Electromagnetic Fields Associated with Transportation Systems

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ABSTRACT

In view of continuing concerns being expressed about the possibility of detrimental EMF effects, agencies with responsibilities for managing health issues have taken some proactive steps to develop information about the EMFs that are or might be associated with existing transportation systems, those systems presently at the stage of early deployment or prototypes and systems still under development. What significantly complicates the transportation system EMFs area compared to EMF concerns raised heretofore, and will likely continue to do so, is the added factor of substantial frequency variability inherent in the most recent trend toward the use of AC motors for propulsion where frequency is used to control speed. So, for transportation systems, the usual exposure variables of time and space have frequency added to them. Any comparison of measured fields to existing standards and guidelines is problematic because they specify limits in terms of temporal and spatial averages assuming exposure is at a fixed frequency. In the most advanced transportation systems the frequency is changing from moment to moment as the speed varies. A substantial portion of the present report deals with the relevance and applicability of present standards and guidelines to concerns that might be raised about transportation system EMFs.

If any simplification of transportation system EMFs is possible in an overall sense, it arises from the scaling factors that exist across the spectrum of systems ranging from small personal vehicles to large, high speed trains. The present report discusses the EMFs associated with transportation systems across the whole range and highlights the connections between exposure and the scale factors.

By way of summary, it is to be expected that magnetic field levels to which occupants or workers are exposed, despite ranging over many orders of magnitude (from a few tenths of µT through several thousand µT), will nonetheless be comparable across the whole range of transportation systems. What is expected to vary more significantly, and also considerably at that, is the extent and distribution of exposure within the body of the person receiving the exposure. For members of the general public, the range of EMF exposures in existing, developing and foreseeable personal scale transportation systems is comparable in magnitude to exposures from other commonly encountered sources. However such exposures are **totally different** in so far as the frequency content is concerned and what, if any, consequences that might entail remains essentially unexplored. Nonetheless, the possibility of significant detrimental effects from the low frequency EMFs associated with transportation systems can only be considered to be rather speculative and remote at the present time.

The overall results of research related to concerns about possible detrimental effects of EMFs, particularly in the context of present knowledge about transportation system EMFs, is reassuring rather than alarming.

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Abstract

[**Author's NOTE**: Throughout this document magnetic fields, usually represented as a vector **H** with unit A/m (ampere/metre), are discussed in terms of the associated magnetic induction, usually represented as a vector **B** with unit T (tesla). The vector nature of the fields, which is critical to the understanding of their distribution patterns and cancellation effects, is commonly ignored in discussions of exposure which tend to focus on the maximum local "apparent" field. At the risk of being accused of exaggerating field levels in certain contexts, but having observed over the years that readers tend to pay attention to **numbers** and ignore the associated **units** (which often incorporate factors of thousands, thousandths, millions, millionths, etc.), it was decided to use μT for magnetic induction throughout the document because it is the unit in which environmentally prevalent field levels are commonly expressed. For example the earth's (static) magnetic field is in the range of 50 μT to 80 μT and 60 Hz fields range from 0.05 μT in rural residences to 0.5 μT in urban residences to as much as 5 μT in urban residences near power corridors. By contrast, MRI (Magnetic Resonance Imaging) systems use (static) fields in the range of 1,000,000 μT. Where a specific frequency or frequency range is not stated in any discussion, the author (or the original author for cited levels) has assumed the frequency or frequency range inherent to the technology or aspect being discussed.]

TRANSPORTATION SYSTEM EMFs

1. Introduction

The increasingly apparent impacts of existing transportation systems on environmental quality, particularly in the form of atmospheric pollution by exhaust emissions from internal combustion engines (ICEs) using fossil fuels, has resulted in growing interest in totally electric so-called zero emission systems and so-called hybrid technologies in which electricity figures prominently for either energy supply or propulsion but a conventional or "advanced" fuel or engine of some sort remains involved. These developments are occurring in an environment where concerns continue to be expressed about the possibility of detrimental effects from exposure to electric, magnetic or electromagnetic fields (EMFs). As more and higher voltage power lines began to appear through the 1960s and 1970s, protests against the installations were mounted and, predictably, health and safety concerns were raised. When Wertheimer and Leeper (1979) reported an apparent association between power frequency magnetic fields and leukaemia in children, concerns escalated dramatically. Similar reports continued to appear through the 1980s (e.g. miscarriages and birth defects associated with emissions from computer monitors as reviewed by Bergqvist and Knave (1989)) and the 1990s (e.g. brain tumours associated with the use of cellular telephones leading to work like that of Lai and Singh (1996)) and continue today (e.g. chromosomal aberrations among [electric] train engine drivers (Nordensen et al. (2001)). In view of continuing concerns being expressed about the possibility of detrimental EMF effects, agencies with responsibilities for managing health issues have taken some proactive steps to develop information about the EMFs that are or might be associated with existing transportation systems, those systems presently at the stage of early deployment or prototypes and systems still under development.

Heretofore, questions about EMF effects have focussed on specific applications of technology - for example microwave ovens or power lines where only a well defined "single" frequency of electric, magnetic or electromagnetic field is involved (2450 MHz or 60 Hz, respectively). In other words, each specific application occupies or is assigned a "station" as in the manner commonly associated with radio and TV broadcasting. The same situation remains true in the case of cellular telephone systems where competing technologies have seen the wide application of 450 MHz systems (initially) in North America followed by 900 MHz systems while Europe and the rest of the world adopted systems at higher frequencies in the range of 750 MHz and 1500 MHz and so-called third generation systems are being developed at frequencies above 2000 MHz - encroaching on the assigned microwave oven frequency of 2450 MHz. Automobile collision avoidance systems currently being offered as an accessory on some new automobiles have been assigned operating frequencies (at least in Canada) in the range of 46 GHz and 76 GHz (Toronto Star, 2001). This development, in itself, immediately and dramatically changes the span of frequencies to be considered under the rubric of "Transportation System EMFs" and underscores the open ended nature of questions about the impact of technology in general, and EMFs in particular, on humans or the environment.

The operative concept in Transportation System EMFs is **variability** at least for the foreseeable future principally because a dominant technology has not yet been established. Of course, variability is always an issue in so far as intensity of exposure is concerned. That variability manifests itself both temporally and spatially. Exposure depends on when you measure it and where you measure it. What significantly complicates the transportation system EMFs area, and will likely continue to do so, is the added factor of substantial frequency variability particularly in those systems where frequency is used to control speed. By contrast, standards and guidelines tend to specify limits in terms of temporal and spatial averages which, in many situations, such as total uptake of a chemical or for ionizing radiation, is quite appropriate since it is clearly established and well accepted that more is worse. However, in the case of EMFs, and especially so at the lower reaches of the frequency range, nothing like a comparable consensus exists.

When exposure assessments are carried out, averages and simplifications rule. So, sinusoidal variations are dealt with by calculating root mean square (RMS) averages. Pulsed exposures are dealt with by employing duty factors representing the fraction or percentage of time the signal is present. Generally, the highest level measured at any accessible location is taken as applying to the whole body on the grounds of erring on the side of safety. If a specific tissue or organ can be identified as being of particular concern for some reason or other, standards or guidelines may be set so as to preclude any part of the body being exposed in excess of what is permissible for the most sensitive part. In the case of transportation system EMFs, the situation is further complicated by the fact that the "signal" itself also varies with time, somewhat in the manner of the sound from a slide whistle - gradually rising to a sustained note (while at cruising speed), sliding up and down as speed increases and decreases and falling again when the vehicle stops.

Standards and guidelines, as initially conceived, addressed single "signals" and assumed whole body exposures. They have evolved to address multiple "signals" and partial body exposures. They have yet to address "signals" for which the frequency varies with time Consequently, not only is any comparison of transportation system EMFs to existing standards problematic, even the applicability and relevance of the standards are debatable! However, as formerly, progress is achievable in the first instance with the aid of simplifying assumptions. This report must be read with these considerations in mind throughout.

2. Background

Ever since their discovery, electricity and magnetism have been exploited by people in various practical ways. The dawn of the past century saw the beginnings of the electrification of society. It has proceeded apace, including industrial applications to an ever increasing extent. The earliest applications were DC, where a constant current driven by a constant voltage is applied to achieve various desired effects. However, it was soon discovered that AC, where an alternating current driven by an alternating voltage, offered significant advantages (mainly stepping voltage up or down, as needed, using transformers) particularly where electrical energy needed to be transmitted over relatively long distances or where it was used to drive motors. At the outset, the frequencies at which the current or voltage alternated were limited to relatively low values (16 2/3 Hz and 25 Hz) reflecting limitations in mechanical technology for massive rotating machines of that era. As time progressed, there was pressure to increase the frequency for a number of reasons, not the least of which was that, when used for lighting, lower frequencies produced noticeable flicker, particularly as fluorescent lamps were developed and began to see increasing use. In Europe, a frequency of 50 Hz was chosen while the US settled on 60 Hz. Significant development and exploitation of electricity occurred in Ontario with its early hydroelectric installations at Niagara Falls. These were initially at 25 Hz (and some of them still exist to serve specific industrial customers with 25 Hz installations). However, for public consumption Ontario initially decided on 40 Hz and maintained that until the middle 1950s when a conversion to 60 Hz was effected probably largely to facilitate interconnections with the US power grid. Incidentally, naval and aircraft systems have widely adopted 400 Hz as the onboard power frequency.

The era of electrification saw the birth of the science of electronics including radio broadcasting and communications and eventually, during World War II, the development of radar. Historically, applications have moved to higher and higher frequencies in search of improvements in coverage, reliability, bandwidth, directionality, etc. Having started out in the kHz and low MHz range (AM radio for example), applications moved into the mid MHz ranges (TV and FM Radio), are presently in the high MHz and low GHz range (microwave relay, satellite links, cellular telephone systems) and are moving through the mid and high GHz ranges (collision avoidance systems, precision air traffic control radars) into the THz range (laser links and fibre optic systems).

3. Transportation Systems

The transportation industry did not ignore the use of electricity at the turn of the last century, at least for railways. Early applications used DC motors for locomotives and they continue to be used in many countries throughout the world. Other countries (particularly in Europe) have adopted systems using 16 2/3 Hz or 25 Hz AC. In North

America, electric railways have been less widely used than in Europe (where they exist they use 25 Hz or 60 Hz) but extensive electrified urban transit systems (subways, street cars, trolley busses) have been built using the dominant 60 Hz supply, although DC remains common and 25 Hz is also used in older North American systems. More recently, magnetic levitation systems have begun to be developed. Advanced prototypes of high speed interurban lines have appeared in Japan and Germany. In the US, seven projects have recently been authorized for pre-construction planning and are undergoing environmental impact assessments (US Federal Railroad Administration, 2001). Canada has flirted with the idea of a high speed maglev line between Montreal and Toronto with extensions to Quebec City and Windsor and a loop to include Ottawa but it has not progressed beyond the early design stages. Most recently, the growing urgency of the need to find an alternative to fossil fuels for use in automobiles to reduce urban atmospheric pollution levels has turned serious attention to electric propulsion systems for personal vehicles, particularly in North America and Europe.

In anticipation of concerns being raised about the EMFs arising from an increasing emphasis on electrical propulsion, it is essential to develop as complete and detailed a picture of the EMFs associated with existing vehicles and systems (both large and small) and to keep abreast of the EMFs associated with new systems as they proceed through development, prototyping and deployment. Some work along these lines has already been conducted. The bulk of it has focussed on occupational exposures (especially for engine drivers) with relatively little attention having been paid to passenger or bystander exposures. With little doubt, the most extensive and detailed survey in the world, to date, was sponsored by the Volpe Transportation Center in the US (Dietrich and Jacobs, 1999). It includes a large amount of passenger compartment data for a wide range of vehicles and will be discussed in greater detail later in the present report. It also brings to the fore the question of what is to be included under the rubric of transportation system EMFs in so far as secondary sources might be involved. This matter will also be elaborated further, later in the present report.

For the purposes of the present report, transportation systems will be divided into three categories as follows:

Category 1:	High speed systems (usually with moderate to low capacity) typically envisaged as suitable alternatives to air travel over intermediate distances. "Conventional" Technology - French - TGV, Japanese - Series 700 Shinkansen; "Advanced" Technology - maglev (Japanese - Chuo Shinkansen, German - Transrapid)
Category 2:	Moderate speed systems (usually with high to moderate capacity) such as are typically employed in urban mass transit systems over relatively short distances and railroads over long distances. "Conventional" Technology - "ordinary" trains, subways, busses (trolley, gasoline, diesel), streetcars; "Advanced" Technology - LRT, fuel cell
Category 3:	Small systems (low capacity, "personal" vehicles) as exemplified by the conventional automobile in its various forms including vans and small trucks. "Conventional" Technology - gasoline, diesel, battery; "Advanced" Technology - fuel cell, hybrid

In essence, a transportation system uses a source of energy (the supply) to activate the final drive mechanism (the motor) using an interface (the control) to regulate the motion of a vehicle. For contemporary "conventional" transportation systems the supply is a fossil fuel and the motor is an internal combustion engine with only the control (ignition) being electrical, ignoring, of course, ancillary features associated with "creature comforts" such as air conditioning, heated seats, sound and video systems, food service, communications and so on. In "advanced" systems, regardless of the Category, the motors are electrical (and may be either AC or DC) and, to an increasing extent, the supply is electrical (and may also be AC or DC). Where both the supply and the motor are electrical, the possibilities are indicated diagrammatically in Figure 1.

The names commonly used for the basic control element in each possible configuration are shown in Table 1. In essence the controls are used to modify some aspect of the voltage or current supplied to the motor to optimize its performance be that while starting, cruising, coasting or stopping. In the most advanced systems this includes recovery of energy whenever the vehicle is slowing down or being stopped rather than simply dissipating it as heat in a resistor or purely frictional braking system.

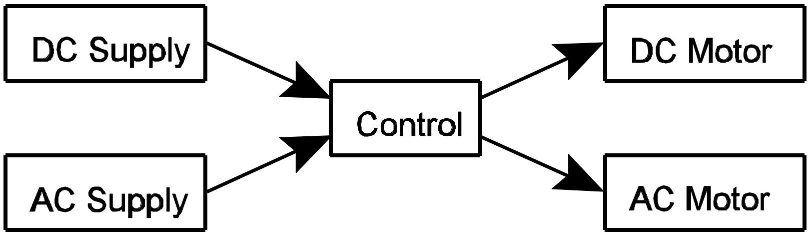

Figure 1. Possible Fundamental Electrical Propulsion Configurations

Early traction drives used DC motors. DC drives continued to be used almost exclusively until recent decades. Petit (1989) describes the rapid evolution and the considerations of possibilities that were a feature of the TGV system in France. In eight short years the traction system changed from twelve 535 kW DC motors to eight 1100 kW AC motors as the associated high capacity solid state device technology advanced. Similar advances and changes have occurred in the past decade and can be expected to continue.

Table 1. CONTROL CONFIGURATIONS

SUPPLY	CONTROL	MOTOR
AC	Rectifier + Chopper	DC
	Converter	AC
DC	Chopper	DC
	Inverter	AC

Before the advent of high power solid state diodes, mercury arc rectifiers were used and since even early diodes had limited capacity as many as 20 would have to be connected in parallel so as to pass sufficient current to meet the demands of the motor. Since the generation, transmission and distribution of electricity throughout the world has been done almost exclusively using AC, the first requirement for most early traction drive systems which used DC motors was to convert the AC to DC using a **rectifier**. Morwood (1998) and Bolton and Johnson (1998) together provide a good, recent summary outlining the changes that have occurred in traction system power supplies as a result of ongoing improvements in solid state technology. Basic two or three phase full wave rectifier bridges are shown in Figure 2.

The output for the three phase case is shown in Figure 3. It is described as being a six "pulse" output. In modern traction rectifiers there are two interconnected three phase bridges giving a so-called twelve pulse DC output. It is clear that, with twice as many pulses per cycle, its output will be more nearly constant than that from a single three phase bridge with six pulses per cycle and much more so than that from a single two phase bridge with four pulses per cycle. However, it is precisely these "pulses" that create the time variations in currents and voltages that show up as power frequency signals (including harmonics) when measurements are taken. They also give rise to interference with safety and communications signalling and add to the complexity of assessing whether or not there might be detrimental effects on workers or passengers.

