIL SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

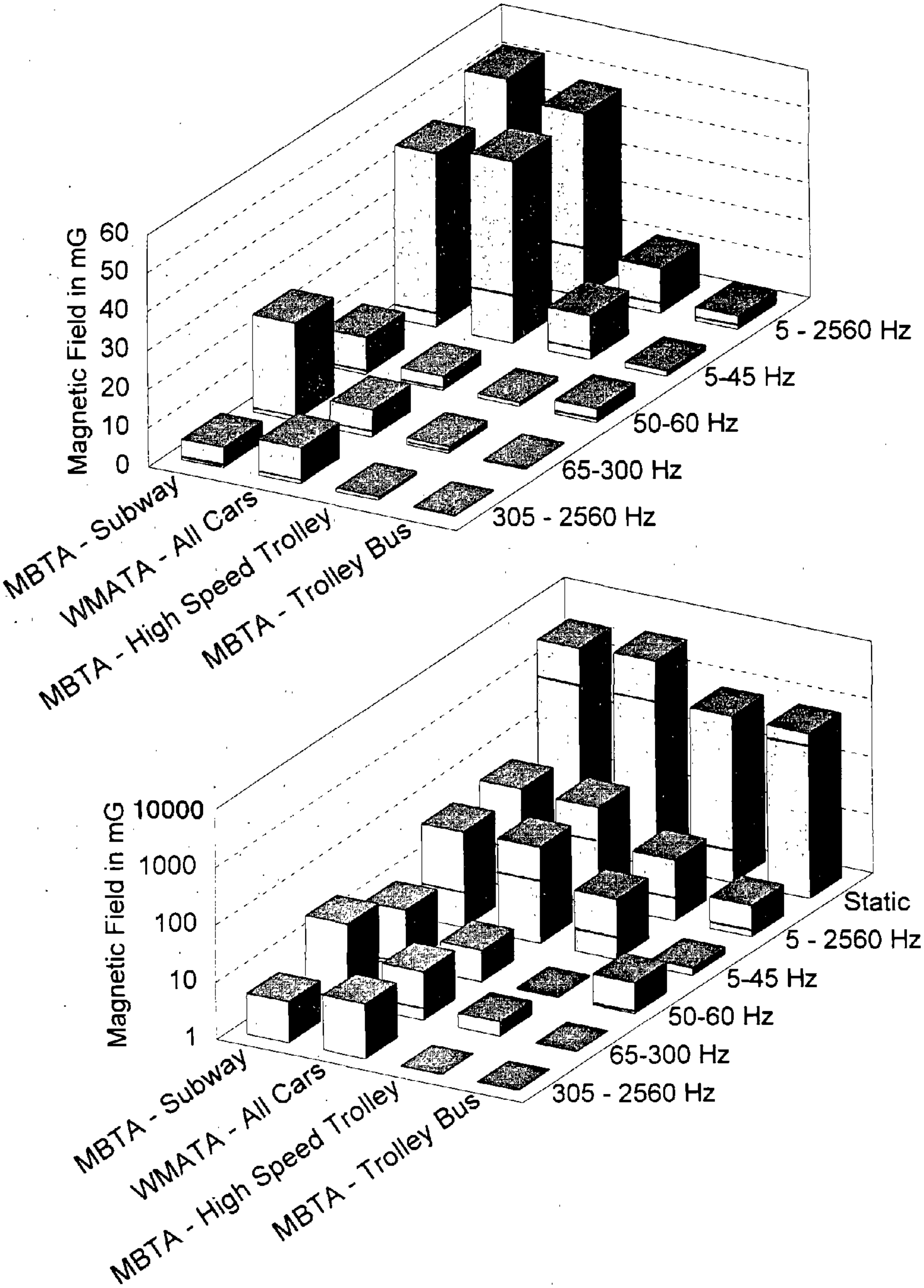


FIGURE 3-8. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS IN OPERATOR'S COMPARTMENT ON URBAN MASS TRANSIT SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

TGV-A train set would be approximately half of those reported previously in Table 3-1 and Figure 3-1 for the double train set.

3.3.2 Control Facilities

Magnetic fields were measured inside four control facilities. These areas include; the Boston South Station dispatch area, the TGV-A Control Center at Gare Montparnasse, the WMATA Red Line Dispatch Room at the Shady Grove Station, and the MBTA Orange Line Dispatch Room.

