A STUDY TO ASSESS THE POSSIBLE EFFECTS ON RADIO BASED SERVICES OF ELECTROMAGNETIC EMISSIONS FROM THE PROPOSED INCREASE OF ELECTRICALLY POWERED PUBLIC AND PRIVATE TRANSPORT

Deliverable 5: Final Report

by L.S Blanchard and D. Whitehead

Unpublished Project Report
PR/SE/186/00

TRANSPORT RESEARCH LABORATORY

PROJECT REPORT PR/SE/186/00

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by L. S Blanchard and D. Whitehead (TRL Ltd)

Prepared for:	**Customer:**	**Radiocommunications Agency** **(Dr N Waby)**

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ABSTRACT

This report describes the culmination of a project carried out on behalf of the Radiocommunications Agency to examine the possible impact of the introduction of new electric and hybrid transport technology on the radio frequency spectrum. A review of the current EMC regulations was carried out and recommendations for future changes to the regulations and standards are discussed. Results of electromagnetic emissions measurements carried out on an electric vehicle, a hybrid vehicle, a data bus fitted to a heavy goods vehicle and an electric train are included and possible sources of interference highlighted.

The report also includes a worldwide review of current, near market and future transport technologies, which includes an investigation into the potential effects of these technologies on the radio frequency spectrum.

1. EXECUTIVE SUMMARY

TRL has been awarded a contract by the UK Radiocommunications Agency to examine the possible effects of new transport technology on the radio spectrum. The project includes a review of current and future systems for transport concentrating on electrical and electronic systems. A small number of tests for electromagnetic emissions have been included in the work.

This project contains:

- A review of current and future transport systems technology including some tests for electromagnetic emissions.
- An investigation and assessment of the potential effects of these technologies.
- A review of current regulations.

Since the invention of solid state electronic devices there has been massive growth in their use for a wide range of applications. The transport sector is an area where considerable benefits exist in terms of cost, performance and reliability. As a result, all aspects of transport now contain significant numbers of electronic devices and microprocessor-based control systems. Applications include powertrain control and management, safety systems such as occupant protection devices, comfort systems, law enforcement such as automatic speed control and datacommunications. Vehicle motive power is also developing in terms of electric, hybrid, fuel cell and flywheel systems together with improvements in conventional motive power systems.

These different systems fall into two categories, sources and victims of electromagnetic disturbances. Any electrical or electronic device can generate electromagnetic radiation that may affect other electrical or electronic devices that are sensitive to these sources of energy. It is essential to ensure that these systems are compatible in terms of both emissions and immunity. Regulations currently exist to control the use of these systems. However, as new ever more complex systems are introduced, it is important to ensure that they are suitably controlled to ensure the safety of the general public, other users and services. This report concentrates on the potential effect of this new technology on the radiofrequency spectrum.

Future vehicle systems are likely to use radar, laser or video cameras to enable the vehicle to ‘see’ the road ahead and detect objects. Such systems will be utilised for collision avoidance, lane detection and automatic cruise control. Inter-vehicle communications and the possible use of roadside beacons and satellite systems could potentially cause electromagnetic compatibility problems. The compatibility of these systems needs to be monitored and controlled.

Results from EMC tests carried out on a hybrid vehicle, an electric vehicle, a heavy goods vehicle fitted with a datacommunications ring, and a railway locomotive have revealed emissions from the vehicles which exceed CISPR limits and could effect the radio spectrum. These emissions are likely to have been generated by the electric motors, which will be used in large numbers in future transport technology. The Automotive EMC Directive should however, satisfactorily control these emissions.

In the next few years high power switching circuits will be used on vehicles for motor control. Such systems already exist on railway locomotives. These systems have the potential to generate significant transient disturbances. However, it is possible that special electronic circuit design and wiring loom construction will overcome many of the problems.

The present trend is for systems to use higher frequencies with reduced power levels. It is recommended that the emissions test frequencies are extended to cover new sources but a continuous sweep is unsuitable. Therefore we propose that the Approvals Authority agrees a range of frequencies, these may be spot frequencies or bands, where protection is important. The obvious transmissions being the terrestrial radio and television broadcasts, satellite broadcasts and mobile communications bands. This concept is already proposed in some regulations such as CISPR 26. This approach will target the critical frequencies and will allow testing to be carried out in a reasonable time scale.