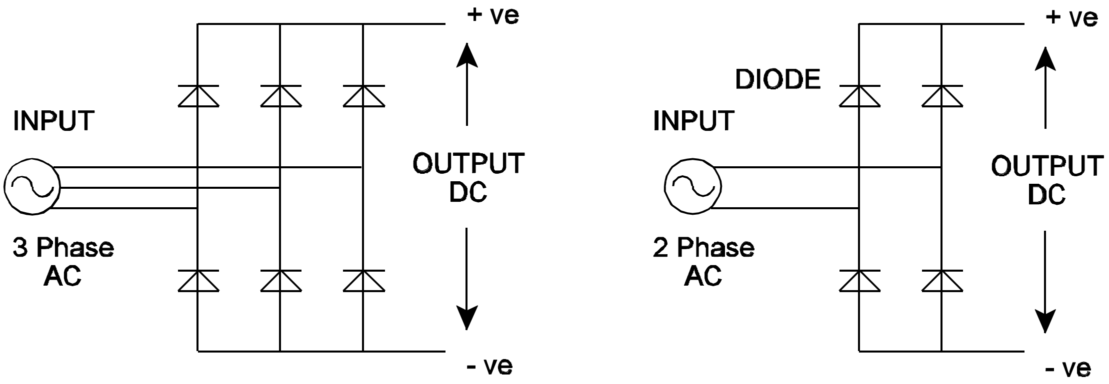

Figure 2. Basic 3 and 2 Phase Rectifier Bridges

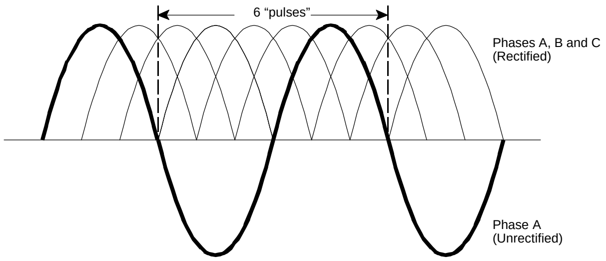

Figure 3. Full Wave Rectified, 3 Phase AC - so-called six "pulse" output

Simply put, the earliest controls for DC motors were wasteful. If the situation did not demand the full source voltage, it was dissipated or diverted using resistors which simply got hot and, coincidentally, carrying high currents and being coiled produce substantial "static" magnetic fields. Gradually less wasteful control systems were developed using electronic (MARs, i.e. Mercury Arc Rectifiers - and corresponding switches) and eventually solid state circuit elements (SCRs i.e. silicon-controlled rectifiers and corresponding switches). For DC motors with a DC supply the control was called a **chopper** and it simply switched the supply on and off regularly. Not surprisingly, the earliest versions were "square" wave controls and would have the motor "off" at least half of the time. Control of speed or power delivered was achieved by having the on and off occurring so quickly that the motor would not have time to respond fully so it would deliver even less than half of the output. It was not long before PWM (Pulse Width Modulated) chopper controls were developed. In such controls the on/off cycle could be made long enough for the motor to have plenty of time to respond but what could be changed was the fraction of on relative to off time. Where the supply is DC and the motor is AC the control is called an **inverter**. Where the AC required for propulsion has a different frequency than the supply, frequency conversion is required and the control is called a **converter** for short rather than, more precisely, a frequency converter. The functional schematics of the various AC and DC controls are summarized in Figures 4 (Rectifier), 5 (Chopper), 6 (PWM Chopper), 7 (Inverter) and 8 (Converter). Each one will have its own "signature" with regard to the EMFs that can be detected in association with their being implemented in one transportation system or another. Such "signatures" are discussed further later in the present report.

In the most advanced contemporary systems, three phase variable frequency AC motors are supplied through VVVF (variable voltage, variable frequency) converters using IGBT (insulated gate bipolar transistor) technology in place of earlier SCR (silicon controlled rectifier or thyristor) or GTO (gate turn off thyristor) technologies.

Morris and Adams (1990) provide a good summary of the benefits and drawbacks of each of the devices which, in simplest terms, are used in the various controllers to switch currents on and off. As time has progressed, the functionality of the controllers has been made increasingly bi-directional so that energy can pass back and forth *ad lib* thereby, as much as possible, returning energy to the supply whenever operating conditions permit. The effectiveness of such bi-directional controls is a characteristic feature of electrical systems that cannot be matched by mechanical systems. Of course, this effectiveness is best exploited in situations where the vehicles are actively being slowed down, i.e. braking is required.

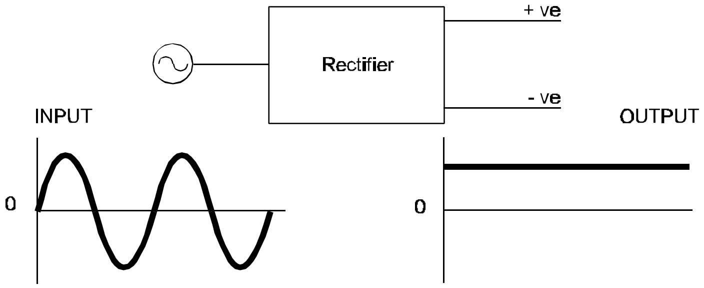

Figure 4. Rectifier (functional schematic)
[NOTE: Zero represents ground. In DC systems the negative terminal is typically grounded]

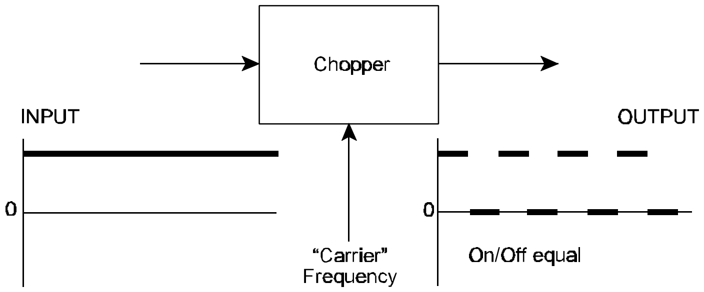

Figure 5. Chopper (functional schematic)
[NOTE: "carrier" frequency determines the On/Off cycle time]

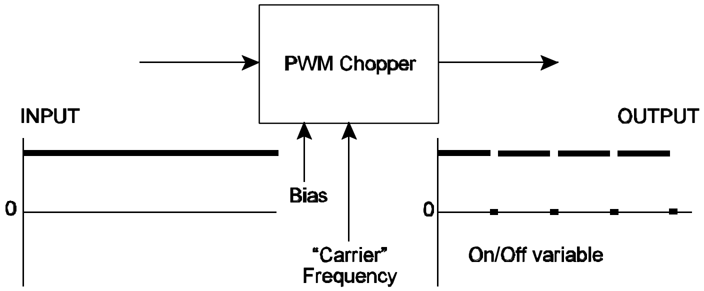

Figure 6. PWM Chopper (functional schematic)
[NOTE: "carrier" frequency determines the On/Off cycle time, Bias determines On/Off ratio]

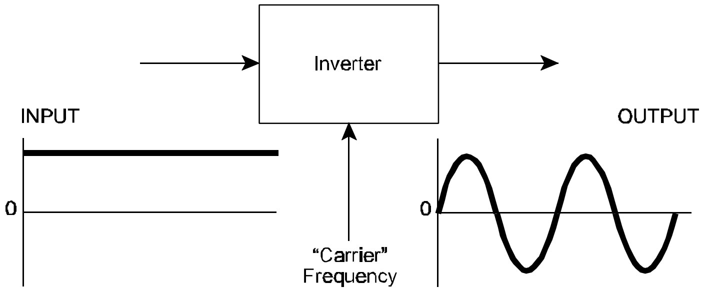

Figure 7. Inverter (functional schematic)
[NOTE: The "carrier" frequency determines the OUTPUT frequency]

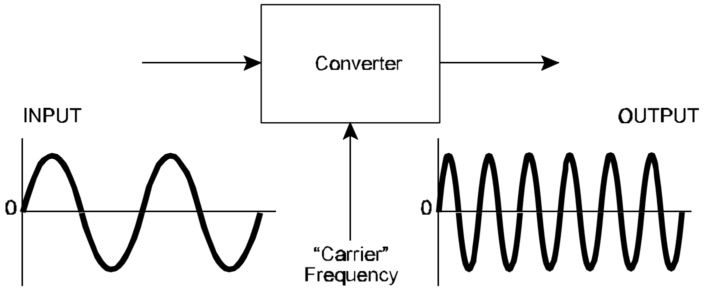

Figure 8. Converter (functional schematic)
[NOTE: The "carrier" frequency determines the OUTPUT frequency]

Conventional transportation systems virtually all use dissipative braking. Brake shoes press on a drum or clamp against a disc, dissipating the kinetic energy of motion by creating heat - a total waste except in so far as it prevents a disaster, i.e. collision with something. In electrical transportation systems, it was soon discovered that by appropriately altering the electrical connections the motor would act as a generator. When switched into generator mode, the motor could be loaded by a resistor and thereby assist any mechanical braking that was installed on the vehicle. However, the additional braking was still dissipative, producing only heat in the resistor. One of the most significant developments in contemporary controls is that they have become bi-directional and thereby permit a good portion of the energy usually dissipated in braking to be returned to the source of supply. This is commonly called regenerative braking. Whether dissipative or regenerative, the braking produced is essentially passive from the point of view of the electricity supply. In emergency situations the switching of the motors into generator mode can also be used to "actively" enhance braking which implies input from the electricity supply to effectively reverse the "thrust" of the motors rather than just create drag.

In maglev systems, the suspension is also electrical (i.e. magnetic fields produced by electromagnets). Furthermore, controls are becoming increasingly electrical in nature as evidenced by the use of computer chips to effect reduction of emissions from internal combustion engines, collision avoidance systems for automobiles and "fly by wire" controls as have appeared in newer aircraft. Railway safety signalling systems have also become increasingly electrical as semaphores and lanterns were replaced first by signal lights and relays then, in recent times, by radio controls. These are all factors that contribute to the interest in and concern about the EMFs associated with transportation systems and also have given and will continue to give rise to an increasing complexity in the EMF environment associated with transportation systems.

In all propulsion systems there is a complex interaction between the various parameters involved in the supply, the control and the motor. Engineers work to optimize the system based on ensuring that all the properties of the system e.g. cost, acceleration, emissions, jerkiness, safety, etc., etc., remain within specified tolerances.

Decisions regarding what system to employ arise from a complex interplay of inputs from science and technology (hopefully based on logic and rationality) with those from economics and politics (too often based on self interest and expediency) in an arena (usually charged with emotion) driven by public demand modulated by media attention. Business decisions, increasingly dominated by profitability, are typically made with short time horizons, e.g. next quarter or next year. Political decisions, all too often dominated by expediency, tend to have time horizons that are somewhat longer, ranging to the next election while societal decisions seem to be dominated by emotion and anxiety and have time horizons ranging to the next generation and beyond although often shortened, sometimes substantially, by immediate self interest. These factors result in a great variety of different configurations for existing transportation systems, much uncertainty about the final configurations for systems under development or yet to appear and a significant system to system variability and uncertainty in the associated EMFs.

As noted earlier, a dominant technology has yet to be established although it would seem that AC motors are favoured probably because a great deal of experience with them has been accumulated over the years in industrial applications. Furthermore, progress in solid state technology has permitted the construction of motor controls capable of handling the high powers required for large, heavy vehicles. As for the supply aspect, particularly for Category 3 systems, DC would seem to be favoured in so far as batteries are used for storage and the output from fuel cells is DC. All these factors contribute to uncertainties in estimating the patterns of exposure that might prevail in connection with future transportation systems. However, what is evident is that the larger and more massive systems demand higher currents and voltages and consequently generally have larger fields associated with them. On the other hand, smaller systems put the user or operator closer to the sources sometimes leading to higher exposures at least locally.

3.1 Category 1 Systems

In terms of development and deployment, the Category 1 system apparently closest to being implemented for regular service would appear to be the Japanese Chuo Shinkansen due eventually to connect Tokyo and Osaka. Advanced development and testing is being carried out on an initial 18.4 km section of a 42.8 km section of the eventual route. The next would appear to be the German Transrapid system (initial implementation being envisaged as a 292 km line between Berlin and Hamburg) for which extensive prototyping and advanced planning has also been done on a 31.1 km test line near Munich. However, in a recent news story (Associated Press, 2001) it was reported that "Germany canceled a planned Berlin-Hamburg maglev line last February for fear it would lose money and harm wildlife with its powerful magnets." but that a contract had been signed with China for a 32 km Transrapid line in Shanghai. As with other aspects of modern society, the situation continues to evolve.

While differing in the way they suspend the vehicles, both the Japanese and the German systems do so using magnetic fields and consequently are called "maglev" (short for "magnetic levitation") systems. Among "conventional" electrified systems within Category 1, the most advanced is the French TGV system followed by Japanese Series 700 Shinkansen and then the whole gamut of advanced high speed electrified railway systems deployed extensively throughout Europe and to some extent in other countries, notably the US northeast.

3.1.1 The Chuo Shinkansen (Japan)

3.1.1.1 Suspension (Magnetic Levitation)

The method by which the Japanese maglev project suspends the vehicles is known as ELD (electrodynamic) levitation (see Figure 9). It is based on repulsive forces that arise between vehicle mounted superconducting coils and stationary (guideway mounted, figure 8 wound) short circuited coils. In addition, the levitation coils on each side of the guideway are interconnected so that if the vehicle is not centered in the guideway it is repelled from the coil in the nearer sidewall and attracted to the coil in the farther sidewall (see Figure 9) thereby providing the forces necessary to keep the vehicle centered in the guideway during cornering and in the presence of crosswinds.

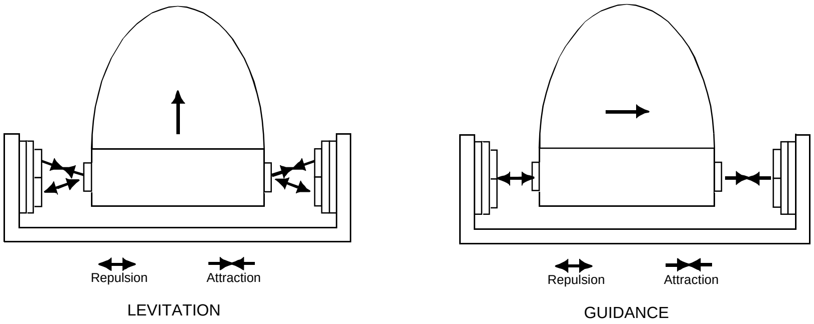

Figure 9. Levitation and Guidance - Chuo Shinkansen
(after Gieras and Piech, 2000)

3.1.1.2 Propulsion (Linear Synchronous Motor)

The same vehicle mounted superconducting coils that provide levitation and guidance also form the moving part of the linear synchronous motor propulsion system by interacting with a third set of stationary (guideway mounted) coils (see Figure 10) energized with 3-phase current (see Figure 11) which produces a magnetic field that travels along the guideway and pulls the vehicle along with it. The speed is determined by the centre to centre guideway coil spacing and the frequency. So, with a centre to centre coil spacing of 1.35 m and a maximum frequency of 56.6 Hz, the maximum velocity works out to 2 x 1.35 x 56.6 = 152.82 m/s or about 550 km/h.

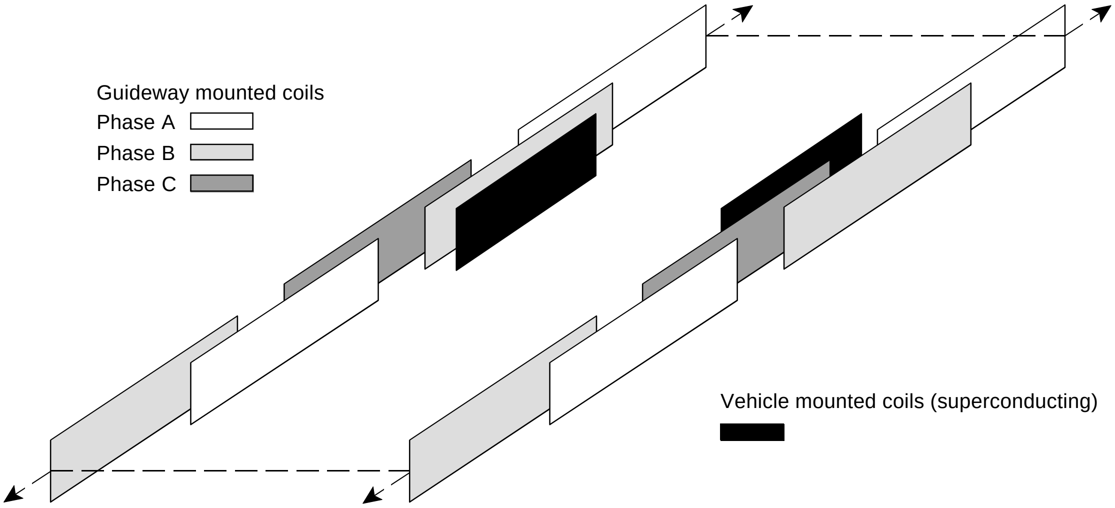

Figure 10. Propulsion coil configuration - Chuo Shinkansen
(after Gieras and Piech, 2000)

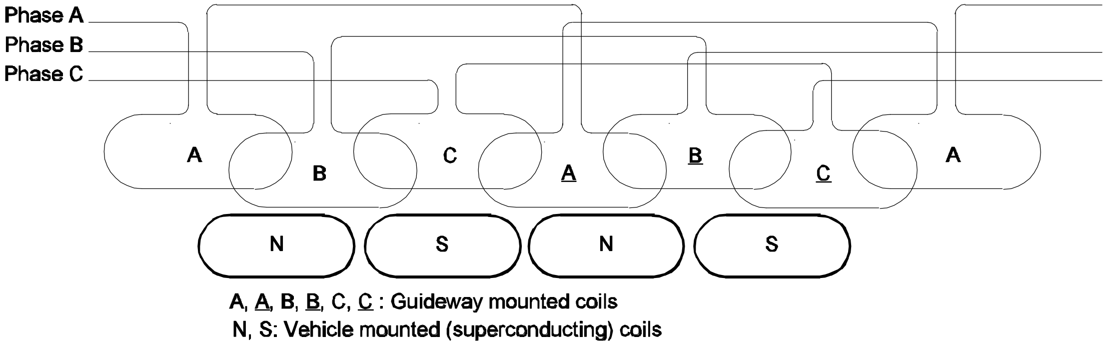

Figure 11. Propulsion Coil Wiring - Chuo Shinkansen
(after Gieras and Piech, 2000)

The electrical energy is supplied from connections to the local 154 kV electrical grid through power conversion substations (see Figure 12). Using rectifiers and inverters these substations supply VVVF (Variable Voltage Variable Frequency) 3 phase electricity to the guideway feed cables.