The magnetic fields inside control facilities are relatively low in intensity and are mostly in the power frequency range. Table 3-5 and Figure 3-9 show the average and maximum rms field levels recorded for the four control rooms. Typically, the fields are produced by the VDTs, other electronic gear, and any house wiring in the floor, walls or ceiling. The differences in field levels between different control rooms appear related more to the characteristics of the video display units at the work positions than any other factor. Characteristics of the individual transportation systems were not factors in the differences because all of the control areas were well removed from transportation system field sources.

TABLE 3-5.

COMPARISON OF AVERAGE (AND MAXIMUM) MAGNETIC FIELD LEVELS IN DISPATCH AND CONTROL FACILITIES OF VARIOUS TRANSPORTATION SYSTEMS IN MILLIGAUSS, AS A FUNCTION OF FREQUENCY RANGES

SYSTEM	STATIC	5 - 45 Hz	50 - 60 Hz	65 - 300 Hz	305 - 2560 Hz	5 - 2560 Hz
NEC - BOSTON SOUTH STATION DISPATCH ROOM	348 (361)	1.3 (5.0)	3.1 (10.5)	2.3 (7.9)	1.0 (3.6)	4.2 (14.1)
TGV-A - MONTPARNASSE CONTROL CENTER	520 (565)	0.3 (0.8)	1.1 (3.1)	1.5 (5.7)	1.0 (3.8)	2.2 (7.5)
WMATA - SHADY GROVE DISPATCH ROOM	827 (1218)	0.3 (0.7)	0.7 (1.0)	1.0 (1.1)	0.2 (0.3)	1.3 (1.5)
MBTA - ORANGE LINE DISPATCH ROOM	344 (507)	0.3 (1.2)	2.7 (4.6)	4.9 (14.0)	1.2 (1.9)	5.8 (14.8)

