

## MEASUREMENT AND ANALYSIS OF ELECTROMAGNETIC FIELDS FROM TRAMS, TRAINS AND HYBRID CARS

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Electricity is used substantially and sources of electric and magnetic fields are, unavoidably, everywhere. The transportation system is a source of these fields, to which a large proportion of the population is exposed. Hence, investigation of the effects of long-term exposure of the general public to low-frequency electromagnetic fields caused by the transportation system is critically important. In this study, measurements of electric and magnetic fields emitted from Australian trams, trains and hybrid cars were investigated. These measurements were carried out under different conditions, locations, and are summarised in this article. A few of the measured electric and magnetic field strengths were significantly lower than those found in prior studies. These results seem to be compatible with the evidence of the laboratory studies on the biological effects that are found in the literature, although they are far lower than international levels, such as those set up in the International Commission on Non-Ionising Radiation Protection guidelines.

### INTRODUCTION

Transportation systems create a number of environmental problems through the emission of harmful gases into the atmosphere. In the *twenty-first century*, inhabitants of both developing and developed countries are consuming more energy for production and transport, thus increasing the level of CO<sub>2</sub> emissions. Consequently, it is vital to limit energy consumption at the same time as developing the transport industry<sup>(1)</sup>. Electrical and hybrid technologies have been introduced to reduce the emission of harmful gases. Most trams, trains and hybrid cars are now electrically operated, therefore emitting less CO<sub>2</sub> and less pollution into the environment. Because of the use of electricity in these transportation systems, the issue of electromagnetic fields (EMFs) has arisen. People using trains, trams and hybrid cars are exposed to higher alternating and static magnetic field strength than are in the surrounding area. This study analyses the weak magnetic field strength from transportation systems. The findings can be used: (1) to reduce the magnetic fields from transportation system and (2) to set-up new laboratory experiments to observe the possible biological effects. Those replicated biological studies can contribute to future recommendations for exposure limits, such as those published by the World Health Organization and the International Commission on Non-Ionising Radiation Protection (ICNIRP)<sup>(2)</sup>. The recommendations of the ICNIRP for an exposure limit value for low-frequency EMFs and microwaves aims to protect people against nerve stimulation and body heating, respectively. About

30 y ago, the question arose as to whether weak, low-frequency EMFs constitutes a major health hazard. This question has still not been answered satisfactorily, particularly in the case of long-term exposure. The understanding of the impact of EMFs can be increased by the replicated biological studies.

Recently, magnetic levitation systems have begun to be developed around the globe. Both the Japanese and the German transportation systems use magnetic fields: these are called magnetic levitation or maglev systems. The most sophisticated ‘conventional’ electrified system is the French TGV system, where high-speed trains having reached 574.8 km h<sup>-1</sup><sup>(3)</sup>. The Japanese Series 700 Shinkansen and a range of sophisticated high speed electric railway systems have been deployed in Europe and, more recently, in other countries, specifically in the northeast USA<sup>(4)</sup>. In ‘conventional’ transportation systems, energy is supplied as fuel and the internal combustion engine (ICE) uses a motor with electrical ignition. In ‘advanced’ systems, the motors are electrical (alternating current (AC) or direct current (DC)) and the power supplies can also be electrical (AC or DC). Railway safety signalling systems also use electricity, initially when lanterns are replaced with signal lights, and more recently by radio controls<sup>(4)</sup>. High-speed intercity lines became popular and some cities (for example Shanghai) hail these infrastructures as prestigious. DC is used in early applications; later, AC is used, particularly when it is essential to transmit electrical energy over extensive distances<sup>(5)</sup>. Hybrid electric vehicles (HEV) produce less carbon dioxide emissions and have better fuel economy than

conventional cars with an ICE<sup>(6)</sup>. Toyota's Prius is the first commercial HEV that is introduced in Japan in 1997, and the batteries are redesigned in 2000<sup>(7)</sup>. All these 'advancements' contribute to the growth in concern about the impact of EMFs from transportation systems. During the 1960s and 1970s, when high voltage power lines are more visible, health and safety concerns were enlarged<sup>(4)</sup>. There is much speculation that there may be a considerable, and still not sufficiently investigated, impact of existing transportation systems (tram, train and hybrid vehicle and high-speed maglev lines) on the environment, specifically on biological tissue that is exposed over a long period. Given the potential effect of EMFs, organisations that are responsible for managing health issues have taken some practical steps to provide clear information about these effects. Managing health issues in relation to the transportation systems is presently at an early stage of deployment. This clarification significantly changes the range of frequencies to be considered for 'transportation system EMFs', producing open-ended questions about the impact of technology on humans and/or the environment. The development of transportation systems towards higher speeds and greater efficiency seems largely to ignore the potential risks associated with these changes.

Higher currents and voltages are required by larger and more efficient systems, which subsequently causes larger magnetic and electric fields. On the other hand, smaller systems put the user or operator closer to the source of the fields, which can sometimes lead to higher local exposures. All these factors demonstrate the difficulty in establishing the patterns of potential exposure that are connected to the transportation systems. A local example is a consideration of the measurements of EMFs that are emitted from the Australian tram, train and hybrid car system. This investigation involves the following measurements: (1) exposure as a passenger inside and outside of a tram, train and hybrid car; (2) field exposure at head level, seat level and floor level; (3) field exposure when engines move at a higher speed, when a tram climbs a hill and when a vehicle is stationary and (4) comparison of exposure levels with existing experimental results for the biological effect of magnetic fields in the literature and with the international limits (ICNIRP), in order to quantify the biological effects.

This paper is organised as follows. In the Research findings section, the scientific studies of EMFs from transportation systems are described that have been carried out in several countries. The operation of trams, trains and hybrid cars are explained in the section on operation of transportation systems. In the experimental setup and results section, the experimental study and results of measured EMF strengths of the Australian transportation system are described. In the discussion, an

analysis of measured field strength from transportation system with ICNIRP limit and the biological effects of the laboratory studies carried out in the literature are given and the conclusion concludes the paper.