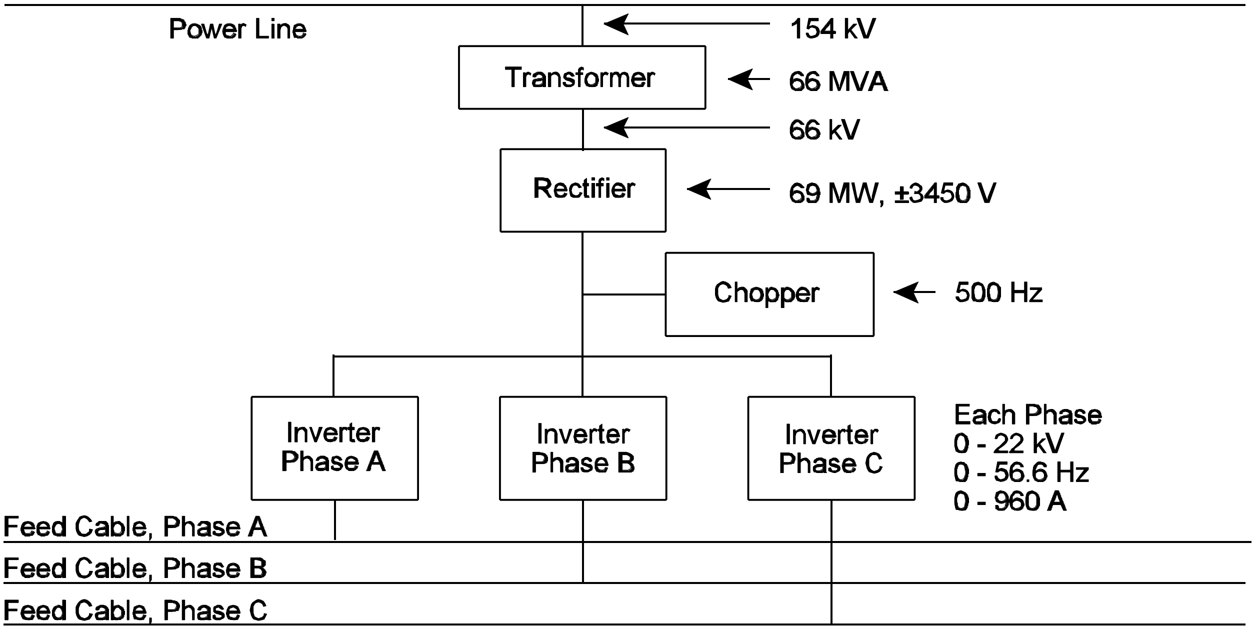

Figure 12. Power Conversion Substation - Chuo Shinkansen
(after Gieras and Piech, 2000)

3.1.2 The Transrapid

The method by which the German maglev project suspends the vehicles is known as EMD (electromagnetic) levitation (see Figure 13). It is based on vertical attractive forces that arise between vehicle mounted energized coils and stationary (guideway mounted) armature coils. Guidance is achieved by a similar coil system producing transverse forces.

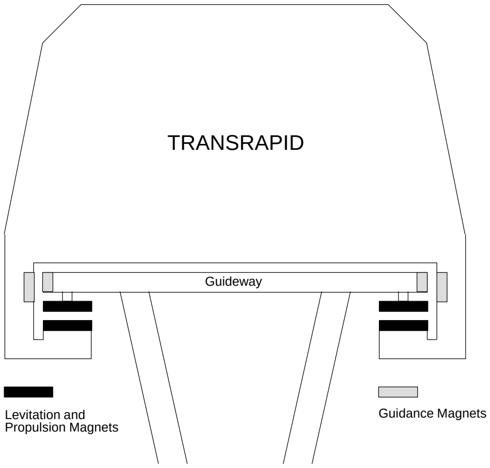

Figure 13. Levitation, Propulsion and Guidance - Transrapid
(after Gieras and Piech, 2000)

It is evident from Figure 14 that the Transrapid power conversion substation is similar to that for the Chuo-Shinkansen. Differences arise primarily from differences in the local electrical grid supply voltage and decisions about the coil size for the LSM, the smaller coils of the Transrapid system demanding a higher maximum frequency for the VVVF inverters. From the point of view of passenger exposures it would appear the Transrapid system would offer the advantage of having the main sources of magnetic fields mounted well away from the passenger compartment.

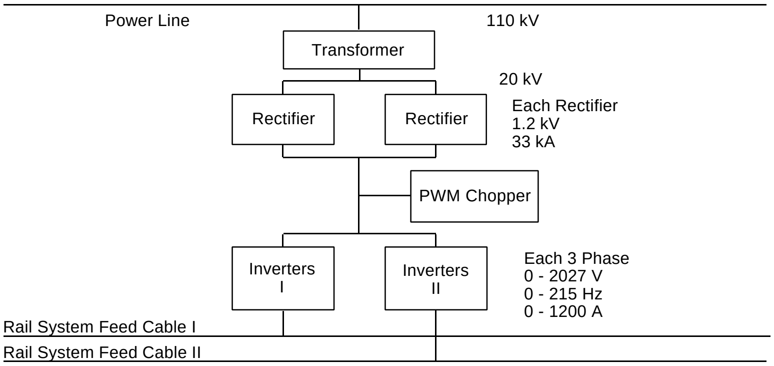

Figure 14. Power Conversion Substation - Transrapid
(after Gieras and Piech, 2000)

The Transrapid also uses a linear synchronous motor propulsion system except that rather than the coils being vertically mounted in the sides of the vehicle and the walls of the guideway they are horizontally mounted under the bed of the guideway and in the suspension arms of the vehicle. Since the rated top speed is 500 km/h and the maximum frequency of the VVVF supply energizing the LSM is 215 Hz the centre to centre guideway coil spacing is about 30 cm.

3.1.3 The TGV

Faced with performance limitations imposed by the existing extensive 25 kV, 50 Hz AC infrastructure and reluctance to abandon years of operating experience associated with the electrified railways in France, a so-called 2 x 25 kV AT system (see Figure 15) was adopted as early as 1981 for the TGV. The traction system is thereby supplied with a 2 phase 25 kV, 50 Hz input which has the effect of doubling the working voltage for the traction system to 50 kV. The effect is similar to typical residential wiring in Canada and elsewhere. Two phase, 110 V, 60 Hz is supplied to the residence. Light appliances (e.g. mixers, toasters, lightbulbs) are connected between one of the phases and "neutral" (ground) and thereby operate at 110 V while heavy appliances (e.g. stoves, ovens, water heaters) are connected between the two phases and thereby operate at 220 V.

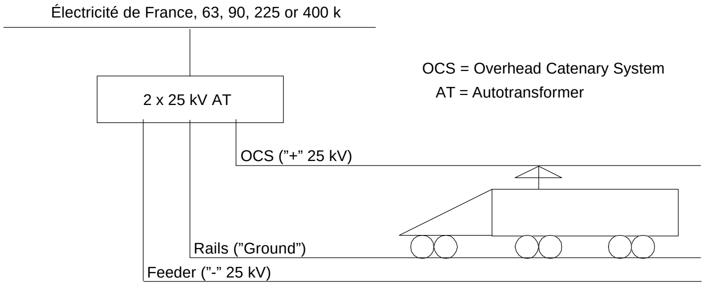

Figure 15. The TGV, 2 x 25 kV AT system configuration [after Roussel, 1989]

The individual trainsets require 6 MW (Southeast TGV) or 8.8 MW (Atlantic TGV) and are doubled to meet capacity demands. Clearly the currents associated with the operation of the TGV are significant and consequently the associated magnetic fields can be expected to be relatively large.

3.1.4 The Series 700 Shinkansen

The Japanese Series 700 Shinkansen described by Ito et al. (1998) is an excellent example of advanced, high speed rail systems not achieving the design speeds of the maglev systems under development but, nonetheless, delivering speeds approaching 300 km/h. It uses the latest Insulated Gate Bipolar Transistor (IGBT) technology to deliver 1850 V, 444 A, 0 Hz to 200 Hz, 3 phase AC to 4 x 275 kW traction motors in parallel (see Figure 16). Trains consist of four, four-car units, three of which each have four traction motors. The fourth car is a so-called "trailer." The first car of each four-car unit carries its four traction motors and a power converter unit. The second car connects to the overhead 25 kV 60 Hz supply and carries the traction transformer (25/1.22 kV, 4.16 MVA). Its four traction motors are supplied from a power converter unit carried by the third car. The third car carries its four traction motors and two power converter units, one to supply its own motors and one for the motors of the preceding (second) car. The fourth car is a "trailer" and only carries some auxiliary electrical equipment.

Ito et al. (1998) also discuss in some detail the various operating regimes associated with optimizing various aspects of the performance of the Series 700 Shinkansen (see Figure 17). Consideration is given to noise from the point of view of passenger comfort but possible interference with safety signalling systems also needs to be taken into account. What is underscored by these features is the previously mentioned variability in the EMF environment associated with such transportation systems.

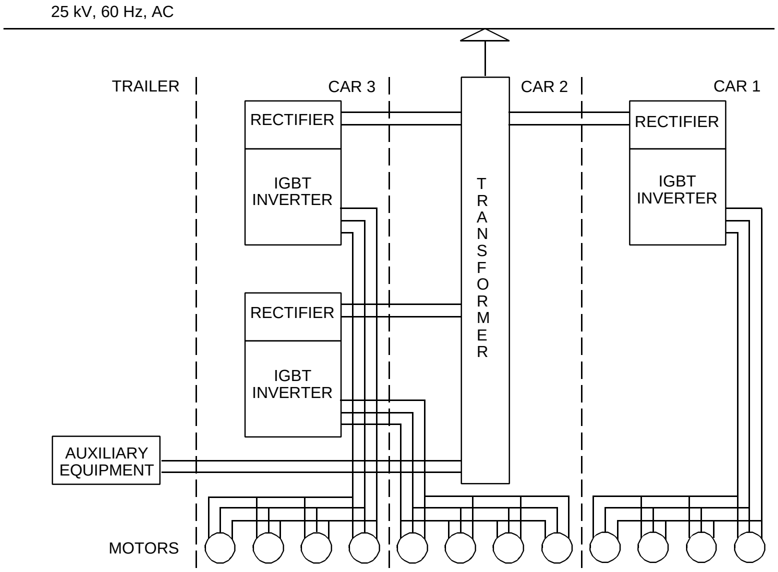

Figure 16. Series 700 Shinkansen - Configuration of Units
(After Ito et al. (1998))

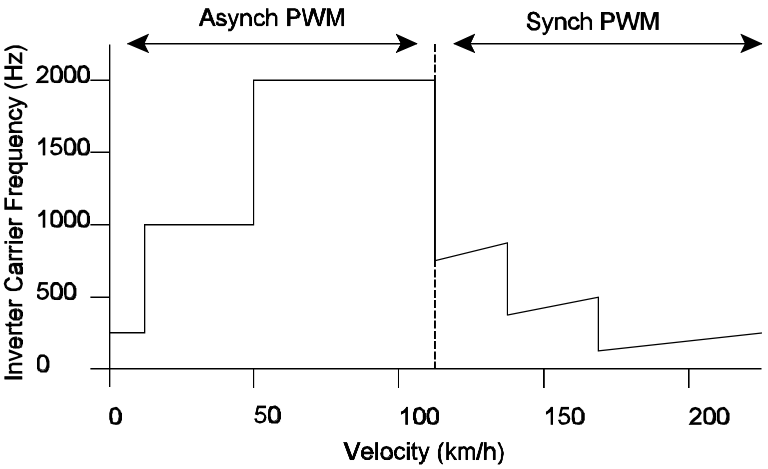

Figure 17. Series 700 Shinkansen - Inverter Carrier Frequency
(After Ito et al. (1998))

3.2 Category 2 Systems

3.2.1 "Conventional" Electrified Railways

Conventional electrified railways simply amount to lower power, lower speed versions of the TGV and Series 700 Shinkansen generally designed for operation at speeds well under 200 km/h. Aside from details such as the characteristics of the electrical connection to the local grid, the configurations are similar to those shown in Figures 15 and 16. In some countries DC is still used to supply the traction motors while in other countries AC of various (16 2/3 Hz, 25 Hz, 50 Hz, 60 Hz) fixed frequencies is used. Magnetic fields associated with these systems can be anticipated to be comparable where the supply voltages are comparable in so far as the powers required to drive the trains are comparable. However, lower supply voltages imply larger currents to deliver the same power so the associated magnetic fields would be expected to be correspondingly greater.

In Canada, there are very few, if any, "conventional" electrified railways.

Hybrid systems have been receiving a great deal of publicity in recent times particularly in the context of Category 2 and Category 3 transportation systems. However, they have, in fact, been in use for many decades in both passenger and freight service in the form of diesel electric railway locomotives where a diesel engine is used to drive a generator which supplies electricity through a controller to the motors. As far as EMFs are concerned, the fields associated with such locomotives are self-contained and would have minimal, if any, impact in passenger cars.

3.2.2 "People Mover" or Light Rail Transit (LRT) Systems

A dedicated, 135 km/h maximum speed, airport to downtown link in Hong Kong is described by Carrington and von Lingen (1998). It is uses by overhead 1.5 kV DC to supply 3 phase AC motors through a GTO Inverter. Braking may be regenerative, returning energy to the overhead DC system as the train slows or rheostatic, where the energy is dissipated in a resistive load when conditions are not suitable for regenerative braking.

In March 1985 the Toronto Transit Commission began regular operation of an LRT system dubbed the Scarborough Rapid Transit (SRT) conceived in the early 1970s as a maglev system (TTC, 1996). Early in 1986 the scheduled operational hours were extended to match those of the subway system. It uses an ungrounded 600 V DC supply with two (one positive, one negative) "live" rails. The configuration is shown in Figure 18. Each vehicle is equipped with two Linear Induction Motors (LIMs) each fed by a 350 kVA inverter. The system incorporates regenerative braking and, for emergency braking, an electromagnetic brake to supplement hydraulic disc brakes. The line extends 7.2 km from Kennedy Road and Eglinton Avenue to McGowan Road near the Scarborough Town Centre. The SRT is characterized as a five rail system (two running rails, two conductor rails and one wide "reaction" rail which forms the secondary for the LIMs). Essentially this type of system is very similar to the extant maglev systems with regard to propulsion. However it replaces magnetic levitation with "conventional" methods for suspension.

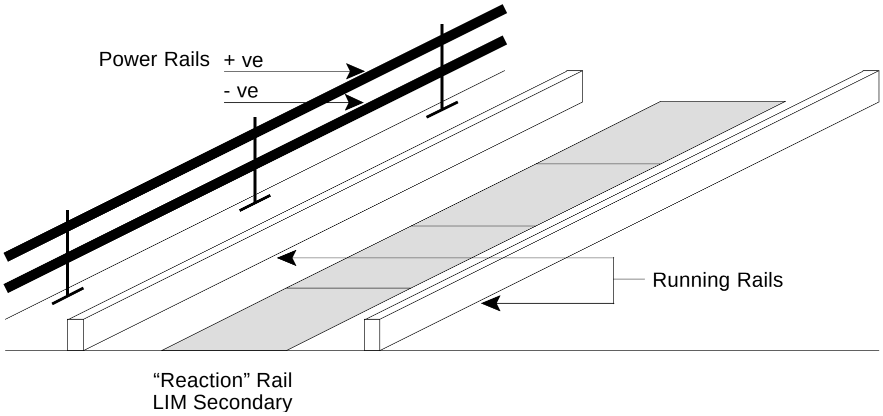

Figure 18: SRT Rail Configuration (Schematic)

The running rails serve only to guide the vehicles. They do not form part of the electrical circuit as in other rail guided systems where the rails also serve as the ground or negative conductor. The "reaction" rail serves as the secondary for the LIM which can be visualized as an "ordinary" electric motor with the stationary (outer) part of it cut, rolled out flat and repeatedly extended over the whole distance to be covered by the line. The coils of the moving part of the LIM are similarly flattened out but mounted in the vehicle and, by interacting with the reaction rail, propel the vehicle along the reaction rail producing linear rather than rotational motion.

The various elevated monorail systems such as that installed recently in Detroit and smaller scale systems operated in places like theme parks or the Metro Toronto Zoo, for example also fall into this category. They are moderate to low capacity systems with correspondingly reduced power requirements but, again, depending on operating voltages used, currents may tend to be high producing correspondingly high magnetic field levels.

3.2.3 Subways

Subways are the epitome of mass transit systems - high capacity, electrically driven, low to moderate speed systems operating in areas with high population densities. Historically the systems used DC with supply voltages in the range of a few hundred V and tend to continue to do so since there is always a demand to maintain compatibility with existing infrastructure elements.

A good example of a Category 2 subway system recently installed in London using 630 V DC supplied by 22 kV 50 Hz AC is described by Murphy (1998). 22 kV was chosen for the AC supply since "The introduction of a voltage other than 22 kV onto the LUL [London Underground Limited] system would have created substantial additional costs relating to maintenance, spares, training etc. and made difficult interconnections with the existing system." The 22 kV AC in a 2 x 2.25 MW configuration is supplied in turn from an LUL substation supplied by 132 kV AC from the National Grid secondary transmission network. The system is designed to accommodate train starting currents of 4.5 kA.

Closer to home, the TTC provides an excellent example of how advances occur in the design of subway systems in particular and transportation systems in general. Typically, once a system is installed, new designs are constrained to maintain as much compatibility as possible with the existing system as in the LUL case described briefly above. The TTC subway system, which opened for regular service in 1954, initially envisaged the use of trains consisting of up to ten 13.7 m (45 ft) to 14.6 m (48 ft) cars similar to those in use at that time in US cities such as Chicago but was finally implemented as trains of up to eight 17.4 m (57 ft) cars (TTC, 1991a) usually in a paired, motored car - trailer car, configuration. The system used the standard 600 V DC third rail configuration (continues to be in use today) for the electrical supply to the trains which used the then standard rheostatic (variable resistor) propulsion controls and conventional frictional braking. The next stage of development, introduced into service in 1962-63 (TTC, 1991a) saw the use of 22.8 m (75 ft) cars (paired A car with batteries, B car with compressor, both motored) with camshaft driven rheostatic propulsion control system and four 89.5 kW (120 hp) DC motors per car. So-called rheostatic (dissipative electromagnetic) braking was mandated to avoid adding to the enormous quantities of brake shoe dust that had been spread through the tunnels and stations by the earlier trains and a 400 Hz motor-alternator was introduced to power a fluorescent lighting system for the cars. In 1976, a new series of cars with regenerative braking and using choppers for propulsion control was introduced into service (TTC, 1996). The most recently introduced cars (type designation, T1) began to enter regular service toward the end of 1996 (TTC, 1998). Its development and features are described in detail by Johns (1998). The propulsion system is based on four, three phase AC, 104 kW (140 hp) electric motors driven by two variable voltage variable frequency (VVVF) inverters per car. The newest cars are not compatible with the earlier versions so that mixed trains are not possible as was the case formerly. However, the 600 V DC third rail electrical supply has been maintained and the performance range is compatible with the existing trains so that complete trains of T1 cars can be intermixed on the lines of the subway system.