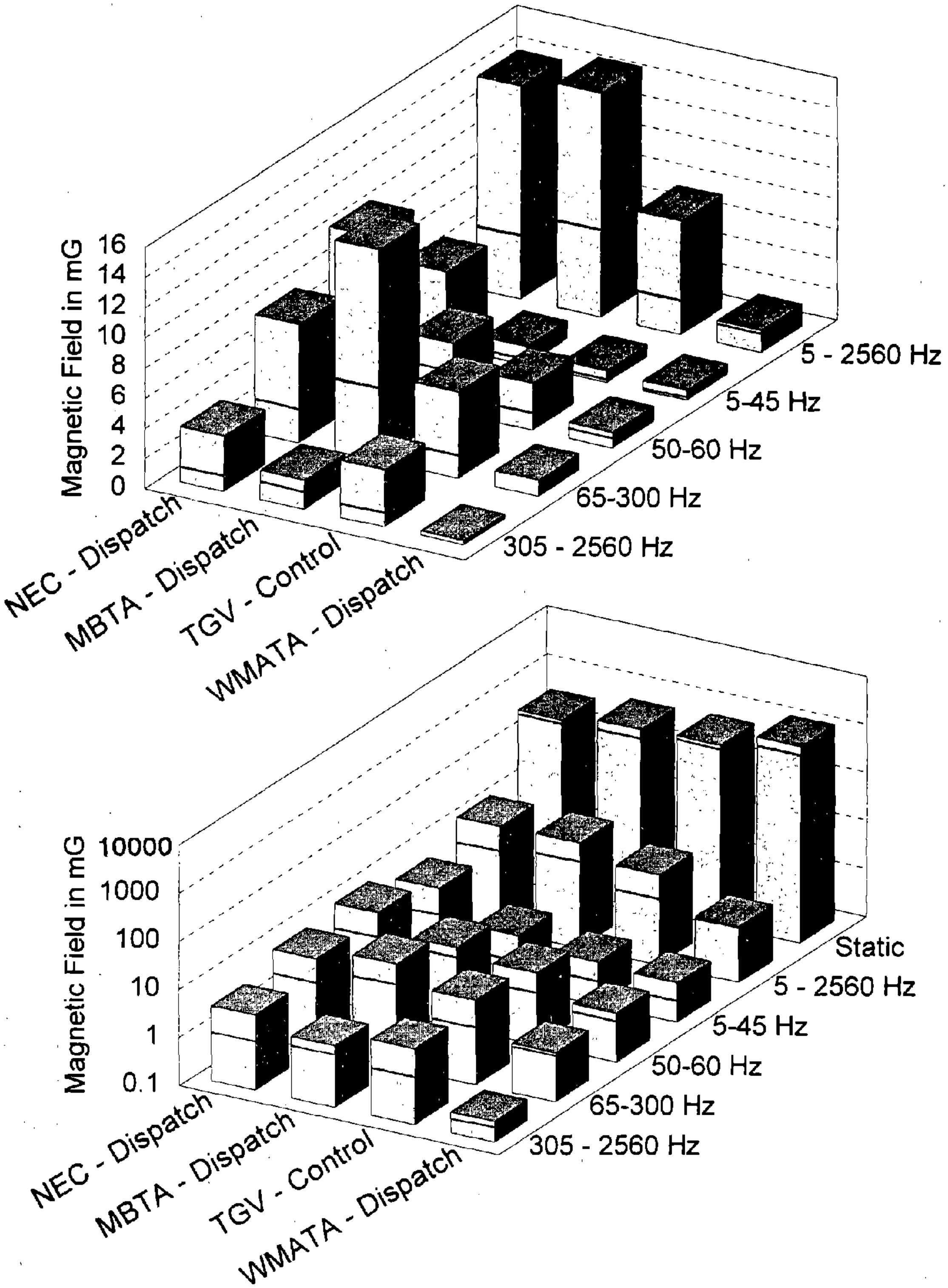


FIGURE 3-9. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS IN CONTROL ROOMS OF ELECTRIFIED RAIL SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

3.3.3 Inside Power Supply Stations and Equipment Vaults

Throughout the studies, magnetic fields were measured inside a few substations, rectifier stations, and equipment vaults. They are not normally manned but are accessible to certain transportation workers for inspections, maintenance or other tasks. These facilities included: an uninterruptable power supply (UPS) vault in the Boston South Station adjacent to the dispatch room; a major 50 Hz substation on the TGV-A system at Gault St. Denis, a TGV-A relay room adjacent to the Vendome Station; and two dc traction power supply stations on the MBTA system. Table 3-6 gives the average and maximum field levels measured at various locations in those facilities where field levels were expected to be high and personnel might be reasonably expected to stand. The same data are presented graphically in Figure 3-10.

The highest magnetic fields were found in the MBTA traction power supply stations. Low voltage buswork carried high ac currents from the rectifier transformers to the rectifier cabinets. High 600 Vdc curents were carried from the rectifier cabinets through the dc switchgear and out to the cables which feed the third rails and catenaries of the urban transit system. As indicated in Figure 3-10, elevated fields are found at all frequencies including the static field. Similar reasons for the wide range of frequencies encountered apply here, as were discussed earlier for fields outside traction power supply stations. There is also considerable variability in the field intensity as the traction power needs of the vehicles out on the system change from minute to minute. The variability is indicated by the considerable difference between average and maximum field levels presented in Table 3-6 or Figure 3-10.