## THE RESEARCH FINDINGS

### Trams and trains

Scientific investigations of the impact of EMFs from transportation systems have been carried out in several countries. These studies have focused on both occupational and public exposure, such as engine drivers, transport workers and passengers. The studies of EMF exposure levels for several types of trains, such as DC underground, AC trains and Maglev, are summarised in Table 1. The measurements were carried out using various types of magnetic field measuring instruments that are operated in various frequency bands. The static and alternating magnetic flux densities in the electric trains and trams used in the UK were studied<sup>(8)</sup>. The recording device was an EMDEX II logging magnetic field dosimeter. The measurements were taken for the London underground 600 V DC system, the suburban railways at 750 V DC, and mainline railways at 25 kV and 50 Hz. In the underground system, static magnetic flux densities and alternating fields on both the standard and experimental trains were observed. Moreover, in the suburban railways, the alternating magnetic flux densities of a train with a variable frequency AC induction motor were recorded. In addition, the (quasi) static magnetic flux densities in the mainline railways were recorded. The maximum alternating flux density was at 100 Hz, and the typical static magnetic flux densities to which passengers might be exposed was less than 300 mG<sup>(8)</sup>. In another study carried out in the UK electric transport system, the static magnetic fields and time-varying magnetic fields near facilities were observed using a root-mean-square (RMS) magnetometer<sup>(9)</sup>. Chen and Yianting<sup>(10)</sup> took measurements of the EMFs emitted from the Beijing 825 V DC metro system using a spectral analysis instrument. EMF's measured from the loop antenna in the Tunis, 750 V DC railway systems were found to lie within the frequency range 100 kHz–20 MHz, which mainly radiated from the power electronic systems embedded in the train<sup>(11)</sup>.

Measurements taken in the USA were carried out on a platform directly above the contact wire for electric traction as a train passed. Measurements performed inside two types of locomotives in the AC Swiss railway system revealed that, in modern systems the maximum magnetic fields are less than those of older systems. Measurements from Japanese trains showed magnetic fields in the substation,

## EMF FROM TRANSPORTATION

Table 1. Exposure levels of several transportation systems.

| Country                                                | Tram/Train type                                  | Magnetic field exposure levels                                                                                                                                                                                                                   | Instrument                  |
|--------------------------------------------------------|--------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| UK(Chadwick and Lowes, 1998) <sup>(8)</sup>            | 600 V DC underground railway system (tube train) | (a) <i>Static MF</i> :<br>(1) Passenger compartments floor: 1–20 G.<br>(2) Driver's cab floor: 2 G.<br>(3) 1 m above floor: 2 G.<br>(4) Floor above chopper: 440 G.<br>(5) Seat height above chopper: 20 G<br>(b) <i>Alternating MF</i> : 200 mG | EMDEX II                    |
|                                                        | 750 V DC suburban railway                        | (a) <i>Alternating MF</i> :<br>(1) Inside table height: 160–640 mG<br>(2) Platform: 160–480 mG<br>(3) 150 mm above smoothing inductor: 10 G                                                                                                      | EMDEX II                    |
|                                                        | 25 kV, 50 Hz mainline railways                   | (a) <i>Quasi-static MF</i> :<br>(1) Driver's cab 1.4 m above floor: 270 mG<br>(2) Passenger compartments floor: 20 G<br>(3) Passenger compartments 0.5 m above floor: static 30 G and 250 mG at 100 Hz                                           | EMDEX II                    |
| (Allen <i>et al.</i> , 1988) <sup>(9)</sup>            | Electric transport system                        | (a) <i>Static MF</i> : 160–640 mG upto 150 G<br>(b) <i>Alternating MF</i> : 50–500 mG at 50 Hz, 150 G at 100 Hz                                                                                                                                  | RMS magnetometer            |
| Beijing (Chen and Yianting, 1997) <sup>(10)</sup>      | 825 V DC metro system                            | 50–70 dB $\mu$ V m <sup>-1</sup> —electric fields emitted by haul and high voltage substations                                                                                                                                                   | 30–300 MHz loop antenna     |
| USA(Bennett, 1994) <sup>(31)</sup>                     | Amtrak train                                     | (1) Above contact wire at 16.67 Hz: 100–200 mG<br>(2) Last car up to 300 mG at 60 Hz and up to 650 mG at 25 Hz                                                                                                                                   | RMS magnetometer            |
|                                                        | AC powered trains                                | Locomotive cabs: at 25 and 60 Hz average 30–50 mG, maximum 80–210 mG                                                                                                                                                                             | Waveform capture system MVC |
| Switzerland (Minder and Pfluger, 1993) <sup>(32)</sup> | AC railway system                                | Height of calves at 16.67 Hz:<br>modern types: 2 G<br>older types: 16.4–61.7 G                                                                                                                                                                   | RMS magnetometer            |