In Montreal the Metro uses a paired configuration consisting of a motored car (16.8 m) and a trailer car (16.2 m). Each motored car carries four 125 kW (168 hp) 375 V DC chopper controlled motors. The system is unique in that the cars run on rubber tires. Electricity is supplied from a third rail carrying a nominal 750 V DC.

3.2.4 Streetcars (also called LRTs)

The distinction between streetcars and LRTs is somewhat blurred and the terms are often used interchangeably. Streetcars tend to be bus-like individually powered single vehicles operated on rails sharing the road allowance with other vehicles. On the other hand, LRTs tend to be train-like assemblies of individually powered vehicles operated on dedicated rights of way. The distinction is particularly blurred in Toronto, where typical streetcars have historically often been operated as connected pairs and the newest LRT line typically operates single vehicles on a partially dedicated right of way. The standard overhead supply throughout the TTC system is 600 V DC. The most recent incarnations of streetcars in Toronto are designated the CLRV (Canadian Light Rail Vehicle, see TTC (1991b)) and the ALRV (Articulated Canadian Light Rail Vehicle, see TTC (1991c)). The CLRV, shown in Figure 19, uses two 138 kW (185 hp) motors with chopper controls and a blend of conventional (pneumatic disc), and electrical (rheostatic and regenerative) braking depending on operating conditions.

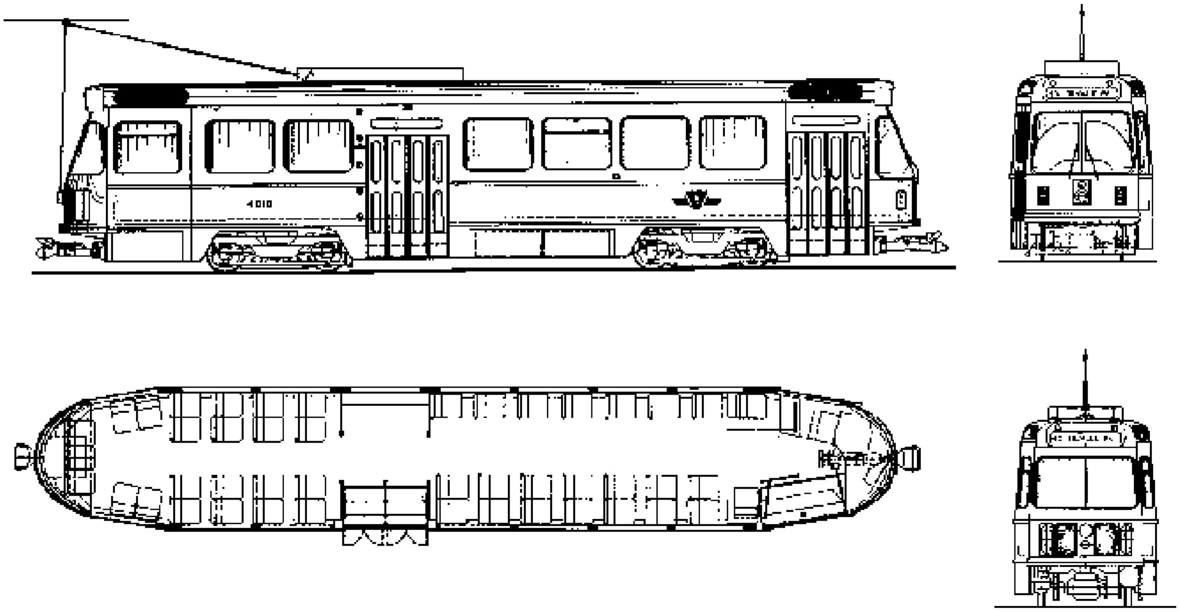

Figure 19. The TTC CLRV (Canadian Light Rail Vehicle)
After: TTC (1991b)

The ALRV, shown in Figure 20, uses four 65 kW (87 hp) motors with chopper controls and a blend of conventional (pneumatic disc), and electrical (rheostatic and regenerative) braking similar to that on the CLRV.

Ho et al. (1998) discuss a light rail transit system operating in the suburbs of Hong Kong. It consists of one hundred individual vehicles each carrying two DC motors driven by DC choppers with an operating frequency of 500 Hz. The choppers are described as hybrid meaning that a conventional thyristor is used to switch the DC with a GTO being used to turn off the former. 750 V DC is supplied from overhead wires.

Pessina and Giraudi (1998) describe an urban light rail transit system that was upgraded ten years ago and currently operates three different types of vehicle on the same 600 V DC supplied system. The oldest vehicles use AC motors with SCR Inverters and Choppers to control voltage delivered to the motors. Of the newest vehicles, purchased during the upgrade, roughly half use AC motors and the others use DC motors. The AC motors are controlled with SCR PWM Inverters and the DC motors with GTO Choppers.

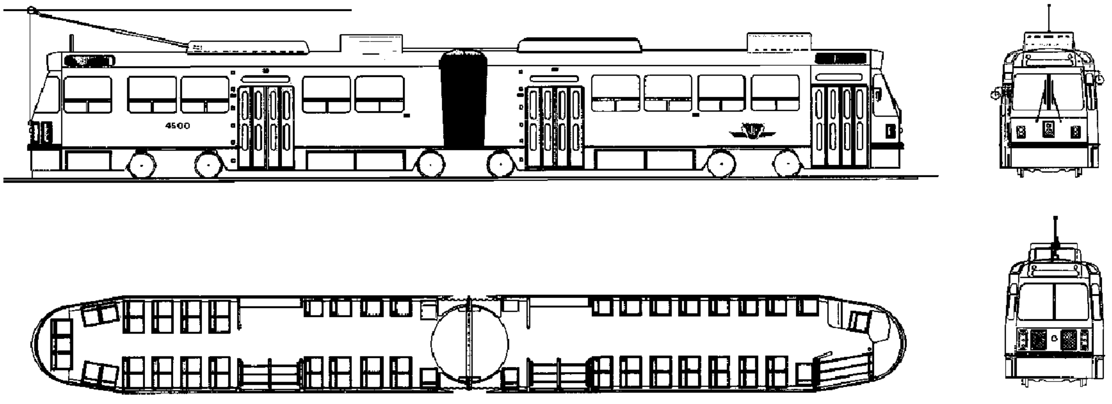

Figure 20. The TTC ALRV (Articulated Canadian Light Rail Vehicle)
After: TTC (1991c)

3.2.5 Busses

The use of batteries to store energy for the propulsion of vehicles has been plagued with the problem of the excessive weight of the batteries themselves to say nothing of maintenance difficulties. Capacity is, of course, also an issue, as is recharging. However, a self-contained electric vehicle cannot be achieved without them unless fuel cell technology advances sufficiently. Busses are the largest vehicles for which batteries have been explored as an on board supply of energy. Even advances which have led to lighter motors and controllers have not resulted in competitively economical battery powered vehicles. However, the prospects of reduced or zero emissions have spurred research and developments targeted at achieving weight reductions which benefitted all aspects of the transportation industry and the search for improved batteries continues.

The result of difficulties with batteries has been to focus attention on so-called **hybrid** technologies where the propulsion of the vehicle is achieved using electricity generated by an engine of some sort or, as most recently envisaged, a fuel cell.

Aside from diesel electric locomotives which qualify for inclusion under the rubric of hybrid, busses constitute a form of transportation where the most advanced of present day hybrid technology is being applied. Hybrid systems are divided into two groups labelled series and parallel. In a series hybrid system (see Figure 21) an engine powers an electric generator which then supplies the motors through a controller as in a diesel electric locomotive. In busses and smaller vehicles a battery is added. The battery becomes the primary supply for the motors and is kept changed by running the engine more or less constantly at maximum efficiency. In the most advanced systems regenerative braking is used and the controller can return energy to the battery under conditions of braking thereby reducing demands on the engine.

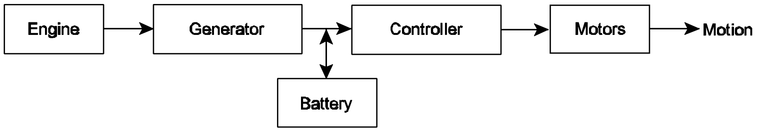

Figure 21. Series Hybrid System

Systems where the wheels may be driven directly by the engine and simultaneously by electric motors are called parallel hybrid systems. Their general configuration is shown in Figure 22. Parallel hybrid systems may be designed so as to have either the engine or the battery as the supply of choice when dealing with peak power requirements.

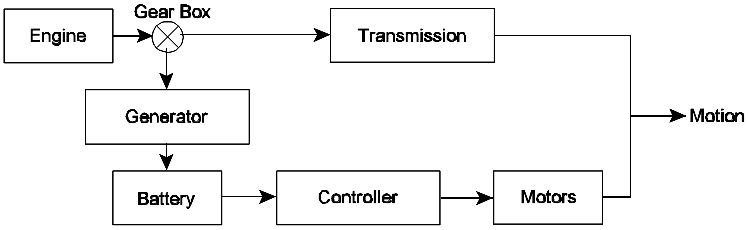

Figure 22. Parallel Hybrid System

Busses using fuel cells have been envisaged for some time already. Romano and Price (1990) discuss and model the functional requirements (see Figure 23) for a transit system bus. Current designs tend to be augmented with provisions for auxiliary loads such as heating and air conditioning.

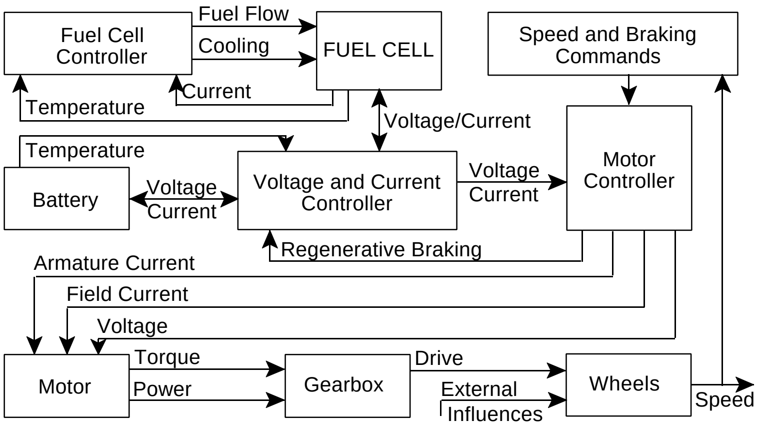

Figure 23. Functional Diagram of a Fuel Cell Vehicle
(After Romano and Price (1990))

Howard and Greenhill (1993) describe the fuel cell bus unveiled at Science World in Vancouver, B.C. on June 8, 1993. It had a 120 kW (160 hp) fuel cell supplying 160 V to 280 V DC to DC motors through a chopper (IGBT, 400 Hz). They do not make any specific mention of currents or current ranges in various parts of the system but they would be commensurate with the powers being generated and delivered.

An erstwhile significant contributor to public transit enterprises, the trolley bus, has all but vanished from the scene. Not being restricted by having to run on rails, trolley busses had the advantage of being able to manoeuver through traffic using most of the available road allowances. However lacking the electrical ground provided by rails, necessitated a relatively intricate, and correspondingly more difficult to implement and maintain, two conductor (600 V DC in Toronto) overhead electrical supply system. In terms of physical and electrical configuration they were similar to streetcars (which, incidentally, are often called trolley cars) with motors, controllers and other components mounted in any available space under the floor of the passenger/operator compartment. The only exception is that they are equipped with two trolley poles, one for each overhead conductor. Once used to a considerable extent in Toronto and Montreal, they have not been in service in either city for decades having been replaced by diesel busses.

3.3 Category 3 Systems

The use of batteries to store energy for the propulsion of vehicles is most attractive where the demand power to be expended in achieving speed, acceleration or load carrying capacity is smallest. Wheelchairs and golf carts come to mind first. The weight, maintenance and recharging requirements are tolerable in these applications. The advances that have led to lighter motors and controllers are enhancing the prospects for small automobiles particularly as demands for reduced or zero emissions have spurred research and development. The series and parallel configurations introduced in discussing Category 2 systems are equally applicable to Category 3 systems except that the components are appropriately scaled down in size. The components themselves are placed according to the demands of the overall design, in front of, behind, under or even within (e.g. under back seats, under the dashboard) the passenger compartment with connecting cabling passing back and forth between the components. Magnetic (and, for that matter, electric) fields are correspondingly complicated and variable from one vehicle configuration to the next.

The Ford Motor Company's TH!NK City currently being offered on its web site for delivery in 2002 is in the vein of small, in this case two passenger, light urban vehicles. It is shown as having front-wheel drive, powered with a 27 kW (36 hp) three-phase AC induction motor supplied from 19 NiCd batteries storing 11.5 kWh capable of delivering 100 Ah at 114 V DC and rechargeable to 80% of capacity in 4 h to 6 h. They are also currently offering a FORD RANGER EV Pick Up. It is a rear wheel drive pick up truck with a 67.5 kW (90 hp) three-phase motor supplied by 39 x 8 V lead-acid batteries and offering "conductive" 240 V (60 Hz) charging, presumably as opposed to "inductive" charging, as being safer, less costly and the "traditional method of connecting electrical equipment to power sources," i.e. the charger is plugged in It also employs regenerative braking.

According to its web site, GM is offering its Precept as a parallel hybrid vehicle. It uses a 35 kW (46.7 hp) three-phase electric motor to drive the front wheels and a lean-burn CIDI (compression-ignition, direct-injection) heat engine to drive the rear wheels. The site web also features a diesel electric bus characterized as being a hybrid vehicle in the same manner as diesel electric locomotives. It was built for New York City's Hybrid Bus Demonstration. Other electric or hybrid vehicles (e.g. a hybrid Pick Up scheduled for 2004, or a passenger car with an unspecified launch date) shown do not appear to be beyond the concept stage.

Fukino et al. (1992) discuss the charger requirements for a 40 kW (53 hp) Ni-Cd battery powered electric vehicle with four passenger capacity. It was driven by two 20 kW AC motors. The inverter used IGBT technology and a carrier frequency of 10 kHz. They also envisaged supplementing the battery charging system with a roof mounted 300 V solar panel although they stated that fully charging the batteries with the solar panel alone would require five weeks of continuously fine weather.

In discussing a battery powered van, Anderson (1990) describes a 50 kW (67 hp) PWM controller typical of the design that supplanted chopper controls in the 1980s (see Figure 24).

As in the case of larger vehicles, the result of difficulties with batteries has also been to focus attention on hybrid technologies for Category 3 transportation systems. Category 3 vehicles using hybrid technology are functionally similar (see Figure 23) to the corresponding Category 2 vehicles except that the power (hence currents and magnetic fields) are reduced by roughly an order of magnitude. On the other hand, while maximum exposures to passengers of Category 2 vehicles can be higher, passengers in Category 3 vehicles tend to be closer to sources so that average exposures may be comparable.

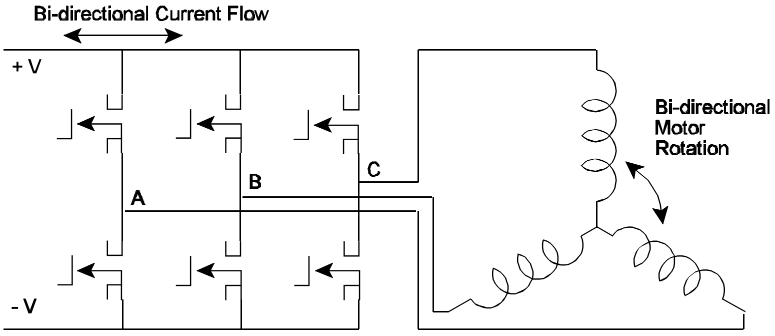

Figure 24. Controller for Battery Powered Van (After Anderson, 1990)

4. Present Knowledge about Transportation System EMFs

A total of 194 requests (initial and follow-up) for information about recent work or work not previously published in the peer reviewed literature was sent out by email to contacts in 54 countries or agencies throughout the world.

Perhaps one of the most significant, from the point of view of the present work, came from one of the respondents in the US who indicated that there had been recent coverage of transportation system EMFs on the local news in the area of Washington DC. It had been noticed that paper clips would stand (in the manner of iron filings in a magnetic field) on the floor of the Washington Metro subway cars, which use "chopped" DC, when they were accelerating or decelerating. Measurements indicated magnetic fields in the range of 10,000 μT to 100,000 μT at floor level in the centre of the passenger areas. The fields were attributed to RF suppression coils carrying currents up to about 600 A. The chopper frequency was not specified. The particular significance of this information is discussed further in the next section of this report.

Overall, the responses confirmed that relatively little scientific investigation of transportation System EMFs has been carried out to date. What has been done has focussed on occupational exposure, especially that of engine drivers and has been conducted largely in Europe. The most recent example of such work is the report of Nordenson et al. (2001) which contains numerous references to the earlier literature. They report an increase in chromosomal aberrations in peripheral lymphocytes of train engine drivers exposed to 16 2/3 Hz magnetic fields ranging from a few to over one hundred μT. They concluded that their studies "support the hypothesis that exposure to MF [magnetic fields] at mean intensities of 2-15 μT can induce chromosomal damage."

In a similar study, Hamalainen et al. (1997) reported on magnetic field levels over a frequency range of 10 Hz to 2 kHz measured in local and long distance electrified trains in Finland. Roughly one third of the rail network is electrified with 16 2/3 Hz AC. They concluded that the average levels to which workers and passengers were exposed were low compared to guidelines recommended by international agencies. However the observed levels varied by roughly a factor of 1,000 (0.3 μT to 290 μT for passengers and 10 μT to 6,000 μT for workers) with the range for workers shifted higher by about a factor of 10. The highest levels for workers exceeded recommended limits.