2. INTRODUCTION

TRL Ltd has been awarded a contract by the Radiocommunications Agency to carry out a study to assess the possible effects on radio based services of electromagnetic emissions from the proposed increase of electrically powered public and private transport.

The project is divided into the following areas:

1. A review of current and future transport systems technology, to include a programme of practical EMC emission measurements on four candidate systems.
2. An investigation and assessment on the potential effects of the technologies reviewed on the RF spectrum.
3. A review of current regulations, including drafts. This review will highlight potential shortfalls in the regulations.

This is the final report for the programme of work undertaken as part of the project. It details all the work carried out during the project, and gives recommendations for future work.

The report starts with the results of a study of the electromagnetic environment carried out by MIRA and supplemented by TRL. Field strengths measured in the vicinity of fixed broadcast transmitters are discussed along with measurements taken of electrical machinery and powerlines. The three categories of transient disturbances and the importance of the vehicle wiring harness architecture in the reduction of coupled transients are discussed.

A worldwide review of current and future technology has been carried out and an investigation into the possible impact on the radio spectrum of the introduction of such technologies identified. A brief explanation of how each technology works and the possible sources of electromagnetic emissions are given. The implications of the introduction of the identified technologies on the radio spectrum are also discussed.

The results of a small test programme to measure RF emissions are included. These tests where carried out on an electric vehicle, a hybrid vehicle, a data bus system fitted to a heavy goods vehicle and an electric train. An analysis of all the test results including identification of the possible sources of interference are discussed.

Finally a review of the current EMC regulations is carried out. The review included CISPR 12, the American SAE standards, and documents that cover motor vehicle and railway applications. Areas of the current regulations and standards, which do not regulate the previously identified technologies, are identified. Recommendations for extending the frequency range of the tests are made and the current test methods are reviewed.

3. THE ELECTROMAGNETIC ENVIRONMENT.

The electromagnetic environment comprises both intentional sources (for example broadcast transmitters) and unintentional sources (for example electrical machinery) of RF emissions. There are also natural phenomena (for example lightning). Current trends in communications show a move towards using higher frequencies, above 1 GHz, whilst using lower power levels.

Although some of the work on measuring the environment is now over ten years old, it does provide a useful insight into the types of electromagnetic sources found in the UK environment, and some specific work has been carried out by TRL more recently. However, the electromagnetic environment is changing rapidly and there is a clear need to carry out a new programme of measurements to bring this earlier work up to date. In recent years there has been a dramatic rise in the growth of communications, and in particular a considerable increase in the use of digital systems such as satellite communications broadcasting, digital television, digital radio, GSM/DCS systems (Global System for Mobile Communications/Digital Communication Systems) and GPS (Global Positioning System).

Transport systems have a significant electromagnetic environment including continuous emissions and transient disturbances. Systems may contain both a large number of electronic modules and a large number of electrical components. These include components that have a high inductance (power devices), a complex wiring harness and several sources of potential spark generation such as railway power pickups.

The vehicle, be it a car, truck or railway locomotive, will behave as a complex set of interacting antennae comprised of the metallic panels of the body/chassis and the electrical wiring. The complexity of the wiring systems can be imagined when one considers that a mid-range car may have a wiring harness consisting of over 2km of wires. Not only do these metallic elements have the potential to transmit, and for that matter also receive, radiofrequency disturbances of a continuous nature, but they also affect the transient disturbances generated on the vehicle. The main source of transient disturbances are likely to be generated within the system itself and include effects due to switching currents that may be produced by switching loads, relays, power controllers and switch mode power supplies.

3.1 Fixed Broadcast Transmitters

UK broadcast transmitters cover the frequency range 198 kHz to 853.25 MHz. The lowest frequency transmitter, which transmits on "Long Wave", is located at Droitwich and has a power of 500 kW; this gave a field strength of 12.6 V/m on a public road nearby. For the Medium Waveband, there are over 100 transmitting sites within the UK and measurements have been made between 693 kHz and 1458 kHz. The highest field strength measured was 11.1 V/m for a 150 kW transmitter at 1053 kHz; the measurements are reported in the MIRA field strength survey and the site is believed to be Droitwich. At 1053 kHz, the current absorbed on a vehicle harness was found to be less than 0.4 mA/V/m.