Continued

Table 1. Continued

| Country                                          | Tram/Train type                                            | Magnetic field exposure levels           | Instrument                  |
|--------------------------------------------------|------------------------------------------------------------|------------------------------------------|-----------------------------|
| Japan (Nakagawa and Koana, 1993) <sup>(12)</sup> | Railway substation<br>Railway station<br>AC/DC locomotives | 3–30 mG                                  | RMS magnetometer            |
|                                                  |                                                            | 2–100 mG                                 |                             |
|                                                  |                                                            | (a) <i>Alternating MF</i> : 40 mG        |                             |
|                                                  |                                                            | (b) <i>Static MF</i> : 500 mG            |                             |
|                                                  | DC train                                                   | (a) <i>Alternating MF</i> : 5–50 mG      |                             |
|                                                  |                                                            | (b) <i>Static MF</i> : 0.5–2 G           |                             |
|                                                  | AC train                                                   | (a) <i>Alternating MF</i> : 2–1500 mG    |                             |
|                                                  |                                                            | (b) <i>Static MF</i> : 1–40 G            |                             |
|                                                  | AC/DC train                                                | (a) <i>Alternating MF</i> : 5–750 mG     |                             |
|                                                  |                                                            | (b) <i>Static MF</i> : 2–10 mG           |                             |
| Germany (Dietrich et al., 1993) <sup>(35)</sup>  | Maglev vehicle transrapid TR07                             | (a) <i>Alternating MF</i> : <47.5 Hz     | Waveform capture system MVC |
|                                                  |                                                            | (1) Passenger compartments floor: 100 mG |                             |
|                                                  |                                                            | (2) Standing head level: 20 mG           |                             |
|                                                  |                                                            | (3) Platform: 20 mG                      |                             |
| Russia <sup>(13)</sup>                           | DC trains electric locomotives                             | (b) <i>Static MF</i> :                   | Waveform capture system MVC |
|                                                  |                                                            | (1) Floor: 800 mG                        |                             |
|                                                  |                                                            | (2) Standing level: 500 mG               |                             |
|                                                  |                                                            | 0–350 mG                                 |                             |
|                                                  |                                                            | 1–1.2 mG                                 |                             |

railway station, DC train, AC train and AC/DC locomotives<sup>(12)</sup>. A waveform capturing system, Magneto-Variation Complex (MVC), was used for recording magnetic fields in AC powered US trains and in the Maglev Vehicle Transrapid TR07 in Germany<sup>(13)</sup>. In Maglev, most of the time-variable magnetic fields were at frequencies below 47.5 Hz and within the waiting area of the passenger station, time-variable magnetic field levels produced by the passing train were observed. A portable waveform capture system MVC was used to measure magnetic levels in Russian DC trains. The most probable DC levels of electric locomotives and the quasi-static fields in DC trains were found to be higher than the natural geomagnetic field<sup>(13)</sup>.

### Hybrid cars

Several research efforts<sup>(14–16)</sup> have showed that significant magnetic fields are radiated from steel belted tyres in hybrid cars. These magnetic fields are generated from the tyres as a result of the reinforcing belts of magnetised steel wire that are used in their manufacture. Passengers in a car can be exposed to alternating magnetic fields generated by the car<sup>(15)</sup>. The vehicle's geometry in relation to the tyres can also be a vital factor in verifying the level of exposure of the passengers. Vedholm and Hamnerius<sup>(15)</sup> have carried out magnetic field analysis while a car is stationary, using a NARDA EFA200 EMF analyser. The field strengths in the 5–2000 Hz range were found to be around 29 mG at the front left seat, 9 mG at the back left seat, 9 mG at the front right seat and 19 mG at the back right seat level. Higher magnetic fields were produced on the left side of the car where the left rear foot level was 140 mG. Another study has observed magnetic field strength in the same low frequency range of 5–2000 Hz while a car is moving at 80 km h<sup>-1</sup>, using 12 different cars<sup>(14)</sup>. Average readings at the left floor level were found to be 32.2 mG and at the back seat were found to be 32.8 mG. This study also measured magnetic field strength from tyres at a distance 2 cm away from the wheel using a balancing machine. Average magnetic field strength from new tyres was 224 mG, and from used tyres was 292 mG. Moreover, field strengths from tyres with steel rims, such as 381 mG, were higher than those with aluminium rims.

Recent work<sup>(17)</sup> has measured the magnetic field strength from Toyota Prius cars in the same frequency range. The magnetic field strength was consistently higher at the rear seats than at the front seats. The study also suggested that the low-frequency magnetic field strength is larger when both the gasoline engine and electric motor were running; for example, when the car is accelerating, warming up, climbing slight hills or charging the battery. For the period of hard acceleration, field strength could

go up to 6–8 mG at the rear seat level; when operating with the electric motor alone, field strength was found to be 3 mG at the seat level.

## OPERATION OF TRANSPORTATION SYSTEMS

### Trams and trains

In an electric railway, the trains and trams are supplied via sliding contacts from a supply line—called the centenary or overhead line—that is situated over the railway tracks. The current generally returns to the substation via the rails, a separate return conductor, or via the earth. The large electrical plants in the network are constituted of sub-plants, which are electrically independent. Each single sub-plant consists essentially of overhead lines, buried cables and rails. Two different substations that are equipped with static AC–DC conversion groups supply the sub-network.

The return path of the current is constituted by the rails that are connected by means of cables to the negative pole of the supply. DC electrical motors controlled by choppers are employed for traction. In order to compensate for voltage drop along the lines, several substations are used as line subway feeders. The power delivered by the substation is transmitted to the traction vehicle via a system of flexible suspension contact lines (overhead or centenary) with which a locomotive mounted articulated device (pantograph) is brought into contact. On the traction vehicle, the power is regulated using choppers and then supplied to electric motors to control the movement. Auxiliary power that is lower than that which is supplied to the electric traction motors is also conditioned and regulated using static converters, inverters and rectifiers (Figure 1). The rails ensure that the current return and the sources of magnetic fields on trains and trams are often under the floors. Melbourne trams and trains use large electric motors and are powered using 650V DC and 1500V DC, respectively. This power is delivered via overhead wires and run on a standard gauge track.

### Hybrid cars

Hybrid cars have both an electric motor and an ICE, which is positioned in the front part of the car, as is shown in Figure 2. One or both power sources are used to maximise fuel efficiency depending on driving conditions<sup>(18)</sup>. Kinetic energy is converted into electric energy by the drive system. This energy is high while in the idling or braking position. Electric energy is stored in the batteries of 273.6 V, which are installed in the luggage boot under the rear seat. The electric motor and the battery are connected via an electric cable, as shown in Figure 2.