Wenzl (1997) reported on measurements on a 25 Hz AC electrified portion of the so-called Northeast Rail Corridor in Maryland and Pennsylvania. It was noted that 60 Hz and 100 Hz fields were also present from transmission lines suspended above the railway catenaries and from the railway safety communications and signalling system respectively. Averages for workers were found to range between 0.3 μT and 1.8 μT. In concluding, he noted that previous measurements reported in passenger cars had shown levels in the range of 10 μT suggesting that conductors average exposures might be expected to be elevated compared to that of other railway workers. Correspondingly passenger exposures would be expected to average somewhere in between since they would not be travelling with the train as much as a conductor.

One exception stands out and that is work carried out by Dietrich and Jacobs (1999) under the auspices of the US Department of Transportation, Federal Railroad Administration. They reported on static and low frequency magnetic field levels associated with conventional and electric cars, trucks and busses, electrified commuter trains, ferries, jetliners, airport shuttle trams, escalators and moving sidewalks. The work was carried out as an extension of measurements made in electrified trains, light rail vehicles and a magnetically levitated train. Positioning of detectors was standardized so as to capture information about field levels at various locations (e.g. head, waist, ankles), standing or seated at a series of selected passenger or worker positions within vehicles, at entrances to vehicles and, where applicable, on platforms. Rather than being representative of each specific transportation mode in a statistical sense, the measurement protocol might best be characterized as a sampling of typical levels associated with various operating scenarios for a broad spectrum of transportation modes. The mass of data collected is difficult to summarize in any simple manner. If anything, the summary produced by the authors of the report underscores the comments made earlier in the present report about the extensive variability in EMF exposures associated with various transportation systems and highlights the variability within transportation systems as well. Overall the electrified commuter train demonstrated the highest time varying magnetic field levels averaging 5 μT. Dietrich and Jacobs summarized their results by reporting the levels associated with the following six "bands": Static - 0 Hz (effectively all frequencies less than 2.5 Hz), ELF (Extremely Low Frequency) - 5 Hz to 3000 Hz (overall frequency range covered by the measurements), Low ELF - 5 Hz to 55 Hz (below power frequency), Power Frequency - 60 Hz, Power Harmonics - 65 Hz to 300 Hz (usually greatly reduced from the 5th on) and High ELF - 305 Hz to 3000 Hz. While the grouping (and the underlying averaging), of necessity, collapses the intricacies and complexities of the data enormously and thereby may obscure significant information, in the absence of an exposure metric other than average (or maximum) magnetic field, their summary separates out the two ubiquitous contributors to magnetic field exposures, static fields (mainly the earth's) and power frequency fields, and highlights the Low ELF and High ELF ranges where individual transportation systems will leave whatever discernible EMF "signatures" they might have. Their summary table is reproduced below (Table 2) with the values changed to show magnetic field levels in μT. In reading the table, care should be taken not to read too much into the differences between the levels in each of the "bands" for a given transportation system since they have differing "widths." In particular, taking the Power Frequency band to have an effective width of 5 Hz and considering that to be a unit band, the Low ELF and Power Harmonic bands have 11 unit and 48 unit widths respectively, the High ELF band has a 540 unit width, the overall ELF band has a 600 unit width and the "Static" band has a 2 unit width. In a sense the values should be weighted accordingly if comparisons are to be made across the bands. Of course, none of this matters if comparisons are made within the bands which will allow ranking of the various transportation systems with regard to measured magnetic field levels. Figure 25 shows a graphic representation of the summarized data (time varying only, maxima) presented in Table 2.

Dietrich and Jacobs expend no small effort in distinguishing the measured EMFs that they could attribute unequivocally and directly to each of the individual transportation systems from those that they attributed to "secondary" sources such as the ubiquitous 60 Hz electrical transmission and distribution lines. They also noted effects from magnetization of steel belted radial tires which could contribute significantly to the magnetic field levels particularly in the back seat of a car. Another interesting phenomenon that they pointed out was observations of time varying (sometimes periodic) components associated with moving through perturbations of the earth's static magnetic field by ferromagnetic materials (iron and steel) in structures distributed along the route being travelled. Just as anywhere else the electromagnetic environment associated with transportation systems is very complex with contributions from numerous sources. Should detrimental effects arising from the use of specific transportation systems be identified in the future, the attribution of the cause of the effects becomes an important consideration (witness the recent tire recall controversy between Ford Motor Company and Firestone Tire).

Discussions about EMI/EMC (Electromagnetic Interference/Electromagnetic Compatibility) issues related to electrified transportation systems are also informative. As new solid state traction motor controls have come into use the chopper or carrier frequencies used in the controls have come into conflict with the frequencies used by the safety related signalling systems. The limits arising from EMI/EMC considerations are discussed by Frasco (1998) in the context of describing experience in the northeastern US with an "extensive revenue service demonstration" operating Swedish X2000 and German ICE (Inter City Express) trains in an environment of 11 kV, 25 Hz AC supply with conventional 90 Hz to 100 Hz relay based safety signalling. He notes that " ... vehicle inductive emissions, the source of the original dc (sic) chopper signalling compatibility problems in the US almost 20 years ago, is (sic) still a major concern." Such immediate safety concerns have received considerable attention to date but demonstrate that standards and guidelines establishing limits to protect against adverse effects of one sort or another have tended to be reactive rather than proactive.

Table 2. Average (and Maximum) Magnetic Field (μT) Measured in Ten Transportation Systems
(after Dietrich and Jacobs, 1999)

Tansportation System	"Static" <5 Hz	ELF Frequencies 5 Hz to 3000 Hz	Low ELF Frequencies 5 Hz to 55 Hz	Power Frequency 60 Hz	Power Harmonics 65 Hz to 300 Hz	High ELF Frequencies 305 Hz to 3000 Hz
Ferry	51.1 (76.0)	0.06 (0.33)	0.02 (0.10)	0.04 (0.31)	0.02 (0.12)	0.01 (0.03)
Escalator	55.7 (95.8)	0.15 (6.14)	0.13 (6.01)	0.04 (0.32)	0.02 (1.05)	0.01 (0.03)
Moving Walkway	57.6 (121.8)	0.37 (20.0)	0.31 (19.54)	0.12 (1.24)	0.07 (3.72)	0.03 (1.90)
Conventional Cars and Light Trucks	32.1 (96.8)	0.57 (12.45)	0.55 (12.42)	0.09 (1.94)	0.08 (1.36)	0.04 (0.78)
Electric Cars and Light Trucks						
Dynamometer	40.8 (128.6)	0.57 (8.08)	0.34 (5.61)	0.09 (1.25)	0.36 (7.99)	0.10 (0.86)
Test Track	38.8 (104.1)	0.57 (9.35)	0.48 (9.27)	0.08 (1.53)	0.19 (2.45)	0.07 (0.69)
Jetliner	55.2 (66.9)	1.35 (21.25)	0.06 (0.35)	0.00 (0.06)	0.02 (0.81)	1.35 (21.24)
Shuttle Tram (AC Electric)	47.0 (83.5)	1.37 (9.04)	1.07 (8.85)	0.55 (2.90)	0.30 (1.44)	0.12 (0.70)
Conventional Bus	40.1 (112.4)	1.68 (14.57)	1.64 (14.42)	0.09 (1.42)	0.19 (2.13)	0.21 (2.48)
Electric Shuttle Bus	38.1 (80.8)	2.04 (48.78)	1.47 (48.67)	0.08 (3.88)	0.89 (22.05)	0.16 (1.07)
Commuter Train (AC Electric)	53.8 (196.9)	4.96 (79.93)	1.85 (45.35)	3.42 (73.88)	1.46 (34.03)	0.59 (4.87)

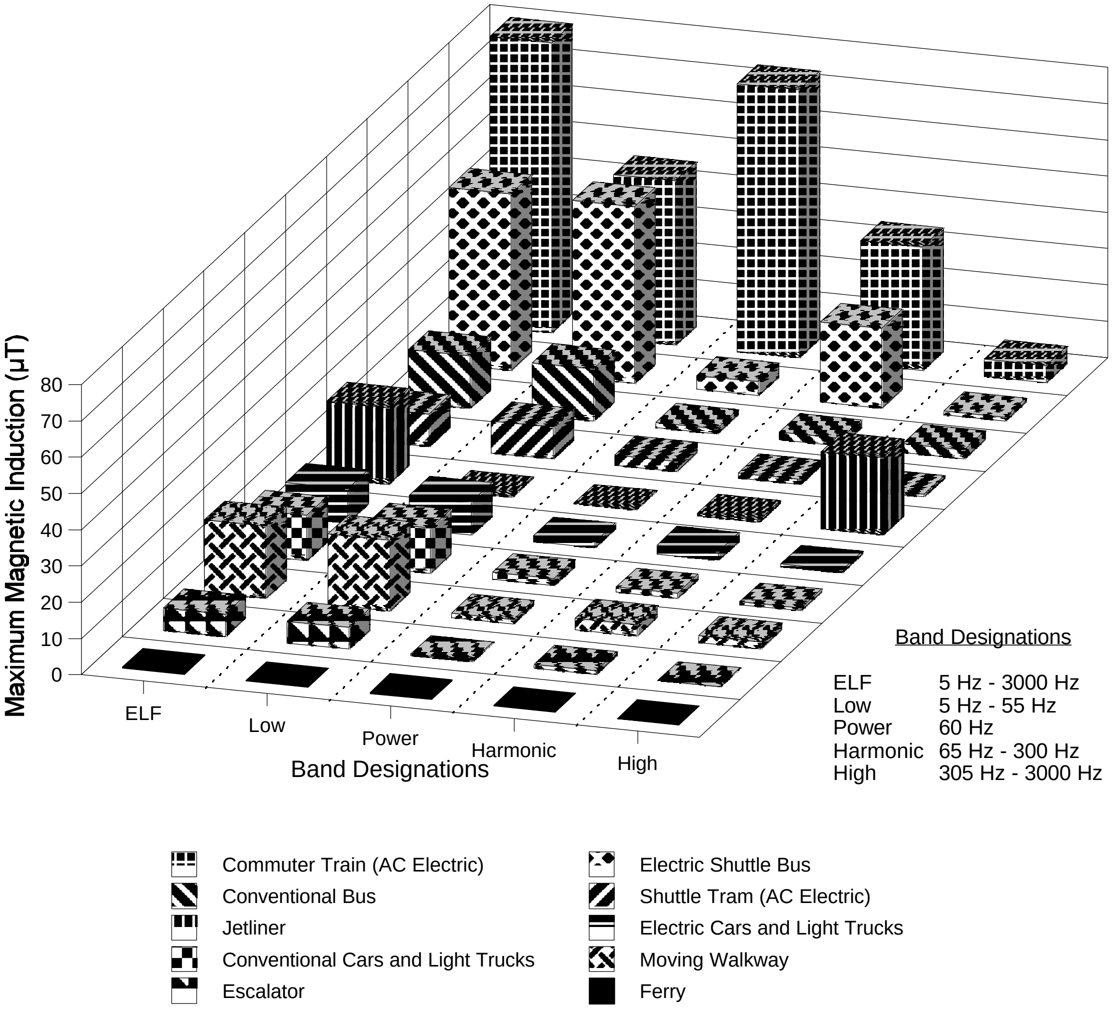

Figure 25. Maximum Time-Varying Magnetic Induction
(After: Dietrich and Jacobs, 1999)

In a similar vein Mouneimne et al. (1998) discuss EMC issues for power converters (supplied by 400 V to 1200 V DC and producing 5.6 kW at 240 V 50 Hz AC) intended to power auxiliary equipment such as air conditioners and other loads. They were to operate in the London Underground system where signalling is carried out using 33.3 Hz, 125 Hz and 10 kHz track circuits. Consideration was also given to meeting "limits for interference with passenger goods by magnetic fields and in communication equipment from radio frequency (RF) emissions and inductive interference." In order to meet a level of 1,000 μT specified to ensure compatibility with "older types of pace-makers" they stated that the design "requires careful magnetic shielding of the large supply filter inductor and other magnetic circuits because **there is already a high background level** [emphasis added] due to the traction current in the rails."

Similarly measurements were carried out around conventional automobiles (Vedholm, 1997). Values inside the vehicles were reported as being around 10 μT near the feet, around 1 μT at the chest and around 0.1 μT outside the vehicles for frequencies in the range of 5 Hz to 2 kHz. An unexpected source of exposure (effects noted earlier) appeared in the form of time varying magnetic fields at frequencies corresponding to the vehicle's tire rotation frequency ranging to a few μT observed in the back seats of automobiles arising from steel-belted radial tires as reported by Vedholm (1996 and 1997) and then by Milham et al., (1999).

5. Transportation System EMFs by Category

In general, regardless of category, **electric fields** associated with transportation systems have not been reported in any great detail nor have concerns about them been consistently expressed. Voltages are low to moderate, energized conductors are sufficiently well separated from passengers or workers and located overhead or as a third rail and, most importantly, shielding is provided by the intervening metallic structures of the passenger and operator compartments. Excluding sources that might be carried in by occupants, electric fields within vehicles are typically highest near windows and do not exceed a few tens of V/m in the lower reaches of the frequency range.

There is considerably more information available regarding **magnetic fields** since they have continued to receive significant attention from the public and in the media and, therefore have been the subject of more numerous and more detailed investigations. Currents can range to values as high as a few kA with correspondingly high magnetic fields near the cables and other current carrying components that may be mounted in relatively close proximity to passengers, operators or other workers. Furthermore, intervening structures provide relatively little shielding. Thus the location of cables and components is more significant from the point of view of determining the distribution of magnetic field levels than is the case for electric field levels.

The basic situation is not very complicated. Simply put, the magnetic field (strictly speaking the magnetic induction, **B** (μT)) in the vicinity of a conductor carrying a current, **I** (A), at a distance, d (m), from the conductor is given by the expression **B** = 0.2 (**I** / d). So, at a distance of 1 m from a cable carrying a current of 10 A one observes a magnetic field of 2 μT. Figure 26 depicts what this relationship implies for the situation of a person touching an insulated conductor carrying 10 A and standing at arm's length from the cable. Unfortunately, the situation is rarely so simple but, in principle, detailed knowledge of all the current paths and the properties of any intervening or nearby materials will permit the field levels at any point in the surrounding space to be estimated. Typically, such estimation is so complicated that measurements provide the only practical means for determining the fields.

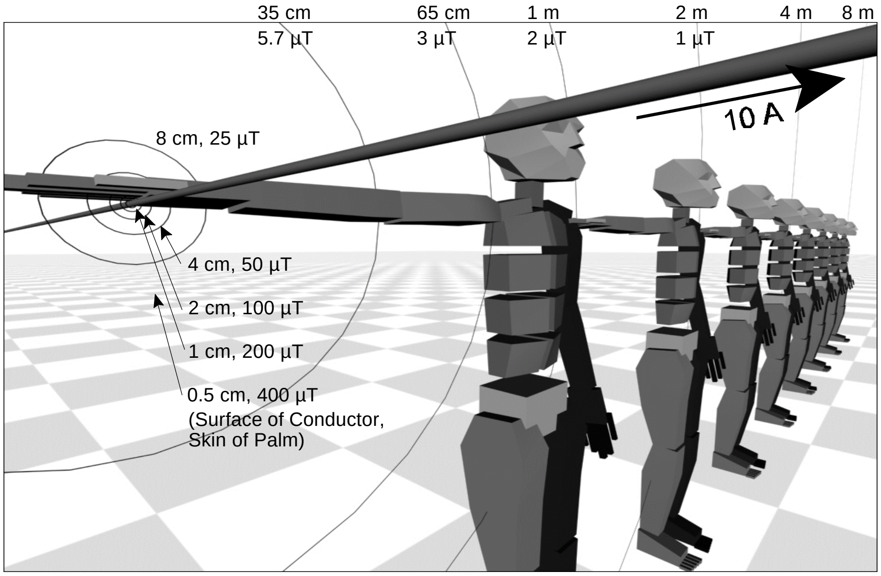

Figure 26. Magnetic Induction around a Conductor Carrying 10 A

Each of the three transportation system categories is considered separately below for situations that assume the magnetic field levels are sustained for as much as a few minutes at a time. Long term averages running to hours, total trip durations, work weeks, etc. are uniformly smaller while short term peak values representing levels averaged over a few seconds or less are often significantly greater. Note that where a specific frequency or frequency range is not stated in any discussion, the author (or the original author for cited levels) has assumed the frequency or frequency range inherent to the technology or aspect being discussed.

Category 1 Transportation Systems

Maglev systems typically run on a monorail or guideway which provides both propulsion and guidance. By contrast, "conventional" high speed trains like the French TGV or Japanese Series 700 Shinkansen are guided by rails while deriving their propulsion from overhead electrical cables.

The magnetic field levels in maglev systems tend to be greater near the floor and toward the sides of the passenger and operator compartments. They also tend to be noticeably greater than those occurring in conventional high speed trains. In addition, down the length of the car, magnetic field levels and spectral content can vary depending on proximity to components such as suspension and guidance coils or coils used to power auxiliary services such as lighting and heating or air conditioning on the car. In describing the Chuo Shinkansen, Moon (1994) notes that "the superconducting magnets are grouped at the ends of cars to reduce passenger cabin magnetic fields to less than [1,000 μT]." The location within the cabin to which the stated "reduced" magnetic field level corresponds is not specified but one would presume levels near the coils are substantially greater. Vranich (1991) attributes magnetic fields of the same order to the German Transrapid system but again without specifying any details of the field distribution. In earlier work published in support of a maglev system envisaged for the Quebec City to Windsor corridor in Canada, Atherton and Eastman (1975) reported passenger compartment fields of 60,000 μT and 20,000 μT at floor level and seat level respectively above the proposed levitation magnets with roughly similar values over propulsion magnets.