Measurements on MW transmitters have also been made by TRL. Field strengths from the Saffron Green 27.5 kW MW transmitter showed values of 1 V/m on the A1 trunk road which passes within 200 m of the site.

Since most of the transmitters will operate at much lower powers than 150 kW, radiated immunity problems due to LW and MW broadcast transmitters are most unlikely to occur.

There will be very little coupling into the vehicle wiring harness at these frequencies as the wavelength of the transmission is much longer than the lengths of cable which make up the harness.

Three high power SW transmitters in the UK - at Skelton (250 kW), Rampisham (500 kW) and Woofferton (300 kW plus 250 kW) were also included in the MIRA survey. Skelton transmits on frequencies between 7.115 and 21.71 MHz and the maximum field strength recorded on a public road was 1.9 V/m at 11.78 MHz and 11.93 MHz. Rampisham transmits on frequencies between 5.97 MHz and 21.695 MHz and the maximum field strength measured on a public road was 35 V/m at 6.12 MHz. Woofferton transmits on frequencies between 5.965 MHz and 27 MHz and the maximum field strength found here was 18.8 V/m at 5.96 MHz.

TRL have also made measurements at Rampisham and obtained 11.6 V/m on the A356 and 12.5 V/m in a nearby lane and observed that there was a slight rise in the field strength when an HGV approached. Field strengths in other nearby locations were less than 2 V/m.

Since the extent of high power SW broadcasting in the UK is declining, the overall field strength levels are likely to decrease.

There are several hundred VHF radio broadcast stations in the UK but most have a power of less than 1 kW. Typical field strengths measured by MIRA were 0.19 V/m at 94.9 MHz (Crystal Palace, 2 kW), 1.3 V/m at 88.3 MHz (Sutton Coldfield, 28 kW) on public roads, 2.3 V/m at 93.7 MHz on a public car park 500 m from the mast (Holme Moss, 250 kW total) and 8 V/m at 88.1 MHz 30 m from the antenna mast (Guildford) on a road labelled 'unsuitable for road vehicles'. Measurements by TRL at Beulah Hill gave similar results to the MIRA data; the measured field strengths were below 2 V/m.

The UHF band which is used for television stations uses frequencies in the range 471.25 MHz to 853.25 MHz. There are several hundred UHF TV stations in the UK and although some have powers of up to 1,000 kW, the vast majority have powers below 1 kW. The field strengths measured by MIRA on public roads are as follows: 1.4 V/m at 543.25 MHz at 2 km from the mast (Crystal Palace), 1.4 V/m at 647.25 MHz in a private car park 200 m from the mast and less than 0.5 V/m on public roads (Sutton Coldfield) and 0.61 V/m at 471.25 MHz on public roads (Sheffield).

TRL have also made measurements at other sites, for example, Membury Service Station (M4 motorway, Wiltshire) and obtained a field strength of 2 V/m from a nearby VHF/UHF relay antennae. A field of 1.7 V/m was measured on the highest flyover of the M25/M4 junction made in moving traffic. Finally, fields at Imperial College, London, were found to be approximately 2.8 mV/m.

3.2 Electrical Machinery

Measurements from electrical machinery were found to be low and unlikely to affect electronic systems fitted to vehicles. Levels were typically no more than about 1 V/m. However, it was found that the emissions from a TIG welder produced an electric field strength of 52 V/m at a range of 3 m with frequencies occurring between 20 and 100 MHz.

3.3 Powerlines

In the UK power line voltages range from 11 kV used for local feeders to 400 kV used for the national "Supergrid" network. There are several intermediate voltages between these levels to enable step down transformers to divide the national levels in stages.

At power frequencies the wavelength of the signal is always much larger than the distance to the equipment within the zone of influence. The electric and magnetic fields are independent and should be treated separately. The electric field is produced by the voltage level in the conductors whilst the magnetic field will depend upon the current flowing in the lines. In general terms, the earth behaves as a good conductor so that the electric field is normally perpendicular to the ground. Any object between the ground and overhead line will cause localised distortion of the field. When dealing with magnetic fields, both the earth and most objects have little effect. The level of the fields also depends upon other factors including the arrangement of the conductors, conductor spacing, conductor height and the relative phasing of the circuit conductors.