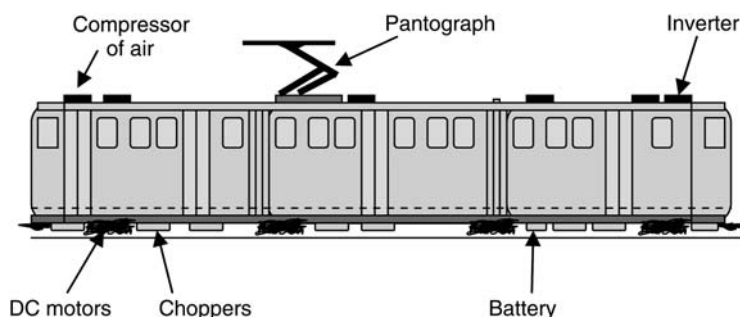


Figure 1. Train: magnetic fields are generated due to the current flow through the circuits.

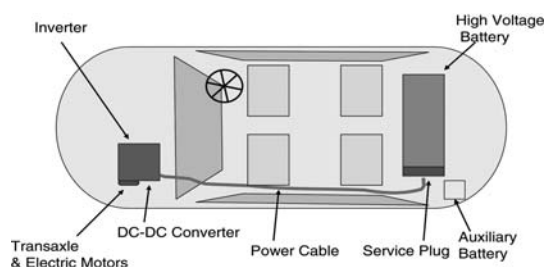


Figure 2. Hybrid car: magnetic fields are generated due to the current flow through the circuits in the vehicle.

Table 2. Tram: the average of minimum and maximum magnetic fields.

| Location                  | Minimum (mG) | Maximum (mG) |
|---------------------------|--------------|--------------|
| Middle floor              | 0.01         | 76           |
| Middle seat               | 0.1          | 11           |
| Rear floor                | 0.1          | 14           |
| Rear seat                 | 0.1          | 17           |
| Front floor               | 0.1          | 55           |
| Front seat                | 0.2          | 9.4          |
| Outside floor             | 2            | 34.5         |
| Above the tram—pantograph | 0.2          | 18.5         |

This energy is used by the electric motor to power the vehicle. The inverter controls the electric power by converting and regulating the electric current between the motor and the battery<sup>(18)</sup>. Magnetic fields are produced by the electric current that flows through the motor, cable and battery while driving.

## EXPERIMENTAL SET UP AND RESULTS

For this pilot study, spot measurements were taken at a number of locations in trains, trams and hybrid cars. A sample of 100 trains and trams was chosen. A selection of methods of sampling and recruitment was investigated: (1) both urban and suburban trains and trams were randomly chosen; (2) measurements were taken on both weekdays and weekends; (3) during the day time and at night and (4) inside and outside of trains and trams, to cover all the possibilities. The magnetic field exposure levels of one hybrid car were measured. The measurements were taken a number of times in the front and rear passenger compartments of the hybrid car, taking into consideration both left and right sides, and near the driver's head. Measurements of the fields at the floor, waist and seat levels in all these transportation systems were taken during each experiment. The

measuring devices for electric and magnetic fields use filtering to limit the frequency ranges; therefore the fields in a specific frequency range can be measured.

This study used an EMDEX II triaxial device to measure the magnetic field strength with a wide frequency range of 40–800 Hz. The sampling rate of this was set to 3 s. The device contains three orthogonally oriented magnetic field sensor coils (induction coils). This is useful for measuring AC EMFs up to 1300 mG (10 mG=1  $\mu$ T) with a measurement accuracy of  $\pm 5\%$ . However, EMDEX II is not suitable for recording variations in DC magnetic fields. An EHP-50 device was also used to measure the electric and magnetic fields, as well as measuring the frequency spectrum from 5 Hz to 100 kHz. The sampling rate of EHP-50 was set to 30 s and the absolute errors of electric and magnetic field measurements are  $\pm 0.5$  dB. This device contains three magnetic loops and three plate capacitors in the orthogonal position and is able to measure the magnetic field strength up to 100 G. The meter measures the RMS magnetic field intensity in each of the three orthogonal directions and records the resultant magnitude. The averages of the minimum and maximum magnetic field strength of three transportation systems are shown in Tables 2–4.

**Table 3. Train: the average of minimum and maximum magnetic fields.**

| Location                       | Minimum (mG) | Maximum (mG) |
|--------------------------------|--------------|--------------|
| Rear floor                     | 0.6          | 3.6          |
| Front floor                    | 0.01         | 87           |
| Middle floor                   | 1.5          | 8.3          |
| Driver side seat               | 0.5          | 4.7          |
| Outside                        | 0.4          | 4.8          |
| Above the train—<br>pantograph | 0.3          | 5.5          |

**Table 4. Hybrid car: the average of minimum and maximum magnetic fields.**

| Location                 | Minimum (mG) | Maximum (mG) |
|--------------------------|--------------|--------------|
| Rear left floor          | 2            | 35           |
| Rear left seat           | 0.9          | 13.2         |
| Rear right floor         | 0.9          | 14.3         |
| Rear right seat          | 1.5          | 8.4          |
| Driver head              | 0.3          | 5.6          |
| Front left floor         | 1.5          | 7.5          |
| Front left seat          | 1            | 23.9         |
| Front right floor        | 0.5          | 13.1         |
| Front right seat         | 0.5          | 17.9         |
| Resting rear right floor | 1.2          | 4.3          |
| Resting front left seat  | 1            | 4            |