In conventional high speed trains, magnetic field levels are often observed to increase with height above the floor of the passenger or operator compartment because of the field from the overhead cable which supplies electricity to the train. In addition the cable carrying current from the pantograph (structure providing contact with the overhead electrical cable) may be carried along a cable on the roof of the car running much of its length and then down to the propulsion control system which may be mounted beneath the floor. Of course, the magnetic fields in unpowered cars only arise from the overhead cabling, auxiliary equipment and, perhaps, braking system components. Such is the case for the TGV passenger cars since it is configured as a locomotive pulling four unpowered passenger cars. By contrast the Series 700 Shinkansen is configured as four car modules, three of which are powered.

By way of generalization, it can be said that for unpowered cars of conventional high speed trains, magnetic field levels tend to be higher toward the top of the passenger or operator compartment although auxiliary equipment and components associated with the braking system may give rise locally to higher fields near the floor. For powered cars or locomotives, magnetic field levels will tend to be higher toward the roof of the compartment and, if the connection to the pantograph is located on the roof, higher than for unpowered cars particularly along the path taken by the connecting cable although field cancellation effects could also be observed depending on the relative directions of the overhead and connecting cable currents. Also for powered cars, the components associated with propulsion control, chopper or other harmonic suppression and, perhaps, braking systems, usually mounted beneath the floor of the passenger compartment, may give rise locally to higher field levels near the floor.

Overall the magnetic field levels in unpowered cars range from a few μT to ten or so μT toward the ceiling of the passenger or operator compartment to the vicinity of a hundred or more μT locally near the floor near specific components. In powered cars the field levels tend to be at least a factor of ten greater.

An example is provided by Creasy and Goldberg (1993) who cite levels ranging to 250 µT in a report prepared for the US Federal Railroad Administration.

Category 2 Transportation Systems

Conventional low to moderate speed electric trains (not used extensively in North America) usually consist of one or more locomotives which receive their electrical supply from overhead cables and pull (or push) a number of unpowered passenger or freight cars. The magnetic field levels in such unpowered cars would be expected to be comparable in magnitude and similarly distributed to those that are observed in unpowered cars of conventional high speed trains, as outlined above, i.e. ranging from the order of a few to a hundred µT.

LRTs are usually rail guided systems of powered vehicles ranging in configuration from single vehicles (usually supplied from an overhead cable) to trains of as many as eight, the tendency being to use a third rail to provide electrical supply to the longer configurations. Electrical supply voltages tend to be lower than for electric passenger and freight trains because the systems are generally smaller and lighter so that power demands are reduced. However, currents remain similar so that associated peak and average magnetic fields are similar. Where overhead cables are used for electrical supply, magnetic field distributions will be similar to those in powered cars of electric trains, often higher toward the top of the passenger or operator compartments but locally higher near the floor in proximity to control, braking system or auxiliary components. Where a third rail system is used for electrical supply, fields generally tend to drop off with height above the floor but again locally higher levels are to be expected along the length of the vehicle according to the proximity of various electrical components. Trolley busses, which are included in Category 2, are also overhead supplied but with two relatively closely spaced parallel cables, one of which serves as ground for the on board electrical system. Some degree of cancellation of magnetic fields would be expected in such vehicles. In so far as each of the vehicles associated with Category 2 transportation systems is powered, the magnetic fields would tend to be similar to those observed in powered cars of conventional high speed trains, as outlined above, i.e. from the order of a few tens to a thousand µT. A system such as the TTC's SRT would be expected to have relatively high magnetic field levels in proximity to the LIM coils. Its electrical supply (600 V DC) is from positive and negative third and fourth rails and consequently magnetic field levels would be expected to decrease with height above the floor but again vary along the length of each car depending on proximity to the location of electrical components.

The possibility of using batteries to supply electrical energy for Category 2 vehicles has been explored but such designs have not come into routine use in even moderate numbers. Nevertheless such systems continue to receive attention as zero emission vehicles. The magnetic fields associated with the implementation of such designs would be anticipated to be similar to those in overhead cable or third rail supplied systems of comparable size, weight and therefore power demands. Of course the fields associated with the "external" electrical supply would be absent. They would be replaced by fields produced by the current drawn from the batteries. How and where they would contribute would depend on the cabling between the batteries and the control system. In general field levels would tend to decrease with height above the floor but vary along the length of the vehicle depending on proximity to specific electrical components.

Electric or hybrid vehicles for heavy haulage by road (transport trucks) appear to have been totally ignored to date, most likely because the combined demands of high power and untethered operation cannot come close to being met by present day technologies.

Category 3 Transportation Systems

The flexibility and independence demanded by and inherent in Category 3 transportation systems virtually precludes continuous connection (i.e. overhead or third rail) of the vehicles to their energy supply system. This has resulted in extant designs aimed at totally eliminating ICEs (internal combustion engines) These are so-called "zero" emission systems that use on board batteries to store, or fuel cells to generate, electricity to supply to the propulsion system. So-called hybrid or reduced emission systems use electric motors for propulsion but rely on an ICE run at optimum efficiency and, perhaps on "advanced" fuels to drive a generator that supplies electricity to the propulsion system. All the features of the electrical propulsion systems that occur in Category 3 transportation systems have their counterparts in Category 2 transportation systems including auxiliary requirements such as lighting, heating air conditioning, etc. Locally, in proximity to the cables, propulsion control components, electrical or regenerative braking system components and auxiliary components the magnetic fields in Category 3 transportation systems would tend to be similar to those observed locally in Category 2 systems, as outlined above, i.e. from the order of a few to (locally) a thousand μT.

Based on numbers of vehicles alone, the prospect of replacing cars and light trucks with zero emission or hybrid vehicles is extremely attractive although it may be that more overall benefit might be achieved by concentrating on heavy haulage vehicles (transport trucks) at the Category 2 level. While Vedholm (1997) and some others have reported on magnetic field levels associated with conventional automobiles there had been no reports dealing with the frequency content of the magnetic fields (in even a limited way) until the work of Dietrich and Jacobs (1999). While their sample of Category 3 vehicles was of necessity relatively limited and does not include any hybrid vehicles, they reported results on several cars and light trucks, both conventional and electric. Figure 27 shows the maximum and average (multiplied by 10 for clarity) values for their "Cars and Light Trucks" category. The highest levels tended to be observed near the driver's or passenger's feet and tended to be progressively lower at waist, chest and head locations. Based on the average over the whole ELF band, the conventional and electric vehicles are identical (see also Table 2). In terms of observed maxima over the whole ELF band, conventional vehicles showed values that were some 30% higher. This latter was due to higher values in the frequency bands below 60 Hz for conventional vehicles. On the other hand electric vehicles showed values about 50% higher than conventional vehicles in the so-called harmonic band where the chopper control frequencies appear. When all is said and done, however, it is very difficult to draw any firm conclusions or attribute observed differences to specific sources because the overall number of vehicles of each given type tested is small and individual observed levels range over orders of magnitude spatially and temporally.

6. Summary of Transportation System EMFs

If any simplification of transportation system EMFs is possible in an overall sense it arises from the scaling factors that can be identified when one looks at the electrical and physical design characteristics of the three categories of transportation system identified for the purposes of the present report.

Consider first the electrical design characteristics. Roughly speaking, Category 3 systems use motors having powers in the range of 50 kW (38 hp), Category 2 systems use motors with powers roughly a factor of ten greater, i.e. 500 kW (380 hp) and for Category 1 systems motors roughly another factor of ten greater, i.e. 5,000 kW (3,800 hp) are used. For any given installed power, electrical designs tend to be limited by the current carrying capacity of the conductors involved. Therefore as the required power increases, maximum design currents tend to remain similar while voltages increase from the order of 10 V for Category 3 systems to the order of 100 V for Category 2 systems to the order of 1,000 V for Category 1 systems. Clearly, the increasing voltages result in greater electric fields but they are "controlled" by spacing (conductors are suspended higher above the ground) and shielding (conductors or components are insulated and encased in metal sheaths or cabinets). The important consideration in all of this with regard to magnetic fields is that the maximum design currents remain roughly of the same order so that the associated maximum magnetic fields remain roughly of the same order regardless of the transportation system category.

The final element to consider is the physical design of the systems. Looking at the vehicle sizes associated with each category (but corresponding scaling considerations apply to component sizes as well), it is roughly true that Category 3 systems are measured on a scale of the order of 1 m, Category 2 systems on a scale of the order of 10 m and Category 1 systems on a scale of the order of 100 m. Correspondingly, the extent in space of the associated magnetic fields scales similarly. From a human effects perspective, the important consideration here is that the human scale is fixed and of the order of 1 m. In so far as the maximum magnetic fields are roughly of the same order regardless of category, this means that what tends to change, as far as human exposure to transportation system magnetic fields is concerned is the amount of the body exposed, i.e. an appendage, a limb or the whole body. Therefore, for a Category 3 system, it is easy to envisage an appendage receiving a roughly uniform exposure but it is unlikely that a whole limb would be uniformly exposed and virtually inconceivable that the whole body would be uniformly exposed. By extension, Category 2 and Category 1 systems will give rise to progressively more extensive (but not greater in terms of magnetic field level), even whole body, exposures. Of course the location of the human relative to the system components within the vehicle will also be a factor. In a Category 3 vehicle both are essentially fixed whereas in Category 2 vehicles the human's position may vary and in Category 1 systems access to individual cars without major drive or braking system components might be possible.

By way of summary, it is to be expected that magnetic field levels to which occupants or workers are exposed, despite ranging over many orders of magnitude (from a few tenths of µT through several thousand), will nonetheless be comparable across all three categories of transportation system. What is expected to vary more significantly, and also considerably at that, is the extent and distribution of exposure within the body of the person receiving the exposure. So whole body averages would tend to be highest in Category 1 systems and all of the body would be relatively uniformly exposed. Correspondingly, whole body averages would tend to be lowest in Category 3 systems but exposure would vary substantially throughout the body with the highest local exposures being comparable to the whole body averages in Category 1 systems. An analogy that comes to mind is the risk of drowning in a bathtub, swimming pool or lake. The **conditions** for drowning are effectively the same in all three cases but the **risk** depends on how the person is positioned and located in the water. Specific design considerations to limit or reduce passenger or operator exposure to magnetic fields do not appear to be applied except in the case of maglev systems where the associated maximum and average levels stand out as being particularly high compared to those associated with other transportation systems.

For members of the general public, the range of EMF exposures in existing, developing and foreseeable (Category 3) transportation systems is comparable in magnitude to exposures from other commonly encountered sources. However they are **totally different** in so far as the frequency content is concerned and what, if any, consequences that might entail remains essentially unexplored. The kinds of investigations which would be most helpful in reducing uncertainties in exposures and effects are discussed later in the present report in the section on gaps in knowledge.

7. Standards and Guidelines

A little reflection leads unerringly to the conclusion that applications of technology drive the establishing of standards and eventually legislation and associated regulations if politicians perceive enough demand from workers and the public. While Dick Tracy's wrist radio/TV communicator can be said to have been foretold by the comic strip's author, little of the detail associated with the present day implementations of wrist sized cellular telephones and internet based video augmented communications was evident at the time. Similarly the details of transportation system EMFs, as they will be in the future, remain rather obscure today since it is difficult to predict which of the presently evolving applications of technology will prevail.

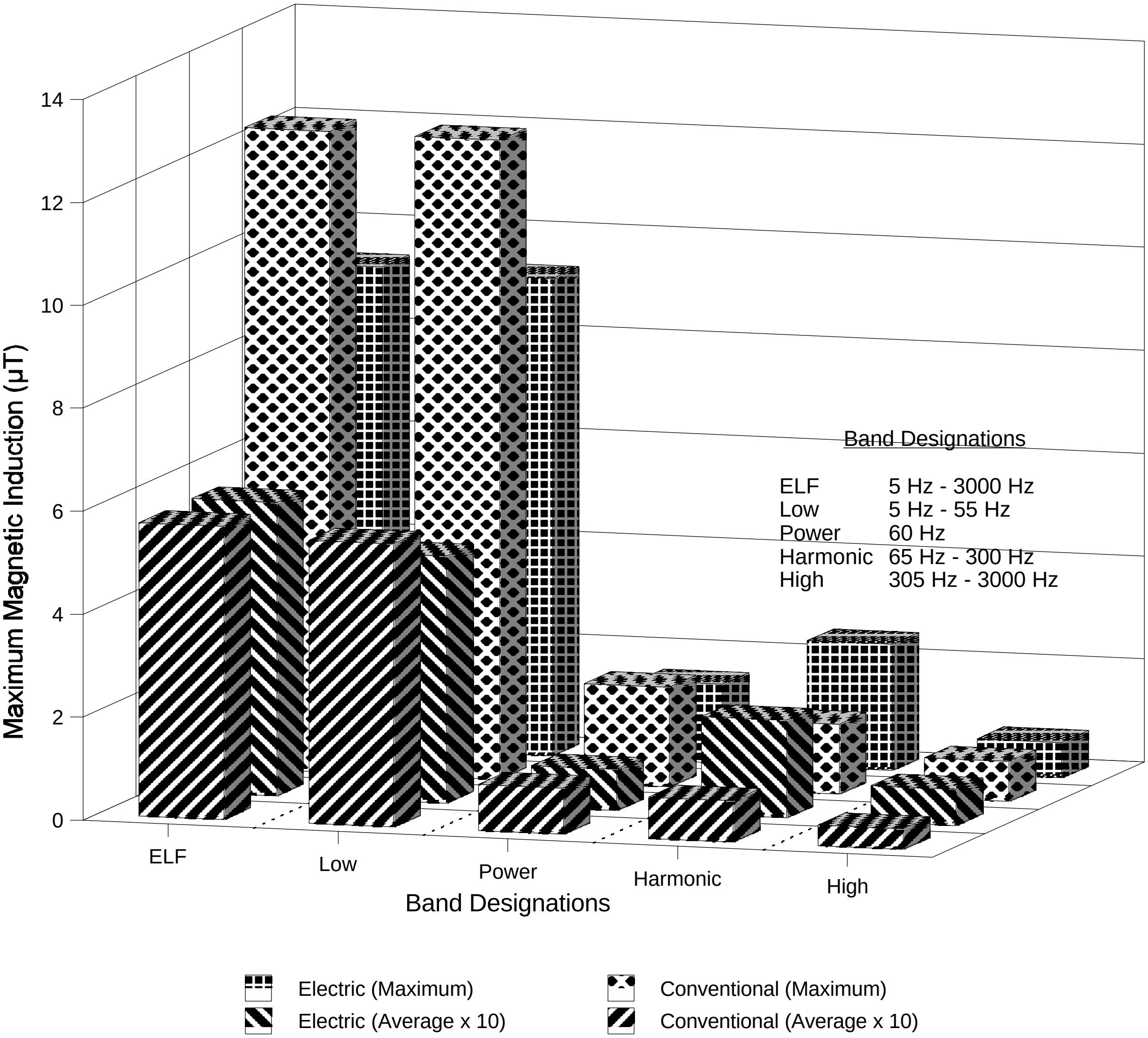

Figure 27. Comparison of Cars and Light Trucks
(After: Dietrich and Jacobs, 1999)

7.1 Historical Review of Applications and Standards

Occupational and environmental standards or guidelines were virtually non-existent at the turn of the century, both for chemical agents and for physical agents. What little there was of such activity resulted from whatever senses of benevolence or philanthropy Victorian society had. However, as concern for occupational health and safety has grown and as measurable impacts of human activities on the environment have been documented, efforts to control more and more chemical and physical agents in progressively more sophisticated ways have been put in place.

Prior to the end of World War II (WWII), EMFs hardly received a second thought. Radiation (ionizing), principally as a consequence of the growing use of X-rays, but also in association with the exploitation of radium, had received most of the attention up to then and with the evidence of the dreadful consequences of nuclear weapons, remained in the forefront of concern. However, by the late 1950s and early 1960s, increasing demand for electricity, the extensive deployment of radars in civil aviation, consumer applications such as microwave ovens and wide use for radio and TV broadcasting began to draw attention to EMF issues as both occupational and environmental factors and standards and guidelines addressing concerns in those areas began to appear. Probably the most sophisticated standard of the time came from the US. It was developed by the Institute of Electrical and Electronic Engineers (IEEE) and adopted by the American National Standards Institute (ANSI). It did not address power frequencies (60 Hz in North America) probably because electrocution (arising from direct contact with energized conductors) only resulted from relatively massive currents and was being dealt with by the Electrical Codes of the day. Currents arising from induction by power frequency electric and magnetic fields themselves (where contact with energized conductors does not occur) were, by comparison, minuscule and therefore discounted as inconsequential. Consequently the first formal standard in the US (and anywhere else, for that matter) covered the frequency range from 10 MHz to 10 GHz. Even AM radio stations, which operate below 10 MHz were, so to speak, "grandfathered" more or less by virtue of their having been in use without overt adverse indications since the 1920s. The first formal standard addressed what were, in effect, the most recently developed high frequency applications of electromagnetic "radiation" for communications, broadcast (TV and FM radio), radars and microwave ovens. By the 1970s, the massive change to computer based business systems led to demands for standards in the kHz range as a result of concerns connected with computer monitors. In the 1980s, power frequency magnetic fields assumed centre stage, largely as a result of reports of an association between exposure to power frequency magnetic fields and leukaemia in children. Eventually, the range of applicability of standards was expanded to the point where it presently covers, with varying degrees of detail and certitude, the whole range associated with human experience and beyond (i.e. frequencies from zero to infinity). Most recently, cellular telephone systems have shifted the limelight back up to higher frequencies largely because highly localized exposures need to be addressed.

Consider Figure 28 which depicts the spectrum as electricity began to be exploited at the turn of the last century. Note particularly that the frequencies used were (not surprisingly) under 100 Hz.