For comparison the fields associated with a 240 V, 50 Hz appliance operating in the home would generate about 10-250 V/m at a distance of 30 cm with a magnetic flux density of 0.01-30 μ T. In the UK there is a recommended field strength for people. According to the National Radiological Protection Board there is no difference between recommended levels for exposure to domestic and overhead lines.

Measurements made by MIRA and TRL found that the levels of both electric and magnetic fields were within the recommended limits. The TRL measurements also monitored the level of the disturbance coupled into an electronic anti-lock braking system. The results showed that the levels of disturbance, at the powerline frequency of 50 Hz, coupled were so low as to be beneath the noise level of the measuring equipment and are therefore thought unlikely to pose a threat to vehicle electronic systems. Measurements of radio frequencies generated by powerlines, performed as part of the EMCATT project, were also low, typically no more than about 1 V/m.

3.4 Radar Systems

Radar systems fall into two categories:

1. Airfield and aircraft mounted systems

2. Vehicle mounted systems

Airfield and aircraft mounted radar systems are likely to pose a threat to electronic equipment as they use high power levels. However, modern systems use frequencies above 1 GHz which currently are less likely to cause problems to vehicle electronic systems except when at close range. Peak fields of 54 V/m for an L band system operating at 1-2 GHz and 292 V/m for a C band system operating at 4-8 GHz have been measured. Measurements on public roads near airports have found field strengths of nearly 20 V/m peak at 2.882 GHz and 22.8 V/m at 600 MHz. Whilst these levels are significant they are below the required levels of immunity according to the Automotive EMC Directive which does not require testing above 1 GHz. Early types of UHF radar operating at high power levels (for example 500kW) have been found to generate peak fields up to about 700 V/m.

Vehicle mounted radar systems are now being used on motor vehicles for automatic cruise control and collision detection systems. These systems usually operate in the 24GHz and 77GHz bands. The use of these systems is likely to increase as new vehicles are fitted with this technology. Currently several luxury cars have these devices, for example the Jaguar XK8 automatic cruise control.

3.5 Mobile Transmitters

Mobile transmitters can be considered in the following categories:

(i) Systems for Emergency Service vehicles.

(ii) Private mobile radio (PMR).

(iii) Amateur mobile radio.

(iv) Telephones and datacommunications.

3.5.1 Emergency Services Vehicles

In the past emergency service vehicles have used VHF transmitters in the frequency band 143-174 MHz, with a maximum power of 25 W, for transmission from the vehicle to the base station and 450-470 MHz, with a maximum power of 10 W, for transmitting from a small portable transceiver to the vehicle and vice versa.

MIRA measured the following field strengths around a police car fitted with a transmitter: 3.2 V/m (at 3 m) and 4.6 V/m (at 1 m) in the 143-144 MHz band, 20 V/m (at 3 m) in the 146-148 MHz band and 5.1 V/m (at 3 m) and 7.8 V/m (at 5 m) in the 154-156 MHz band. It should be noted that the field strength values are average values; for amplitude modulated signals the peak values were up to 4.2 dB (1.6 times) higher. All distances were measured from the antenna base.

Most of the problems with Emergency Services transmitters relate to the host vehicle, rather than adjacent vehicles, where field strengths of up to 200 V/m have been measured in the passenger compartment. However, since the power levels do not exceed 25 W it is possible, by careful installation and the use of codes of practice tailored to the specific vehicle in question, to limit the field strengths to acceptable values (Home Office VIDG 5, 1991) and (Home Office VIDG 6, 1991).

Current systems have moved on from the old analogue VHF systems and today there is a mix of communications systems with the inclusion of cellular telephone equipment operating in the 900 MHz and 1.8 GHz bands together with the TETRA systems operating between 410 and 430 MHz. Digital systems are used in each of these bands and some analogue systems are still used in the 900 MHz band. Measurements by TRL have shown that field strengths inside a vehicle fitted with a simulated GSM transmitter operating in the 900 MHz band generated typically less than 10 V/m with a maximum of about 15 V/m.