## DISCUSSION

Magnetic field strength was observed inside and outside of trams and trains. In the hybrid car, only inside measurements were taken, as a part of the study. The measurements were taken on the seat and floor levels and considered the front (near the drivers' cabin) and rear sides of trams, trains and hybrid car. The fields in the  $x$ -,  $y$ - and  $z$ -directions and the harmonics were observed. The figures illustrate the resultant measurements of the magnetic field strength from the trams, trains and hybrid cars. The continuous variation of field patterns that were observed is due to the acceleration and deceleration of the trains, trams and hybrid cars. The magnetic field patterns inside the tram near the drivers' cabin for both the floor and seat levels are shown in Figure 3, whereas Figure 4 illustrates that of the rear side of the tram. The magnetic field readings were consistently higher at the front side than at the rear side. Further, the field strength at the front side of the tram on the floor is significantly higher when compared with the magnetic field strength on the seat level as shown in Figures 3 and 4. Several peak magnetic fields were recorded as a result of other trams passing near the tram where the measurements were taken. As an example, a peak magnetic field strength of 76 mG was recorded in the middle of the tram on the floor level when another tram passed. The magnetic field strength near the floor on the outside of the tram reached up

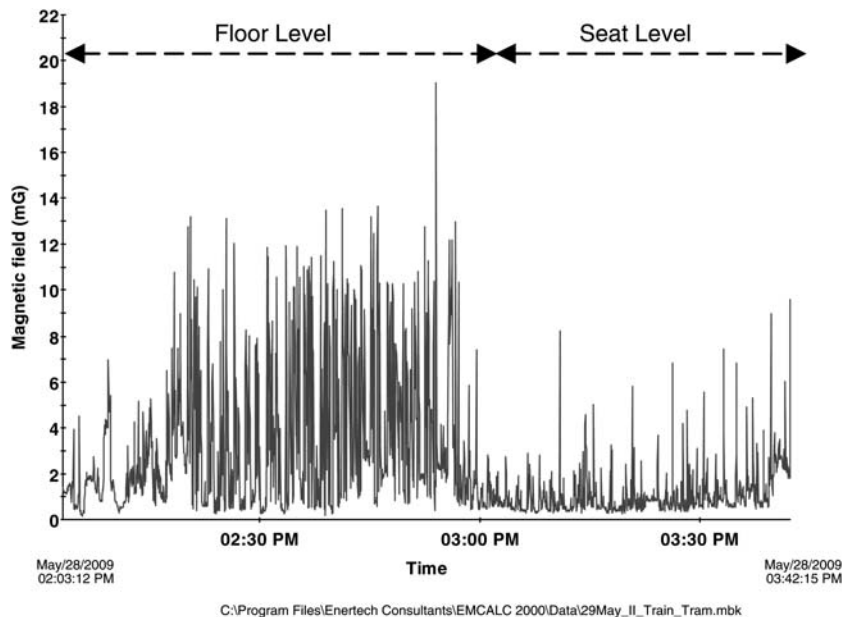


Figure 3. Tram: magnetic fields in the front side (floor and seat levels).

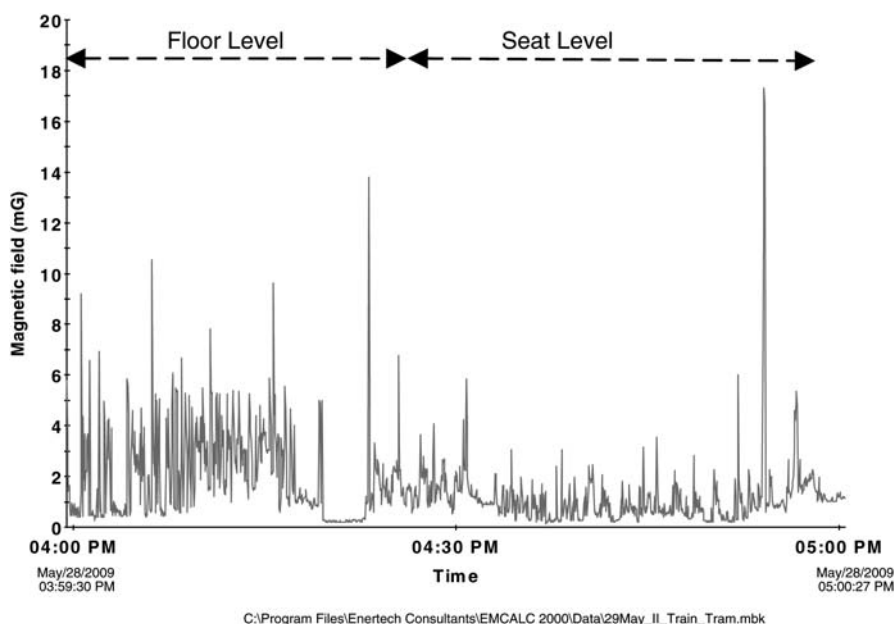


Figure 4. Tram: magnetic fields in the rear side (floor and seat levels).

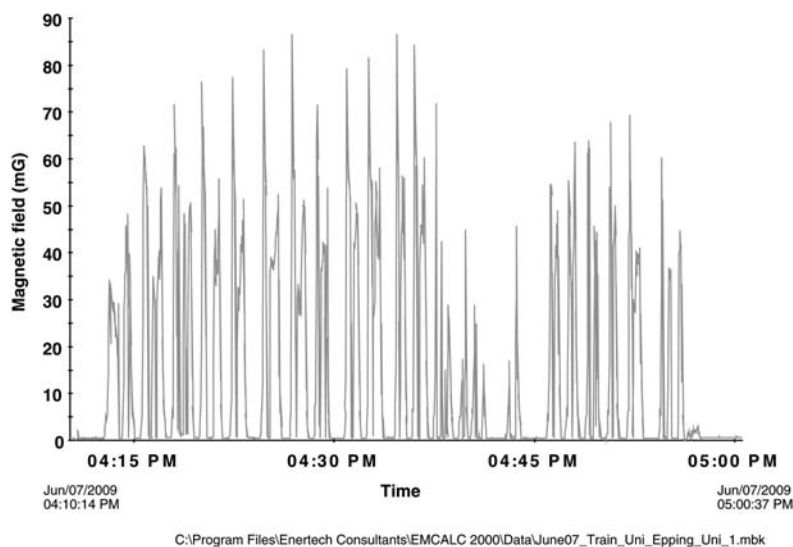


Figure 5. Train: magnetic fields in the front side (floor level).

to 35 mG when a tram passed on the rail. Most of the field strength was in the range of 0.1–55 mG. The magnetic field strength above the centenary tramline varies, with a maximum of 18.5 mG when the pantograph of a tram touches it.