The highest average magnetic fields of any unattended work site measurements were found in the UPS vault near the dispatch center in the Boston South Station. However, since the power load on the UPS system is made up of computers, video display terminals, lights, and other equipment in the dispatch center, the load is uniform over time and the resulting magnetic field shows little temporal variability. Hence, the maximum magnetic field levels are relatively close to the averages. The fields in the UPS vault display a frequency spectrum similar to that measured in the dc traction power supply station. This is due to the UPS unit containing ac components, rectifier banks, and dc circuits similar to those in traction power supply stations. Although the power capacity of the UPS system is much less than that of the traction power supply stations, the fields are similar because in the small vault, the worker is very close to the UPS system.

The control room of the Gault St. Denis Substation is very near the 50 kV bus that runs from the station transformer bank to the low voltage switchyard. All of the power drawn by trains on the central third of the TGV-A line flows through the bus. The resulting high current creates a significant magnetic field. The

TABLE 3-6.

COMPARISON OF AVERAGE (AND MAXIMUM) MAGNETIC FIELD LEVELS INSIDE POWER SUPPLY STATIONS AND EQUIPMENT VAULTS OF VARIOUS SYSTEMS IN MILLIGAUSS, AS A FUNCTION OF FREQUENCY RANGE

SYSTEM AND FACILITY	STATIC	5 - 45 Hz	50 - 60 Hz	65 - 300 Hz	305 - 2560 Hz	5 - 2560 Hz
NEC - CONTROL RM UPS VAULT	669 (1176)	1.9 (2.8)	37.4 (46.4)	18.3 (21.3)	37.2 (44.6)	56.4 (66.4)
TGV-A - GAULT ST. DENIS SUBSTATION	349 (358)	0.4 (0.9)	10.9 (34.3)	0.7 (2.1)	0.6 (1.5)	10.9 (34.7)
TGV-A - VENDOME RELAY ROOM	326 (464)	0.3 (0.5)	1.4 (2.8)	0.8 (1.8)	0.6 (1.1)	2.0 (3.0)
MBTA - TRACTION POWER STATION	841 (2750)	1.1 (18.4)	9.6 (110.7)	3.8 (78.4)	3.4 (55.8)	12.3 (133.1)

principal field component is the standard 50 Hz European power frequency but fields are also present in the higher frequency bands from harmonic current in the bus.