3.5.2 Private Mobile Radio Systems

These systems are not dissimilar to the systems used by the Emergency Services and the same requirements in terms of installation and operation are recommended. There is now a trend to use the more modern digital systems.

TRL has performed measurements on the field strengths experienced by both a host car fitted with a PMR transmitter and by an adjacent vehicle. At a 0.5 m separation field strengths of up to 20 V/m at 86 MHz, 14 V/m at 172 MHz and 8 V/m at 456 MHz were measured near to a car fitted with a 25 W transmitter and a centre roof mounted antenna. For a 1 m separation, the respective maximum levels were 13, 11 and 7 V/m. For a motorcycle host vehicle and a separation of 0.5 m the corresponding approximate figures were 60 V/m, 40 V/m and 20 V/m.

Fields experienced by the host vehicle were substantially greater. At 85 MHz, a maximum field of 90 V/m was measured in one spot around the driver's door and a field of 50 V/m near the dashboard. Field strength levels at 172 MHz generally showed fewer large peaks, a maximum of 50 V/m was recorded in the vicinity of the dashboard, and at 456 MHz the overall readings were, on the whole, significantly lower. Further measurements made with the sunroof open gave substantially higher fields. As would be expected, measurements made with the presence of a driver inside the vehicle indicated that the driver tended to damp the field and so normal chamber tests with an empty vehicle represent the worst case situation.

3.6 Amateur Radio Users

Amateur radio users are allowed to transmit in a number of frequency bands principally between 1.91 MHz and 434 MHz although other frequencies up to 5.85 GHz are available. Measurements by MIRA have shown that field strengths of up to 56 V/m were produced at a range of 3m from the aerial at a frequency of 3.74 MHz and a power level of 15.1 W. Measurements at a range of 1m were found to be 113 V/m at this frequency, 43 V/m at 1.91 MHz operating at 2.6 W, 71 V/m at 7.04 MHz operating at 15.1 W and 19.8 V/m at 434 MHz operating at 2.5 W.

3.7 Transient Disturbances

System generated transients can be classed in three categories:

(i) Inductive load switching which gives rise to a smooth variation in current but a sharp change in the voltage and thus gives rise to capacitive coupling. Relays, injectors, solenoids and motors fall into this category and so suggest that the culprit line can be protected by shielding and grounding on one end of the shield only. However, shielding in the automotive situation is rarely a practical solution except in extreme cases.

(ii) Capacitive load switching which gives rise to a smooth change in voltage but a fast current transient and thus inductive coupling. Filament lamps are a good example because of the high inrush current. The suggested solution is a series inductance in the culprit line or twisted pair/shielded cable with the shield grounded at both ends for the victim line. Again, there are practical problems with providing twisted pairs/shielding and the insertion of an inductance may cause an unacceptable voltage drop to the lamps involved.

(iii) The third case involves devices with arc discharges such as ignition systems and, more recently, the gas discharge lamp. There is a high voltage gradient before breakdown followed by a high current gradient during the discharge.

High current electrical equipment fitted to the system may also cause considerable interference. Alternators can generate voltage spikes of several hundred volts and electric retarders are also capable of generating transients. The new generation of electric or hybrid vehicles use high current electronic switching devices and motor controls, all of which are capable of producing large conducted transient signals that can be passed into electronic systems via the power supply wiring.

The importance of the harness architecture cannot be overstated particularly in the case of coupled transients. For example, an electrical component (such as the vehicle horn) emitting high levels of transients would not give rise to substantial coupling to the rest of the wiring harness if it were located physically and electrically near to the battery. However, on the other hand, a rear screen wiper may give substantial coupling to the rest of the harness since its power supply runs for the whole vehicle length.

Electrostatic discharges are another form of transient disturbance. The most common source of static electricity is known as contact charging. This occurs when two dissimilar materials are brought into contact and a charge is developed depending upon the electrochemical potentials of the materials. An electrostatic charge can be built up of tens of thousands of volts but the current is low. This type of discharge is likely to have relatively little effect on radiofrequency broadcasts. Lightning is a special case of electrostatic discharge and can develop tens of thousands of volts at very high currents, for example 400,000 A. Such discharges can have devastating effects when a direct strike occurs and will generally create noise on many broadcast transmissions. However, the nature of these disturbances is short and can usually be tolerated unless a direct or close strike occurs.