The measurements of magnetic field strength in the front side of a train on the floor level were in the

range of 34–87 mG (Figure 5). The exposure levels were high at the front side compared with those at the rear side, as was noted with the trams. These levels are shown in Figure 6, where the magnetic field strength was recorded on the floor level in the range of 4–7 mG of the tram at the rear side. The field strength was lower at the seat level than at

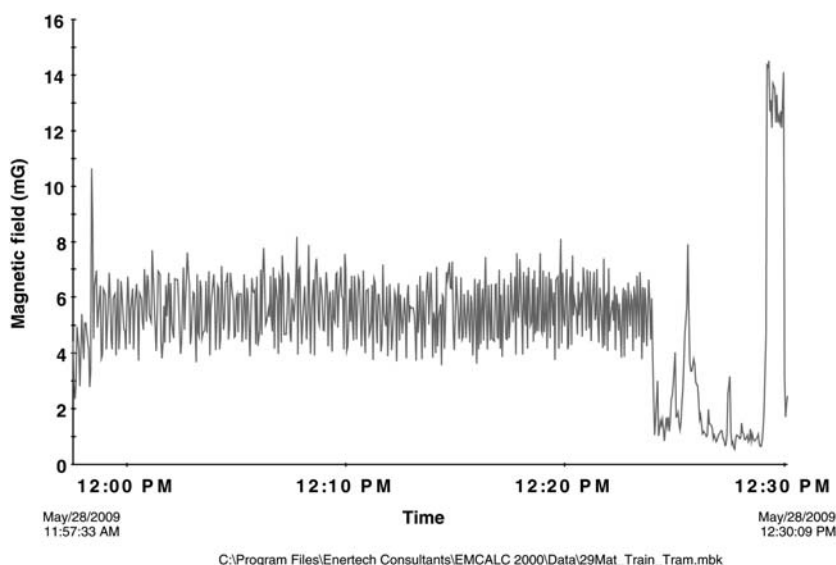


Figure 6. Train: magnetic fields in the rear side (floor level).

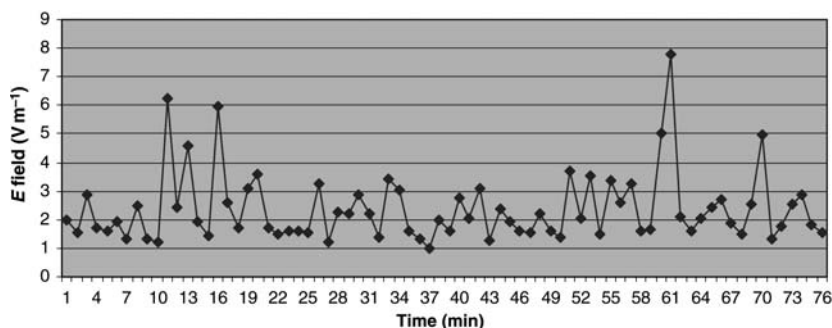


Figure 7. Train: electric fields on the rear side (seat level).

the floor level. Further, the field strength observed above the overhead line of the trains is around 5.5 mG when the pantograph of a train touches the overhead line. The field strength inside a train, on the floor, and directly below the pantograph gave the highest value of around 18 mG. The electric field strength patterns observed from EHP-50 (5–1000 Hz) and peak electric field strength of  $7.8 \text{ V m}^{-1}$  was recorded at the seat level on the rear side of the train as shown in Figure 7. Most of the sources of magnetic fields on trains and trams, such as electric motors, converters and inverters, are under the floor. Hence, the magnetic field strength at the floor level tends to be greatest when compared with the seat level. The magnetic field strength from the pantograph catenary interface is significant because of the high voltage carrying lines. When another tram or train is passing nearby, a peak magnetic field

strength was observed. Moreover, in the front side near the driver's cabin, magnetic field readings were higher.

The magnetic field strength of the hybrid car is shown in Figures 8 and 9. The measurements were obtained when the hybrid car was at the resting position and in the driving mode as shown in Figure 8. The magnetic field strength increases and decreases with the acceleration and the deceleration of the hybrid car as shown in Figure 9. There was a peak 5.6 mG magnetic field strength near the driver's head. The measurements at the right side seat level in the rear were significantly higher than those at the front side. Figure 9 illustrates the magnetic field pattern on the left side floor at the rear of the hybrid car. The hybrid car has a high voltage battery pack and circuitry that is positioned under the rear seat. Hence, the magnetic field exposure levels are higher

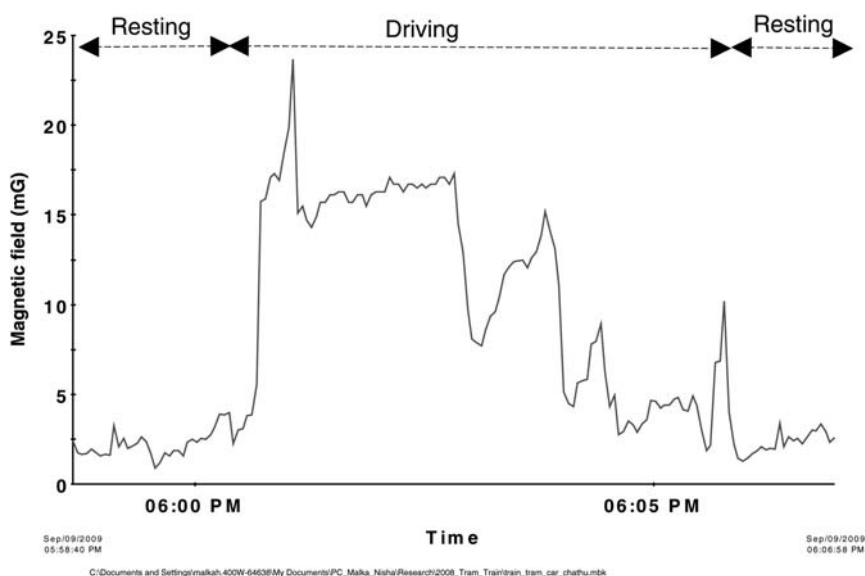


Figure 8. Hybrid car: magnetic fields in the left front side (seat level).