There is moderate temporal variability in the time varying field in the Gault St. Denis control room due to the fluctuating power needs of the trains on the system. But, since this station is supplying power to several trains operating on a large portion of the system, the individual traction power needs tend to average out. This produces less temporal variability in the field than is seen close to or onboard a TGV-A train.

The TGV-A relay room at Vendome contains many racks housing hundreds of relays which operate the transportation system's signaling and control systems. The room also contains a large backup battery bank, dc power supplies and battery chargers, and some communications equipment. It is not a power facility and that is reflected in the low magnetic field levels found in that room.

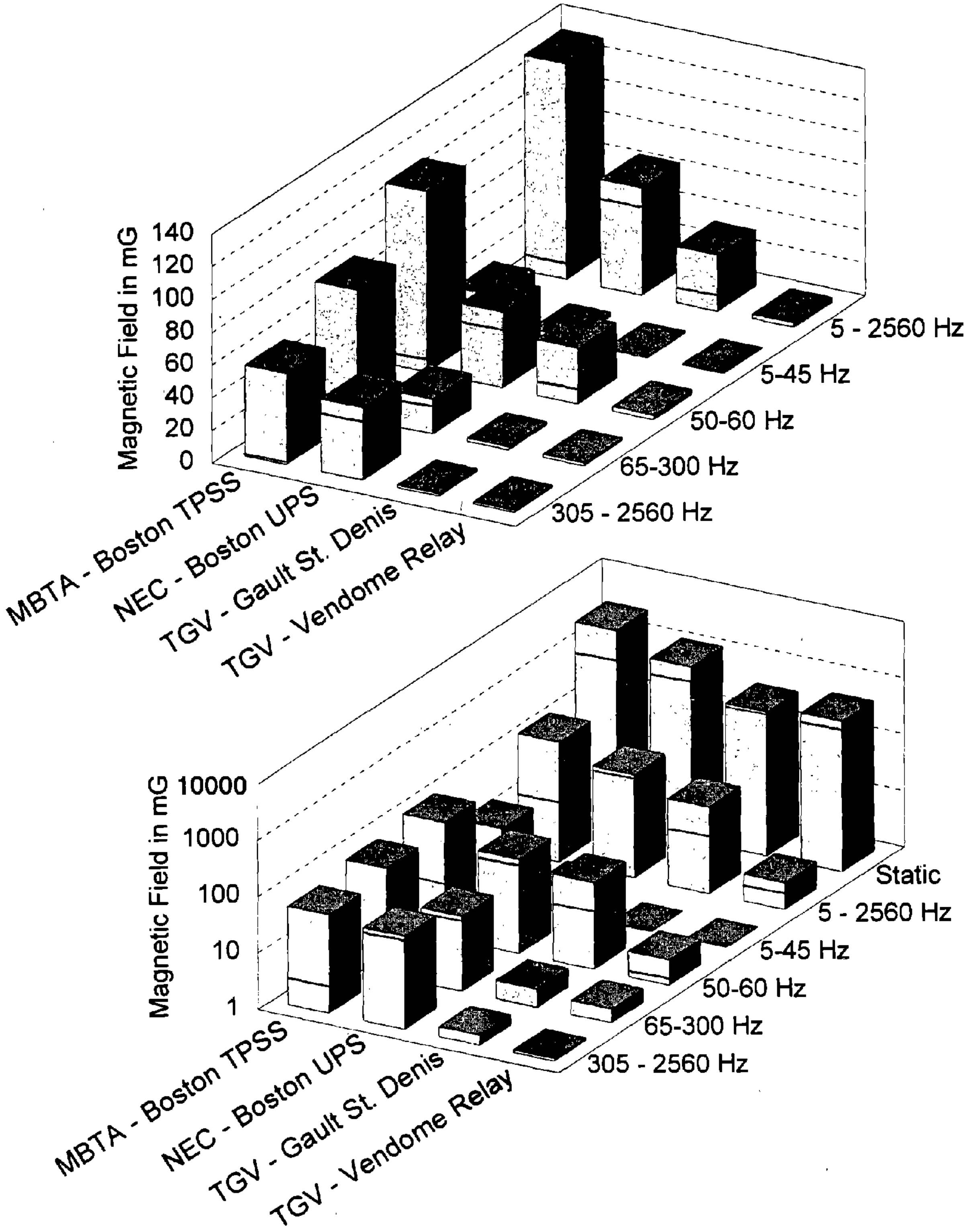


FIGURE 3-10. MAXIMUM (BAR TOP) AND AVERAGE (HORIZONTAL LINE) MAGNETIC FIELDS IN POWER CONTROL AREA OF ELECTRIFIED RAIL SYSTEMS AS A FUNCTION OF LOW FREQUENCY SUB-BANDS. TOP: TIME VARYING MAGNETIC FIELDS PLOTTED ON A LINEAR SCALE. BOTTOM: TIME VARYING AND STATIC MAGNETIC FIELDS PLOTTED ON A LOG SCALE

4. CONCLUSIONS

The goal of this EMF survey and measurements program was twofold: first to quantify the electric and magnetic fields associated with electrified transportation systems; and secondly, to create a database of the electric and magnetic field characteristics of conventional existing electrified systems. These systems include rail and urban mass transit systems, against which the field characteristics of new systems and technologies, such as the Transrapid TR07 maglev, can be evaluated. To compile a comprehensive database, a number of diverse electric field transportation technologies were studied, including ac and dc powered rail systems and urban mass transit systems. In-depth field characterization and source analysis is provided in earlier published reports [1-5]. These reports provide the most comprehensive quantification and characterization of fields associated with electrified transportation systems available.

The overall results and conclusions, summarized in Figures 4-1 and 4-2, are that the average time varying or ac magnetic field levels are at least an order of magnitude less than the strictest EMF exposure guidelines in existence today. The comparison is made of the six key electric field transportation technologies, plus the non-electrified rail measurements, so that the effect of electrification can easily be seen. The comparison centers around the field values obtained onboard the passenger compartments of inter-city and urban mass transit vehicles. These values are, in most cases, higher than in any other surveyed locations. The 60 cm height readings were chosen because they are at the approximate body center of a seated passenger. The operator's compartment levels are of the same general magnitude as levels in the passenger compartments, and average magnetic field levels in other areas near, or associated with the transportation facilities are usually less. Data at the center of the 3000 series Washington, DC Metrorail cars are shown separately because they represent an unusually high field (worst case) condition in a localized area of that type of vehicle only (although passengers can only stand there).

4.1 COMPARISON OF ELECTRIC AND MAGNETIC FIELDS IN ELECTRIFIED TRANSPORTATION SYSTEMS

Sections 2 and 3 cross-compared the measured magnetic and electric fields in key areas: passenger compartments, operator's compartments, wayside, passenger platforms, near the substations supplying power to the trains, and the operator control rooms. The datasets collected in the passenger compart-ments of the different electrified transportation systems give an overview of the general findings of these studies. Figure 3-1 showed the maximum magnetic fields measured on the inter-city trains during this study. The magnetic field axis is presented on the top graphic as linear scale