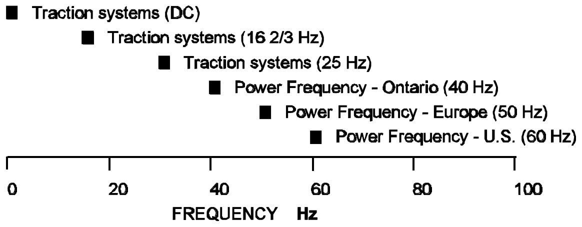

Figure 28. Early Applications

During the pre-WWII era, applications in communications and broadcasting were developed and industrial and medical applications were explored as depicted in Figure 29. The frequency limits were extended into the MHz range. Note that all of Figure 28 is "collapsed" into 0.005% of the first interval on the horizontal (frequency) axis.

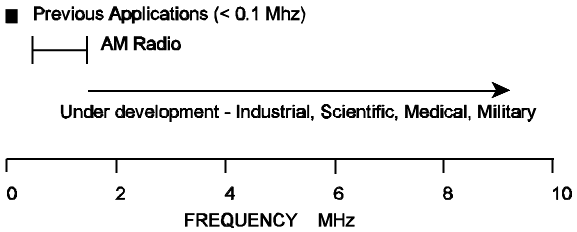

Figure 29. Pre-WWII Applications

During the post-war period, developments continued on all fronts and the frequency limits moved toward the GHz realm. Early concerns about possible detrimental effects were raised particularly as the word "radiation" began to be associated more and more commonly with the newer high frequency applications in the microwave region. This is depicted in Figure 30. Concerns about previous applications remained dormant or were relegated to lower priority because decades of use had not manifested any obvious risks that were not being addressed by "conventional" electrical safety measures. Note here that all of Figure 29 is "collapsed" into 0.001% of the first interval on the horizontal (frequency) axis.

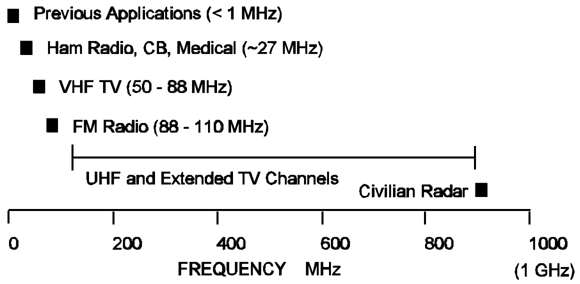

Figure 30. Post-WWII Applications

By the 1960s concerns about health risks had mounted to the point where formal standards were put in place in the US for the frequency range of 10 MHz to 10 GHz. Figure 31 depicts the situation when the first standards were established. Note here that all of Figure 30 is "collapsed" into 50% of the first interval on the horizontal (frequency) axis.

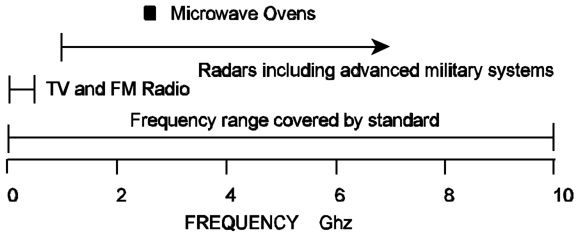

Figure 31. Situation in the 1960s (first standard established)

The engineering community (it was IEEE that developed the standard) saw the burgeoning of new applications at ever higher frequencies associated with demands for more capacity (bandwidth), reliability, directionality and miniaturization and effectively ignored low frequency issues as being only a minuscule part of the spectrum and not a matter connected with "radiation." If you look closely at Figure 31 you will see a barely discernible offset between the low frequency end of the bar (indicating 10 MHz) showing the frequency range covered by the standard of the day. Clearly, the majority of the spectrum had been covered! Applications above 10 GHz were either military and hence "secret" or nothing more than a gleam in the eyes of entrepreneurs and development engineers.

As technology advanced and applications moved into still higher microwave frequencies and lasers were developed it became desirable to establish a transition between "conventional" radio technology and that associated with infrared lasers. The dividing line settled upon has been 300 GHz corresponding to a wavelength of 1 mm. From there on, the technology is considered to be "optical" rather than "radio." So Figure 32 depicts the situation as it currently exists. Note here that all of Figure 31 is "collapsed" into 10% of the first interval on the horizontal (frequency) axis.

As time has passed, standards have come to cover what appears to be the whole spectrum and, as depicted above, concerns related to low frequency effects appear totally inconsequential. As a result, to many, if not most, engineers and many others, the merest thought of effects or any consequence occurring in a frequency range (frequencies <100 kHz) represented by one millionth of the smallest subdivision of the horizontal axis of Figure 32 seems difficult to accept. Nonetheless, in the late 1970s and early 1980s attention was riveted on that minuscule range and on "fields" rather than "radiation" by reports of an association between power frequency magnetic fields and leukaemia in children and concerns about cathode ray tubes (CRTs) as computer monitors. Consequently concerns about transportation systems which mainly involve "static" and very low frequencies attain a heightened degree of relevance again.

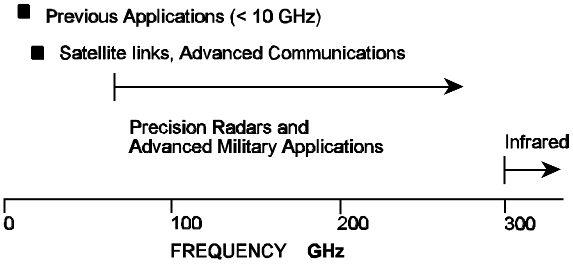

Figure 32. The present day situation

7.2 Present Day Standards and Guidelines below 100 kHz

Possibly the most exhaustive compilation of EMF standards and guidelines worldwide was carried out by the EMF Project of the World Health Organization as a part of its International Standards Harmonization efforts (World Health Organization, 1999). The compilation forms a part of "Inaugural Round Table on World EMF Standards Harmonization: Minutes of Meeting, 18 November 1998, University of Zagreb, Zagreb, Croatia." What emerges from a review of the material submitted by each country or agency/organization representative to that meeting indicates that, among countries where any significant formal attention is paid to EMF issues at all, one of three situations or approaches has been adopted. For convenience these can be grouped under the headings IEEE, ICNIRP and Eastern Europe (former Soviet Union, exemplified by Russia). In effect, these three approaches are vying for acceptance world wide. Since transportation systems, at least in so far as the propulsion mechanisms are concerned, only involve frequencies in the lowest reaches of the range - under 100 kHz and so-called "static" fields, the limits associated with each of the three approaches identified above have been summarized in Table 3 below. It is evident from Table 3 that the Eastern Europe approach has not yet come to grips to any significant extent with EMFs in the frequency range relevant to transportation systems. Only the ICNIRP approach (of the three main approaches) covers all the situations that enter into discussion. Individually, Austria, Bulgaria and ACGIH also do so. The situation in Canada (see Tables A1 and A2, Appendix A) resembles the IEEE most closely. Therefore Canada lacks formal limits to apply at frequencies under 3 kHz. A summary of all the country or agency/organization standards and guidelines, at least as far as it has been possible to collect appropriate information, is given in Appendix A.

It must be kept in mind that "static" is a loosely used term. It is often used where DC current is supplied to a motor using a chopper. Even though the current is delivered to the motor intermittently at a frequency in the range of hundreds of pulses per second, the associated time variations are sloughed over. Of the individual countries or agencies that specify a general public guideline value for "static" fields the strictest is Austria's 1600 A/m which corresponds to 2,000 μT. However, ACGIH, which specifically limits the applicability of its TLVs to occupational situations, specifies a limit of 500 μT for workers with electronic medical devices. If the usual extra safety factor for members of the public or "uncontrolled" situations is applied, then the ACGIH TLV would imply 100 μT as a limit for transportation system passengers.

Table 3. Summary of Guideline Approaches
(After: WHO (1999), ICNIRP (1998), IEEE (1999))

Label Given to Approach	"Static"	Value in lowest frequency range if range ends at or below 3 kHz (frequency range)	Values above lowest frequency range (second, third, ... frequency ranges) but below 100 kHz
	Limits (Magnetic Fields)		
IEEE	N/S	N/S	163 A/m or ~200 µT (3 kHz - 100 kHz)
ICNIRP	40,000 µT (>0 Hz - 1 Hz) Occupational, five times greater	$40,000/f^2$ µT (1 Hz - 8 Hz) 5,000/f µT (8 Hz - 800 Hz) 6.25 µT (800 Hz - 150 kHz) Occupational, five times greater	6.25 µT (800 Hz - 150 kHz) Occupational, five times greater
Eastern Europe	N/S	N/S	N/S
	Limits (Electric Fields)		
IEEE	N/S	N/S	614 V/m (3 kHz - 100 kHz)
ICNIRP	N/S	10 kV/m (1 Hz - 25 Hz) 250/f kV/m (25 Hz - 3 kHz) Occupational, two times greater	87 V/m (3 kHz - 150 kHz) Occupational, two or more times greater (different "break" frequencies)
Eastern Europe	N/S	N/S	25 V/m (30 kHz - 300 kHz) Occupational, 20 times greater

[NOTE: f represents frequency in Hz]
[NOTE: IEEE does not distinguish between general population and occupational exposures]

8. Discussion

When the history of standards and guidelines (reflecting common engineering practice as discussed earlier) is taken into consideration, it is not surprising that the most detailed work to date (that sponsored by the Volpe Transportation Center) takes a very similar approach to the "low" end of the ELF frequency range - defined in the report by Dietrich and Jacobs (1999) as 0 Hz to 3000 Hz. Such an approach makes it possible to simplify the analysis and presentation of the enormous amounts of data collected. This approach to dealing with transportation system EMFs is depicted in Figure 33. The arbitrary set of frequency "bands" shown in the figure is used to group the collected information so as to allow for comparisons between the various transportation systems they studied. While the chosen bands (any consistently used set of bands can be used) serve as a basis for comparison between the various transportation systems, the bulk of the underlying structure of the data, shown in the many graphical presentations provided in their report, is lost. What is most striking from the graphical presentations is that an enormous amount of detailed structure is crunched against the "zero" of the linear scale that is used. Furthermore, in so far as magnetic field level alone (ignoring frequency) is deemed to be the parameter of significance with regard to biological effects, the so-called "static" and low frequency bands stand out as prime areas for concern.

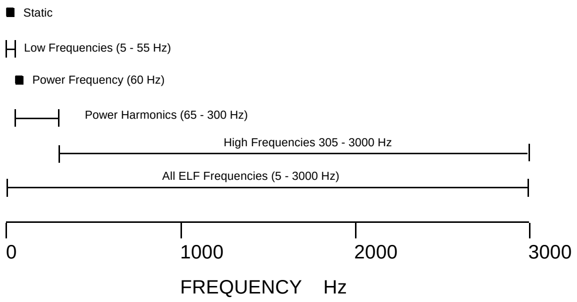

Figure 33. "Bands" used in the Volpe Center Report (Dietrich and Jacobs, 1999)

As is evident from the review of applications, and standards and guidelines, the frequency scale used to depict the status at any given time has been linear in each case. As technology has advanced to ever higher frequencies, low frequency issues have apparently faded into insignificance and, indeed, would appear to be easily accommodated by an "obviously" minor extrapolation of existing guidelines or rationales. However, a very different perspective is attained by considering the situation, particularly the situation of transportation systems, using a logarithmic depiction of frequency bands because, for transportation systems, the operative frequencies are at very low frequencies. This is shown in Figure 34. In effect, rather than giving disproportionate representation to the highest frequencies thereby creating an incorrect impression that the lower reaches of the range are totally insignificant, it gives each decade equal representation.[1] Furthermore, while it appears from the Volpe Center report that the measuring equipment used by Dietrich and Jacobs had a frequency resolution limit of 5 Hz [2] (they use 5 Hz bands for depicting harmonic content of the observed signals), there is equipment available with a resolution limit of 1/8 Hz (and there are techniques that can provide still finer resolution). Only by bringing to bear such improved equipment and techniques will it be possible to explore the characteristics of transportation system EMFs in more detail. Since the very existence of detrimental effects continues to be disputed, the relevant metric for exposure remains undefined. Therefore just what features of the fields should be measured remains unclear. However more detailed knowledge of the temporal, spatial and frequency variability of transportation EMFs cannot but be more informative than the best that is available to date.

---

[1] Of course, the counter argument can be made that a logarithmic representation gives a disproportionate and incorrect impression of the lower reaches of the frequency range.

[2] It was subsequently noted (Brecher, 2001) that the 5 Hz limitation was chosen for convenience only and that at some future time the actual data could be analyzed to extract more details at finer resolution should that be deemed necessary or advisable. On the other hand, Wenzl (1997) reporting on measurements using the same MultiWave TM system states that measurement durations are 200 ms thereby limiting periodicities that can be detected to frequencies greater than or equal to 5 Hz.

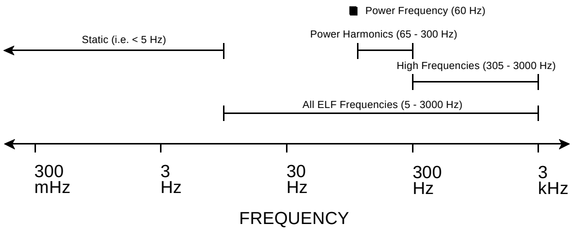

Figure 34. Volpe Center Report "Bands" on Logarithmic Scale

Further to the issue of depicting the whole of human experience of EMFs in a way that gives comparable representation to all of the ranges involved, consider Figure 35. Note that because the scale is logarithmic, it is open ended. Zero does not even appear. This has the salutary effect of removing the erroneous concept of "static" effects which, in principle, do not exist. Perhaps the best example of this is the earth's magnetic field which is glibly spoken of as "static" (which it IS for all practical "human lifetime" purposes) but which is known to ALTERNATE with a period of about 50,000 years, i.e. at a frequency of about 60 fHz! Of more practical relevance to effects in humans and animals would be circadian rhythms which have a frequency of 11.6 μHz. Suffice it to say that arbitrarily lumping anything under 5 Hz into a bin called "static" can hardly lead to enhanced understanding of "low" frequency effects and especially not transportation system EMFs since it is evident that the bulk of the detail is in the ultra low region (as indicated in Figure 35) and below.

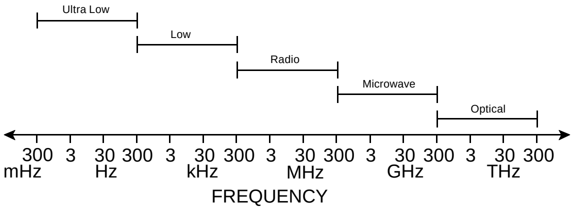

Figure 35. Range of Human Experience of EMFs (Logarithmic Scale)

Another very important reason for a more detailed exploration of transportation system EMFs at better than 5 Hz resolution is that many biological functions (nerve impulses, brain waves, cardiac rhythm) have periodicities throughout the ultra low frequency region.

9. Current Status of Knowledge About Health Effects

The EMF health effects literature has grown to enormous proportions over the past four or five decades. The opening paragraph of the present report touches on the highlights of the effects reported and investigated over that period of time. Reviews have appeared with mind-numbing regularity and frequency. Certainly not a year goes by without at least one more review being added to the total. The present section might well be characterized as a meta review of health effects.

A great deal of the accumulated literature deals with frequencies significantly greater than those observed and reported near transportation systems. Nevertheless the subset of the literature dealing with the lowest frequencies and consequently of relevance for transportation systems is still substantial. The most thorough review of that portion of it was carried out during the course of the US EMF RAPID program (concluded in 1999) which directed particular attention to power frequency effects. Similar reviews have been carried out in other countries as well. In the US, the IEEE has undertaken to develop an annotated database of the EMF health effects literature. Internet connections to some of these sources can be made through the web site of the WHO's EMF Project at

<www.who.int/emf>. The conclusions of the reviews that have been carried out to date have been similar. The World Health Organization (1999), which is typical, draws the following three conclusions in ending its web based course on static and ELF fields:

- Despite the large number of studies already reported, further research is still necessary in order to make a complete assessment of health effects of exposure to static and ELF fields;
- Many inconsistencies must be resolved, reported effects must be replicated and major concerns (e.g. cancer) must be properly addressed;
- Advances in our knowledge will allow better evaluation of possible risks and ensure that exposure guidelines provide adequate protection for all, both in the community and the workplace.

Such calls for more research are characteristic of science based approaches and, beyond the "typical" bases of such calls for research, the logarithmic representation discussed above opens yet another new perspective on EMF issues that is particularly relevant to transportation EMFs. From an academic point of view, such explorations of the boundaries of knowledge are inherently justified. By contrast, from an engineering point of view they tend to impede development and restrict or complicate designs and from a business point of view they just add costs and unnecessary concerns.

Science based approaches have some prospect of providing a firm basis for standards and guidelines where cause and effect can be established. Not unreasonably, safety factors are usually incorporated to take account of uncertainties and variations in individual susceptibilities arising from age or infirmity. Beyond such considerations which scientists like to call "rational" there are various social and political considerations which give rise to the introduction of concepts like ALARA ("as low as reasonably achievable," firmly entrenched in ionizing radiation safety), the more recent concept of "Prudent Avoidance" (introduced in the US in the context of concerns about possible power frequency effects) and, most recently, the "Precautionary Principle" (introduced into the deliberations of the European Community in the context of dealing with environmental factors and concerns and applied in the Canadian Environmental Protection Act, 1999 where it is defined as meaning that "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation"). Even though strenuous attempts are made to provide scientific rationales for such extended safety considerations they remain more tenuous than the apparently arbitrary factors of 2 or 5 or 10 used for caution at the outset in the setting of exposure limits.

10. Gaps in Knowledge

Despite all the research carried out to date, none of it has been able to settle at least two essential questions. The first is, "What is the mechanism by which effects are produced?" The second is, "What is to be measured?" The latter may refer either to end points or exposure metrics. Both of the questions hinge on a still more basic question which is, "Can any effects be demonstrated?"