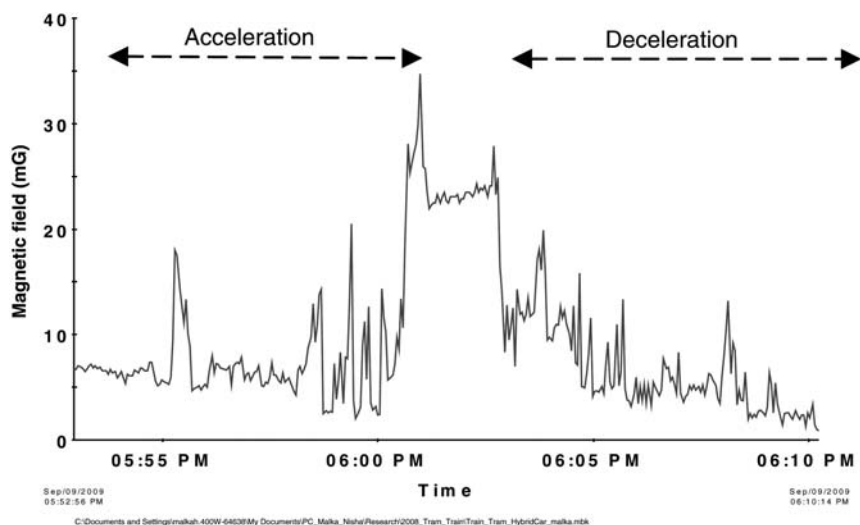


Figure 9. Hybrid car: magnetic fields in the left rear side (floor level).

at the rear side than at the front side. In the front left side of the hybrid car, there are a number of electric components, such as the power splitting device, two electric generators, inverter and an AC–DC converter. Further, a power cable runs from the high voltage batteries to the components at the front along the left side of the hybrid car. The electric cable is closer to the passenger compartment and therefore the passenger on the left side might be exposed to higher magnetic fields.

Low-frequency magnetic fields can penetrate the body and produce an electrical current. If the currents are too high, the central nervous system can be slightly excited. An early study by Nordenson *et al.*<sup>(19)</sup> reports an increase in chromosomal aberrations in the peripheral lymphocytes of engine drivers who were exposed to 16 2/3 Hz magnetic field strength from a small degree to over 1000 mG. This study<sup>(19)</sup> concluded that ‘exposure to magnetic field strength at mean intensities of 20–150 mG can

induce chromosomal damage'. The hydrogen nuclear polarisation model<sup>(20)</sup> predicts a biological response for oscillating magnetic field strengths above 10 mG. The presence of a static magnetic field is required for the resonance behaviour and biological effects can be expected for all frequencies below a few hundred hertz. In 2001, Belova and Lednev found that the gravitropic bending of flax seedling deviated anomalously from the expected values at very low amplitudes ( $0.75 < B < 50$  mG) of the time-varying magnetic field<sup>(21)</sup>. Lednev explained the results by assuming that the hydrogen nuclei in water molecules are polarised by the combination of co-parallel static and dynamic magnetic fields<sup>(20)</sup>. The biological effect is expected to be dependent on the amplitude of the time-varying magnetic field for a given frequency. In this model, no resonance frequencies occur; however, amplitude windows do occur. Consequently, in principle, all frequencies that occur in the environment up to several hundred hertz can give rise to biological effects. The presence of the earth's magnetic field in parallel to the time-varying magnetic field still needs to be included, but the strength of this static magnetic field is not critical for the predicted biological effect.

Most studies did not intend to clarify how these weak fields can interact with biological molecules; rather, environmental frequencies and unrealistically high amplitudes were used to determine the effect of exposure. A crucial problem that any interaction model must deal with is how a large enough signal-to-noise ratio can be obtained to enable the living cell to detect the signal. For strong signals, the biological effects are well understood due to their thermal effect. For example, strong microwave

radiation heats body tissue, mainly by setting water dipoles into rotation; and strong low-frequency electric or magnetic fields will induce electric currents in the body that can lead to nerve excitation. On the other hand, for extremely weak electromagnetic signals there is no generally accepted theory that can explain all the biological effects reported in the literature<sup>(20,22)</sup>; Halgamuge *et al.*<sup>(23–25)</sup>.