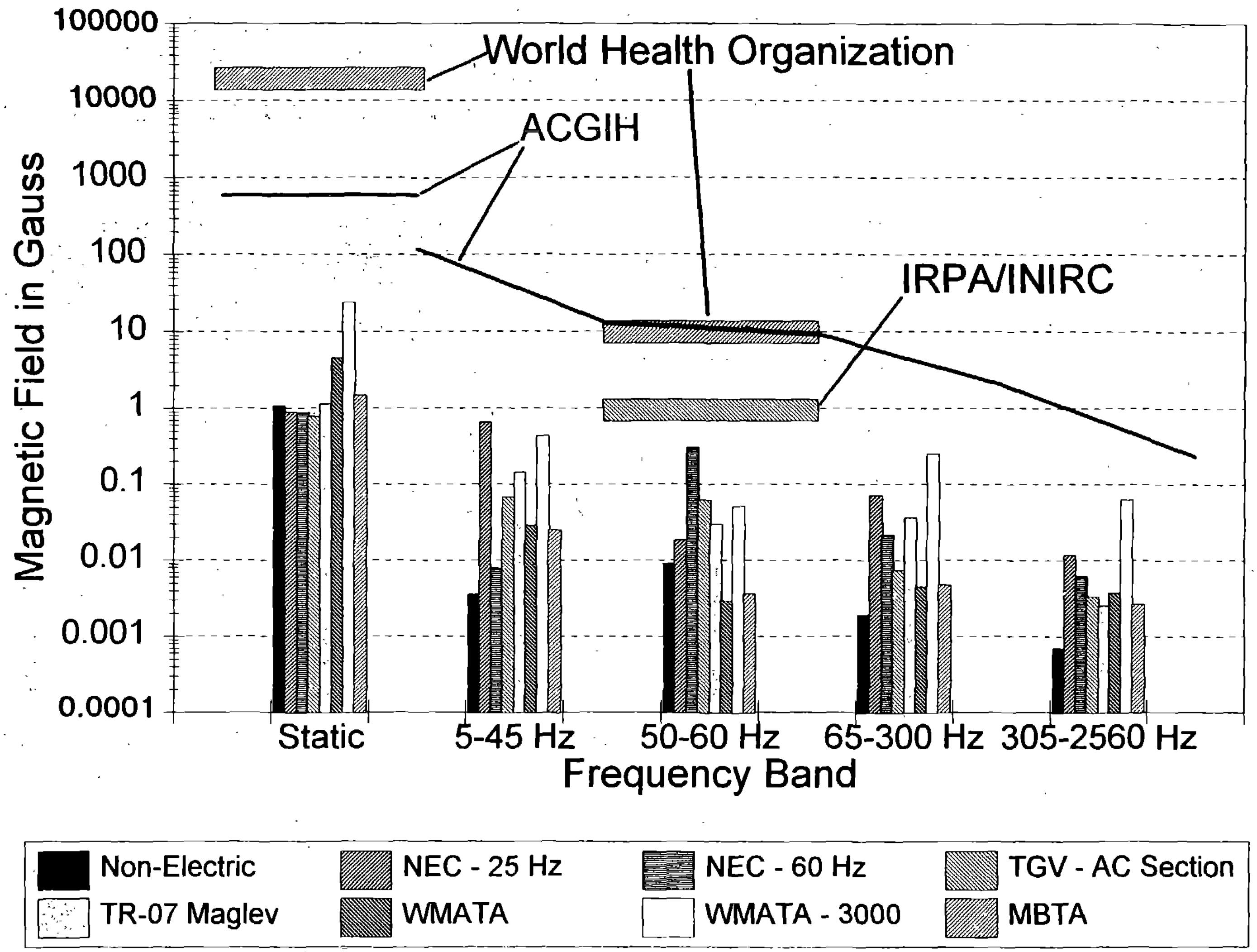


FIGURE 4-1. MAXIMUM MAGNETIC FIELDS PRODUCED BY TRANSPORTATION ELECTRO-TECHNOLOGY COMPARED TO THE GUIDELINES SET BY THE WORLD HEALTH ORGANIZATION (WHO), THE AMERICAN CONFERENCE OF GOVERNMENT INDUSTRIAL HYGIENISTS (ACGIH) AND THE INTERNATIONAL RADIATION PROTECTION ASSOCIATION (IRPA)