The answer to the basic question is that indeed effects can be demonstrated. The flow of currents within tissues produces heating and can interfere with nervous system function. At extreme levels burns, shock and cardiac arrest occur. It is to address such clearly demonstrated effects that existing guidelines (which incorporate substantial safety factors) have been established. In addition to the clearly demonstrated effects there are numerous possible, perhaps even plausible, effects that are hinted at by epidemiological, behavioural, electrophysiological, biochemical, genetic and other studies at the atomic, molecular, cellular and tissue, whole organism and community levels that are not clearly established. All of these point to gaps in knowledge.

The following is an excerpt from World Health Organization (1999) detailing the EMF Project's Research Agenda intended to assist in addressing the gaps in knowledge for ELF electric and magnetic fields and for static fields.

> ELF ELECTRIC AND MAGNETIC FIELDS
>
> Some epidemiological studies have suggested an increased risk of leukaemia in children living near power lines. Whether this is due to exposure to ELF magnetic fields or some other factor in the environment, has yet to be determined. Other unresolved issues for health relate to studies suggesting that ELF exposure may be associated with increases in breast and other cancers in adults, neurodegenerative diseases, such as Alzheimer's, and subjective or non-specific effects, e.g. "hypersensitivity" to electricity.
>
> There have been no published studies specifically investigating possible biological effects from exposure to transients (from switching electric currents) or high frequency harmonic fields that are normally superimposed on 50/60 Hz fields in living and working environments. On theoretical grounds, transient or high frequency harmonic fields are more likely to cause biological effects than sinusoidal 50/60 Hz fields. Additional studies identified as necessary to complete WHO's EMF Research Agenda include:
>
>> (i) Thorough surveys of transients and other perturbations of 50/60 Hz fields are needed to better characterize actual fields and to determine their prevalence in the environment. These fields are more likely to produce biological effects [than] pure sinusoidal 50/60 Hz since they may induce signals in cells above their normal electrical noise levels.
>>
>> (ii) At least two 2-year standard bioassay animal studies, like those conducted by the US National Toxicology Program, with exposures to ELF fields that include transients (described in (i) above), that test for common types of cancer.
>>
>> (iii) At least one 2-year standard bioassay animal study, similar to that described in (ii) above, using sinusoidal 50/60 Hz fields and two such studies using transient-perturbed fields, to test specifically for breast cancer.
>>
>> (iv) Epidemiologists and physical scientists should discuss how to refine their methodologies and assessment of past and present exposure to 50/60 Hz fields and transients. This should be followed by pilot studies that test and validate these refinements. At least two further large, multi-centred epidemiological studies of childhood leukaemia are needed that use the best available methods of exposure assessment, including assessment of transient and higher frequency harmonic fields.
>>
>> (v) Large epidemiological studies are also needed to investigate possible associations between exposure to 50/60 Hz fields and breast cancer or neurodegenerative diseases. These studies should be conducted on highly exposed occupational groups using the best available methods of exposure assessment.
>>
>> (vi) Human volunteer studies are needed to determine whether ELF fields affect certain hormone levels (e.g. melatonin). These studies should extend the exposures beyond the one night used in past experiments and also test both sexes. It is important that future studies test for effects caused by transients and other perturbed fields.

If results of current studies of people claiming hypersensitivity [to] ELF fields are confirmed, particularly studies of their responses to fields applied in controlled laboratory situations, these reports should be investigated to determine what further research is needed.

> (vii) In vitro studies are needed that are directly relevant to possible in vivo effects, and that address the issues of ELF exposure thresholds and reproducibility for reported positive effects on cell cycle kinetics, proliferation, gene expression, signal transduction pathways and membrane changes.

Theoretical modelling investigations are also needed that support in vivo studies by proposing testable basic mechanisms on how low-intensity fields and realistic environmental transients might interact with biological systems.

STATIC FIELDS

Research to date indicates that static electric fields do not produce deleterious health effects in humans at levels found in the environment or workplace. Therefore, further research into their possible effects is not recommended at this time.

Static magnetic fields are known to produce health effects only at very high field strengths. Technologies, such as magnetically levitated trains, medical diagnosis and treatment, and industrial applications are increasing in use or are being developed. They use intermediate or high-intensity static magnetic fields, which could increase public and worker exposure significantly. More information on possible long-term effects on health from exposure to static magnetic fields is needed. Studies needed to provide this information include:

> (i) At least two standard 2-year animal bioassay studies concentrating on cancer-related effects. These studies should follow criteria used by the US National Toxicology Program.
>
> (ii) At least two large-scale, multi centre epidemiological studies on workers that characterize static magnetic field exposure well, minimize confounding factors, and include measurements of exposure from other sources of EMF.
>
> (iii) Additional studies are needed that examine biological effects of exposure to combined static and time-varying fields, including transients, particularly those found in transportation systems.

11. Summary

It is clear that users of transportation systems are exposed to any associated EMFs in the same manner as users of microwave ovens or cellular telephones and exposed to the EMFs associated with each of them and, of course, they are exposed to a greater extent than non-users. Maximum fields approach and even somewhat exceed guideline levels, particularly for workers but average exposures remain within present limits (where they exist). It is evident that the complexity and variability of the EMFs associated with transportation systems far exceeds the complexity addressed by present standards and guidelines. It is also clear that there is no consensus, comparable to that for ionizing radiation or tobacco use, that detrimental effects even occur.

There is no accepted theoretical model by which suggested effects might be caused. There is no obvious metric for exposure or dose determination. It has not even been established that more is worse in as much as many suggested effects are associated with "windows" of effectiveness so that only certain critically precise conditions in terms of frequency, amplitude or modulation must be established (similar to the conditions for successful MRI - magnetic resonance imaging) for the effects to occur. Therefore, at least on the basis of such abstract and theoretical arguments, the possibility of significant detrimental effects from the low frequency EMFs associated with transportation systems can only be considered to be rather speculative and remote at the present time.

A concern always remains as to whether summaries such as that given above are rash or reasonable. In view of past and continuing experiences with health effects and general degradation of the environment, should responsible agencies, organizations and individuals not be more cautious rather than less? It is the opinion of the present author that the overall results of research related to concerns about possible detrimental effects of EMFs, particularly in the context of present knowledge about transportation system EMFs, is reassuring rather than alarming.

In a short paper, in Italian, elicited by requests for input sent to many countries and agencies, Molfese and Petrini (1996) concluded "Le conoscenze attuali, per i valori riscontrati mediante misurazione su autoveicoli elettrici ed a combustibile, non hanno dimonstrato l'esistenza di rischi per il guidatore." [According to knowledge available to date, for levels determined by measurements taken in electric and conventional automobiles, the existence of any risk to the driver has not been demonstrated.] While a check of the detailed reference will disclose that the quote above can hardly be claimed to have been made in a peer reviewed publication, the authors nonetheless summed up the present status, not only for automobiles but also for transportation systems in general. That said, as always, the frontiers of knowledge beckon.

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APPENDIX A

Standards and Guidelines Summary
"Static" and Frequencies less than 100 kHz

NOTE: "Static" is a loosely used term. It is often used where DC current is supplied to a motor using a chopper. Even though the current is delivered to the motor intermittently at a frequency in the range of hundreds of pulses per second, the associated time variations are sloughed over. Where a value for "static" fields is not specified in a standard or guideline, there is usually a lower limit frequency specified. That frequency is taken as the start of the lowest frequency range specified by the standard or guideline. Where a "static" value is not present, N/S (Not Specified) is entered. Sometimes there are values specified for specific frequencies - usually the power frequency. The middle column under "Limits" indicates the value(s) specified for frequencies less than 3 kHz, including the value specified for the power frequency with frequency or frequency range in brackets. The right-hand column under "Limits" indicates the value(s) specified for frequencies greater than 3 kHz but less than 100 kHz again with frequency or frequency range in brackets. Frequency break points occur where the specified value changes from a constant to some function of frequency or back to a constant value. 100 kHz is taken as the upper limit of the range of applicability of the standard or guideline as far as transportation systems are concerned. The break points vary widely and apparently arbitrarily although each has some sort of rationale behind its choice.

The information presented in Tables A1 and A2 which appear on the following pages has been compiled with particular reference to WHO (1999), IEEE (1999) and NRPB (1993).

Table A1
"Static" and Low Frequency Limits World Wide
MAGNETIC FIELDS

[NOTE: expressions below containing "f" always assume the frequency is expressed in Hz so they may appear different from the way they are presented in the individual standard or guideline]

Country or Organization	Limits		
	"Static"	Value in lowest frequency range if range ends at or below 3 kHz (frequency range)	Values above lowest frequency range (second, third, ... frequency ranges) but below 100 kHz
Australia New Zealand	N/S	N/S	N/S (3 kHz - 100 kHz) average 5 A/m (6 µT) (3 kHz - 100 kHz) peak Occupational, five times greater
Austria	1,600 A/m (2,000 µT) Occupational, five times greater	1000 A/m (1,260 µT) (>0 Hz - 4 Hz) 5000/f µT (4 Hz - 250 Hz)	16 A/m (20 µT) (250 Hz - 10 kHz) $16x10^{-8}f^2$ A/m (10 kHz - 30 kHz) $1.19x10^7/f^{1.098}$ A/m (30 kHz - 30 MHz) Occupational, five times greater (different "break" frequencies)
Bulgaria	60,000 µT	60,000/f µT (>1 Hz - 60 kHz)	50 A/m (63 µT) (60 kHz - 3 MHz)
Canada	N/S	N/S	2.19 A/m (2.75 µT) (3 kHz - 1 MHz) Occupational, 2.236 times greater

Germany	N/S	300 μT 16 2/3 Hz 100 μT 50 Hz	N/S
Hungary	N/S	N/S	N/S
Italy	N/S	N/S	N/S
Japan	N/S	N/S	163 A/m (10 kHz - 30 kHz) 4.9x10^6/f A/m (30 kHz - 3 MHz)
Russia	N/S	N/S	N/S
Slovenia	N/S	4,000 μT (>0 Hz - 0.1 Hz) New/rebuilt sources; 10 times greater for existing sources	2,800 μT (>0.1 Hz - 1.15 Hz), 500/f μT (>1.15 Hz - 1.5 kHz), 2 μT (>1.5 kHz - 10 kHz), 5.3 A/m (>10 kHz - 42 kHz), 2.2x10^5/f A/m (>42 kHz - 680 kHz) New/rebuilt sources 10 times greater for existing sources
IEEE/ANSI (US)	N/S	N/S	163 A/m or ~200 μT (3 kHz - 100 kHz)
ICNIRP	40,000 μT (>0 Hz - 1 Hz) Occupational, five times greater	40,000/f^2 μT (1 Hz - 8 Hz) 5,000/f μT (8 Hz - 800 Hz) Occupational, five times greater	6.25 μT (800 Hz - 150 kHz) Occupational, five times greater
NRPB (UK) "Investigation" Levels	200,000 μT 24 h avg. 2,000,000 μT max whole body 5,000,000 μT max limbs only	200,000 μT (>0 Hz - 0.4 Hz) 80,000/f μT (>0.4 Hz - 1 kHz)	80 μT (1 kHz - 535 kHz)

ACGIH (US)	60,000 µT Whole body, 8 h TWA 600,000 µT Limbs, 8 h TWA 2,000,000 µT Whole body, ceiling; 5,000,000 µT Limbs, ceiling; 500 µT Medical electronic device wearers	N/S under 1 Hz; 60,000/f µT (1 Hz - 300 Hz) Whole body, ceiling; 300,000/f µT (1 Hz - 300 Hz) Limbs, ceiling; 600,000/f µT (1 Hz - 300 Hz) Extremities, ceiling; 100 µT 50/60 Hz Medical electronic device wearers	200 µT (300 Hz - 30 kHz) ceiling 163 A/m or ~200 µT (30 kHz - 100 kHz) RMS average

Table A2
"Static" and Low Frequency Limits World Wide
ELECTRIC FIELDS

[NOTE: expressions below containing "f" always assume the frequency is expressed in Hz so they may appear different from the way they are presented in the individual standard or guideline]

Country or Organization	Limits		
	"Static"	Value in lowest frequency range if range ends at or below 3 kHz (frequency range)	Values above lowest frequency range (second, third, ... frequency ranges) but below 100 kHz
Australia New Zealand	N/S	N/S	N/S (3 kHz - 100 kHz) average 87 V/m (3 kHz - 100 kHz) peak Occupational, five times greater
Austria	15 kV/m Occupational, two times greater	10 kV/m (>0 Hz - 25 Hz) 250/f kV/m (25 Hz - 1 kHz) Occupational, two times greater	250 V/m (1 kHz - 3 MHz) Occupational, two or more times greater (different "break" frequencies)
Bulgaria	25 kV/m	25 kV/m (>0 Hz - 100 Hz)	$2.5 \times 10^6/f$ V/m (100 Hz - 4 kHz) 625 V/m (4 kHz - 60 kHz) 500 V/m (60 kHz - 3 MHz)
Canada	N/S	N/S	280 V/m (3 kHz - 1 MHz) Occupational, 2.236 times greater

Germany	N/S	10 kV/m 16 2/3 Hz 5 kV/m 50 Hz	N/S
Hungary	N/S	5 kV/m 50 Hz	50 V/m (30 kHz - 3 MHz)
Italy	N/S	N/S	N/S
Japan	N/S	3 kV/m (50 Hz)	614 V/m (10 kHz - 3 MHz)
Russia	N/S	N/S	25 V/m (30 kHz - 300 kHz) Occupational, 20 times greater
Slovenia	N/S	700 V/m (>0 Hz - 0.1 Hz) Peak, new/rebuilt sources 20 times greater for existing sources	500 V/m (>0.1 Hz - 60 Hz) New/rebuilt sources 20 times greater for existing sources 30/f kV/m (>60 Hz - 1.5 kHz) New/rebuilt sources 20 times greater for existing sources 40 V/m (>1.5 kHz - 10 kHz) New/rebuilt sources 10 times greater for existing sources 126 V/m (>10 kHz - 680 kHz)
IEEE/ANSI (US)	N/S	N/S	614 V/m (3 kHz - 100 kHz)

ICNIRP	N/S	10 kV/m (1 Hz - 25 Hz) 250/f kV/m (25 Hz - 3 kHz) Occupational, two times greater	87 V/m (3 kHz - 150 kHz) Occupational, two or more times greater (different "break" frequencies)
NRPB (UK) "Investigation" Levels	N/S	25 kV/m (>0 Hz - 24 Hz) $6x10^5$/f V/m (24 Hz - 600 Hz)	1000 V/m (600 Hz - 600 kHz)
ACGIH (US)	25 kV/m Ceiling	25 kV/m (>0 Hz - 100 Hz) Ceiling	2.5×10^6/f V/m (100 Hz - 4 kHz) Ceiling 625 V/m (4 kHz - 30 kHz) Ceiling 614 V/m (30 kHz - 3 MHz) 0.1 h average 100 kV/m (30 kHz - 100 kHz) Peak

APPENDIX B

Units

SI (System Internationale) Unit Prefixes, Their Symbols and Their Values

Prefix	Symbol	Value
exa	E	10^{18} i.e. 1 000 000 000 000 000 000
peta	P	10^{15} i.e. 1 000 000 000 000 000
tera	T	10^{12} i.e. 1 000 000 000 000
giga	G	10^{9} i.e. 1 000 000 000
mega	M	10^{6} i.e. 1 000 000
kilo	k	10^{3} i.e. 1 000
		10^{0} i.e. 1
milli	m	10^{-3} i.e. 0.001
micro	μ	10^{-6} i.e. 0.000 001
nano	n	10^{-9} i.e. 0.000 000 001
pico	p	10^{-12} i.e. 0.000 000 000 001
femto	f	10^{-15} i.e. 0.000 000 000 000 001
atto	a	10^{-18} i.e. 0.000 000 000 000 000 001

Units used in the Present Report, Their Symbols and What They Represent
[NOTE: SI Unit names are not capitalized]

Symbol	Unit Name	What the Unit Represents
A	ampere	electric current
A/m	ampere per metre	magnetic field strength
C	coulomb	electric charge
Hz	hertz	frequency
m	metre	length
s	second	time
T	tesla	magnetic induction
VA	volt-ampere	effective power
W	watt	power

APPENDIX C

Abbreviations and Acronyms

AC	Alternating Current
ACGIH	American Conference of Governmental Industrial Hygienists
ALARA	As Low As Reasonably Achievable
ALRV	Articulated Canadian Light Rail Vehicle
AM	Amplitude Modulation
ANSI	American National Standards Institute
AT	Autotransformer
CIDI	Compression Ignition, Direct Injection
CLRV	Canadian Light Rail Vehicle
CRT	Cathode Ray Tube
DC	Direct Current
ELD	Electro-Dynamic Levitation (magnetic levitation based on repulsion)
ELF	Extremely Low Frequency
ELM	Electro Magnetic Levitation (magnetic levitation based on attraction)
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field (sometimes: Electric and Magnetic Field)
EMI	Electromagnetic Interference
FM	Frequency Modulation
GTO	Gate Turn Off Thyristor
hp	horsepower
ICE	Internal Combustion Engine (sometimes: Inter City Express)
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronic Engineers
IGBT	Insulated Gate Bipolar Transistor
LIM	Linear Induction Motor
LRT	Light Rail Transit
LSM	Linear Synchronous Motor

LUL	London Underground Limited
maglev	magnetic levitation
MAR	Mercury Arc Rectifier
MF	Magnetic Field
MRI	Magnetic Resonance Imaging
PWM	Pulse Width Modulated
RF	Radio Frequency
RMS	Root Mean Square
SCR	Silicon-Controlled Rectifier
SRT	Scarborough Rapid Transit (TTC)
TGV	Train à Grande Vitesse
TLV	Threshold Limit Value
TTC	Toronto Transit Commission
UHF	Ultra High Frequency
VHF	Very High Frequency
VVVF	Variable Voltage Variable Frequency
WHO	World Health Organization