Figures 10–12 compare magnetic field strength of transportation systems (tram, train and hybrid car) with the ICNIRP limit<sup>(26)</sup> and provide some laboratory experimental evidence<sup>(27–30)</sup> for biological effects around these fields. These figures illustrate that the magnetic field strength from tram, train and car are below the ICNIRP limit. However, several experiments demonstrated that the effects of weak magnetic fields on a biological system occur in the same range of the magnetic fields and frequencies radiated by these transportation systems. The magnetic field exposure at the seat level is relevant as ones sensitive organs are at this height and above; however, this is not the case for those recorded at the floor level (foot exposure). The magnetic field strength variation with frequency was measured using an EHP-50 instrument in the frequency range from 5 Hz to 100 kHz. We observed that the frequency of emitted fields varied with the speed of the transportation systems. The magnetic field strength measured from a tram with a frequency of 50 Hz was the maximum (Figure 10). The frequency of the maximum magnetic field strength recorded in a train was in the range of 15.25–16.5 Hz. Also, higher magnetic field strengths were caused by frequencies of 21.25–31.25 Hz, as is shown in Figure 11. Similarly, Figure 12 shows the magnetic field

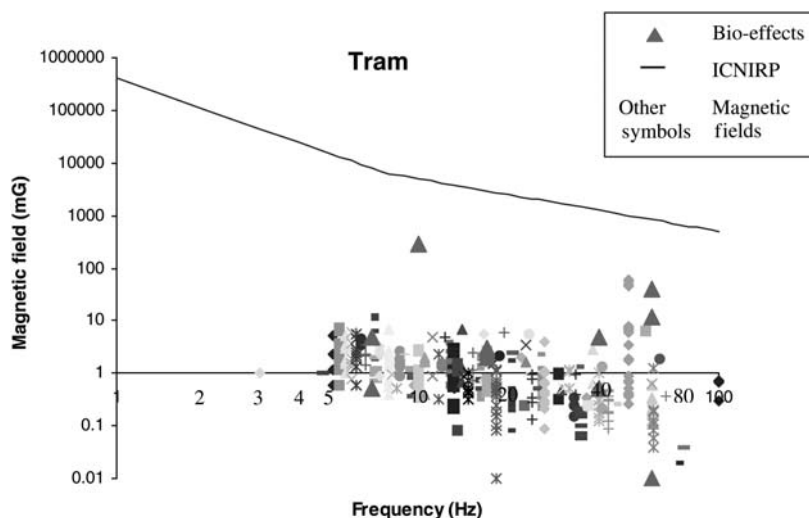


Figure 10. Tram: comparison of magnetic field strength for different frequencies with ICNIRP limit and experimental evidence for biological effects.

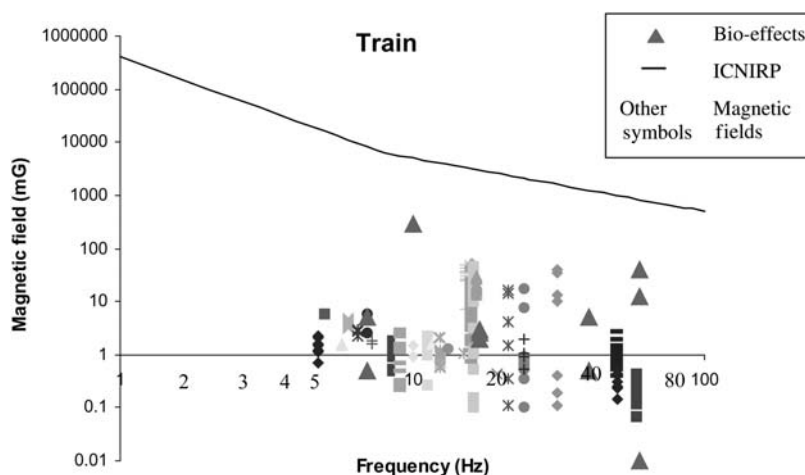


Figure 11. Train: comparison of the magnetic field strength for different frequencies with the ICNIRP limit and experimental evidence for biological effects.

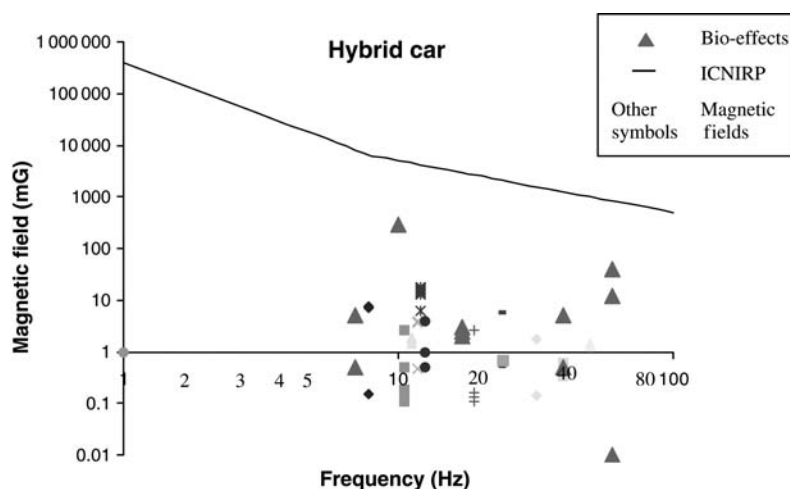


Figure 12. Hybrid car: comparison of the magnetic field strength for different frequencies with the ICNIRP limit and experimental evidence for biological effects.

variation and frequency for a hybrid car. It was observed that the maximum magnetic field strength above 10 mG was radiated at 12 Hz. According to some experiments, as is shown in the figures, biological effects are evident at these frequencies and magnetic field strengths.

## CONCLUSION

Exposure values at the floor level and seat level from the Australian tram and train in urban and suburban areas, and from a hybrid car, were investigated.

The magnetic field strength was measured at different points inside and near the moving train, trams and the hybrid car. The results seem to be compatible with the evidence of the laboratory studies on the biological effects that are found in the literature; nonetheless, the results are far lower than those levels recommended by the ICNIRP. Some further conclusions that can be drawn from this work are: (1) magnetic field strength are higher in the front side (closer to driver's cabin) than the rear side of trams and trains; (2) when several trams or trains passed by, higher peaks in the fields occur; (3) the

frequency and magnetic field strengths vary with speed and these are higher during acceleration; (4) magnetic field strength are higher at the rear side than at the front side of the hybrid car; (5) magnetic field strength are higher at the left side than at the right side of the hybrid car and (6) the maximum levels of recorded magnetic field strength are emitted at 50 Hz in the tram; 15.25–16.50 Hz in the train and 12 Hz in the hybrid car.

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