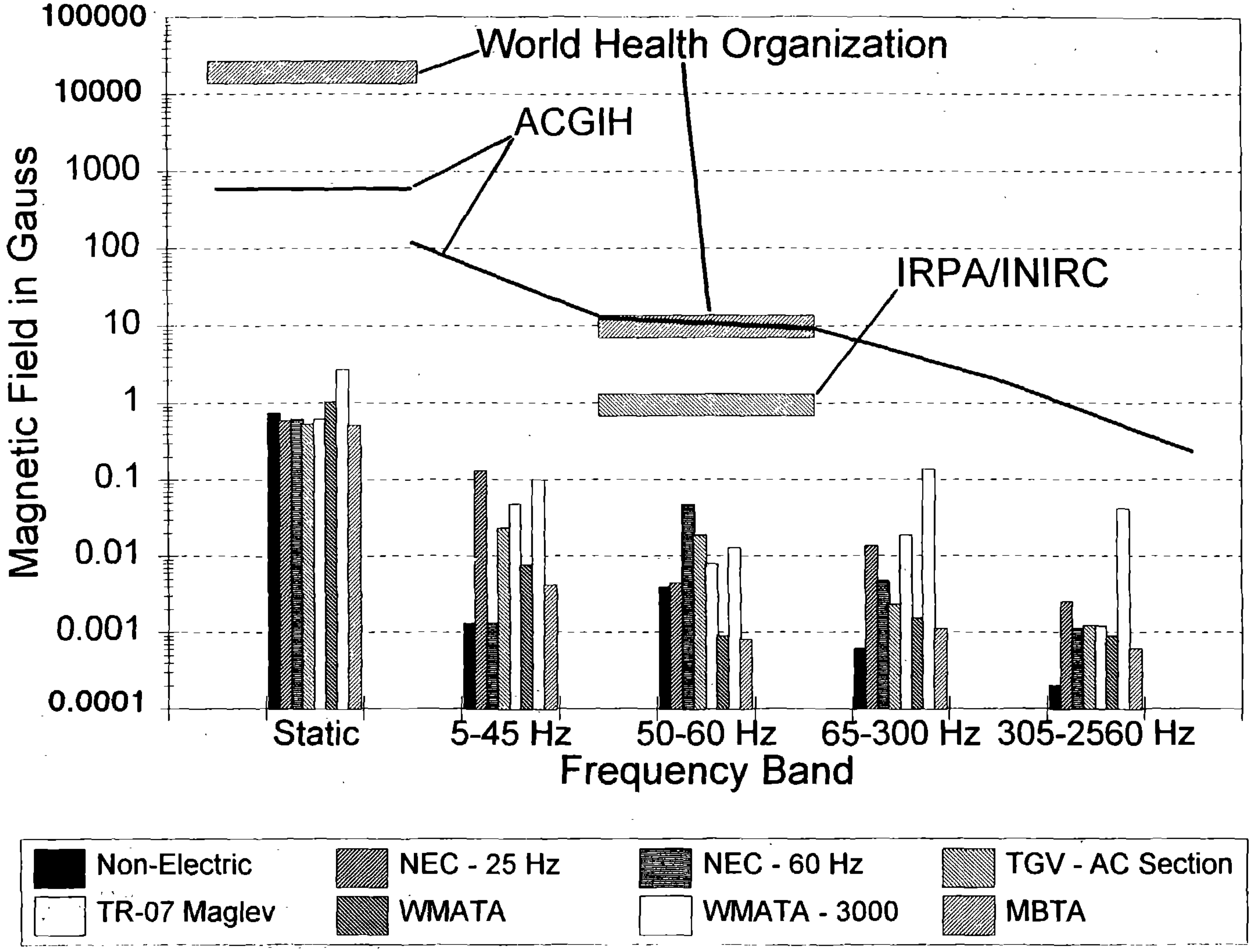


FIGURE 4-2. AVERAGE MAGNETIC FIELDS PRODUCED BY TRANSPORTATION ELECTRO-TECHNOLOGY COMPARED TO THE GUIDELINES SET BY THE WORLD HEALTH ORGANIZATION (WHO), THE AMERICAN CONFERENCE OF GOVERNMENT INDUSTRIAL HYGIENISTS (ACGIH) AND THE INTERNATIONAL RADIATION PROTECTION ASSOCIATION (IRPA)

which shows the magnitude differences. The bottom graphic is presented as a log scale, which makes it possible to see the low-level fields and the higher-level fields. Figure 3-2 is a similar plot for typical urban mass transit systems namely the Washington, DC WMATA and the Boston MBTA systems. As was noted previously, this comprehensive study was initiated on the basis that maglev systems appeared to produce magnetic fields which were unique in terms of their frequency characteristics. The data presented earlier in these figures and in Figures 3-6 and 3-7 for areas outside power substations and for the engineer's compartment, show that the Transrapid TR07 maglev system magnetic fields are not only reasonably typical of magnetic fields found on electrified transportation systems, but their frequency characteristics are also not greatly different from the frequency characteristics found for other electrified rail technologies. In fact, it can safely be assumed from inspecting these figures that maglev systems of the Transrapid TR07 design do not present any uniquely strong magnetic field environment, that is not already encountered in a number of different electrified transportation systems within the United States. However, some unique frequency spectrum signatures were noted above. It should be noted that other design concepts for achieving magnetic levitation using superconducting magnet technologies, may produce significantly higher (primarily static) magnetic fields and have not been addressed in this study.

4.2 COMPARISON OF ELECTRIC AND MAGNETIC FIELDS TO EXISTING GUIDELINES AND STANDARDS

The United States has no national standards to establish limits on the intensity of ELF magnetic fields. There are two guidelines published by international organizations, and one established by a domestic professional trade organization. Furthermore, there are two state standards limiting ELF magnetic fields, and several others limiting ELF electric fields. The state standards presently apply only to electric power lines and substations. This subsection of the report compares the magnetic field levels onboard electrified railroads and near related facilities to the field levels permitted under the above-mentioned standards. Figure 4-1 compares the maximum magnetic fields to the existing standards, and Figure 4-2 compares the average magnetic fields to the same standards. The comparison is also made with non-electrified rail, for six electro-technologies. The unusually high fields at the center of the WMATA 3000 series car represent a worst case, upper limit of EMF intermittent exposure.

4.2.1 <u>World Health Organization</u>

The World Health Organization's *Environmental Health Criteria 35: Extreme Low Frequency (ELF) Fields* [12] addresses both electric and magnetic fields but focuses more heavily on electric fields. Although the document concludes that "adverse human health effects from exposure to ELF electric field levels normally encountered in the environment or the workplace have not been established" and sets no numerical limits for general or occupational exposure, it recommends limiting long-term exposures to 50/60 Hz electric fields to levels between 1 and 10 kV/m as "levels as low as can be reasonably achieved (ALARA)." In the studies summarized here, the highest electric field levels were found in the NEC on elevated platforms. They were less than 1.2 kV/m, which is at the lower end of this criterion.

The World Health Organization's *Environmental Health Criteria 69* [13] addresses ELF magnetic fields. The document concludes that available scientific knowledge does not permit establishment of a definitive limit for static or time varying magnetic fields. The document indicates that adverse human health effects are unlikely at static field levels less than 2 T (20,000 gauss), or with time varying ac magnetic fields which induce current densities of less than 10 mA/m^2 within tissue or extracellular fluids. Based on available scaling data for magnetically induced currents in the human body, the 10 mA/m^2 threshold is reached at power frequency field levels of approximately 10 gauss. The maximum magnetic fields, at any ELF frequency, measured in the vehicles, or on the station platforms, of every transportation system studied were within the World Health Organization Criterion for time varying magnetic fields. Even greater margins of compliance are found for transportation-associated static magnetic fields.

4.2.2 International Radiation Protection Association

The International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA) has developed interim guidelines [11] limiting human exposure to power frequency (50/60 Hz) electric and magnetic fields. The established magnetic field limit for 24 hours per day to the general public is 1 gauss. Short-term exposures of up to a few hours per day are permitted to 10 gauss. Permitted occupational exposure levels are five times those permitted for the general public. In all cases, the magnetic fields measured onboard and near the electrified transportation systems examined in these studies were within the exposure guidelines for the general public.

The numerical field limits in the IRPA interim guideline apply explicitly to power frequency magnetic fields. However, the text of the standard clearly demonstrates that the standard is based on whole-body or limb induced current concerns. Hence, acceptable field limits at frequencies other than 50 or 60 Hz would be related to the 50/60 Hz threshold by the ratio of the power frequency to the frequency of the magnetic field.

4.2.3 American Conference of Governmental Industrial Hygienists

The American Conference of Governmental Industrial Hygienists (ACGIH) has established a "threshold limit value" (TLV) [9] at 600 gauss, for whole-body exposure to static magnetic fields and at 10 gauss for 60 Hz magnetic fields [9]. The document recommends that routine occupational exposures should not exceed the threshold limit values, but states that the values are to be used as guidelines, not as strict determinations of safe and unsafe levels. For example, values comparable to the above TLVs for time varying fields (10 gauss for static fields) are recommended for persons with implanted pacemakers. These TLV values are similar to the guidelines recommended by the World Health Organization, and the tenfold lower level suggested for pacemaker wearers is comparable to the IRPA guideline. As discussed above, the measured magnetic fields on or near the electrified transportation systems meet those criteria.

The TLV for electric fields at frequencies of 100 Hz or less is 25 kV/m [9]. The highest electric field levels found were within the TLV guidelines.

4.2.4 State Power Line Limits

The states of Florida [14] and New York [15] have adopted standards specifically limiting the intensity of the power frequency electric and magnetic fields at the boundaries of transmission line rights-of-way or substation property lines to values from 1.6 to 2.0 kV/m and 150 mG to 250 mG, depending on the type of transmission line. Both standards are established on a "status quo" basis rather than a health or safety basis. Neither standard applies to electrified transportation systems. They do however, provide some guidance as to the levels of magnetic fields which have been judged tolerable at the boundaries of linear power-line facilities, similar to the electrified rail corridors. Generally, magnetic and electric fields measured at the edge of rail rights-of-way did not exceed these status quo limits. The exception was on overpasses where public conveyances are in close proximity to the catenary lines. Such positions would more appropriately be characterized as joint use of right-of-way space and, therefore, may not be considered as edge of right-of-way.

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