4. ELECTRIC AND HYBRID-ELECTRIC VEHICLES

The following is a list of EV's (Electric Vehicles) and HEV's (Hybrid-Electric Vehicles) covering the spectrum of private and public transport, along with their introduction dates and brief details of the technology onboard. This is a representative sample of the many examples that are now available.

- Honda Insight (2000). 1 litre 12V, 3 cylinder VTEC-E (electronic variable valve timing and lift control for economy) engine (which has individual ignition coils for each cylinder), coupled with a 10kW brushless motor. The motor provides motor assist, power regeneration, and acts as a high rpm starter. However, if the system battery charge is low, a separate 12V battery and starter motor will start the engine. Ni-MH (Nickel Metal Hydride) battery packs store regenerative power and provide power for motor assistance. These provide 144V at 6.5Ahr (Amp hour).

- Fiat Multipla (2000). Incorporates a 1.6 litre 16V engine coupled with an AC asynchronous 3-phase motor and 216V Ni-MH batteries. Fiat plans this to be used by local authorities.

- Toyota E-com (1999), 19kW permanent magnet motor, 288V/28 Ah Ni-MH batteries. The vehicle incorporates EPAS, and can be charged via an external high-speed 220V/30A inductive system, or from an onboard 110V/15A system.

- Mercedes-Benz Duo-Bus (1996), 50kW asynchronous electric hub drive motors operate at 11,000 rpm, reduced using planetary gears. The power supply is either from a diesel motor generator or automatic current collector on the vehicle roof. The electrical machines, generators and hub motors are slip ring-less AC generators/alternators. The contact line is 600V or 750V DC which is converted into variable frequency 3-phase current in pulse converters using IGBT (Insulated Gate Bipolar Transistor) technology for hub motor speed control. One ECU between each of the 2 pulse converters (used for current conversion) for the 2 motors on a drive axle performs the differential function when the vehicle is cornering.

- Lotus Elise (1997), 2 x 149kW at 20,000 rpm oil cooled permanent magnet brushless DC motors and lead-acid batteries.

- MAN 'ELVO drive' bus (1997), a 162kW diesel engine drives a 150kW/2,400 rpm TFM generator which produces 350V rectified DC. (TFM - transverse flow machine, a synchronous machine powered by a current inverter with a permanently excited rotor). The 350V DC is converted by 2 IGBT inverters into a voltage/frequency controlled AC current that powers 2 x 50kW at 3,580 rpm asynchronous drive motors (max 10,000 rpm).

- Mercedes-Benz/ZF/Kiepe 'EE drive' bus (1996), consists of a 184kW diesel engine and a permanently excited 150kW synchronous generator producing 600V DC, which is converted by 2 IGBT inverters into a voltage/frequency controlled AC that powers 2 75kW wheel hub motors. Alternatively, power can also be drawn from a Zebra battery pack (natrium nickel chloride) providing 567V/68kWh.

- Neoplan/Magnet motors N4121 DES bus (1997), 191kW at 2,300 rpm diesel engine has a direct link to a 150kW at 2,100 rpm oil-cooled permanent-magnet synchronous generator. The rectified AC current is made available to the 4 oil cooled 65kW/2,750 rpm wheel hub motors via IGBT inverters.

- Westinghouse power trains for bus and car EV's (1995). Both systems operate a 3-phase induction motor with a maximum 13,000 rpm. The motors are nominally rated at 50kW (car) and 150kW (bus). The car motor has a single 3-phase winding and is driven by an IGBT controller, whereas the bus version has two 3-phase coils and 2 controllers. The IGBT controllers are of a 3-phase vector PWM control design operating between 150V and 400V. The current rating is 320A (car) and 640A (bus).

- Switched reluctance motor drives (1999) are being demonstrated by a UK company for applications in EV's. Several EV drive systems have been developed including a 30kW SRM drive for a battery or fuel cell EV and a 20kW crankshaft-mounted starter-generator for a parallel hybrid vehicle.

Note: For further details of IGBT inverter technology, refer to section 9: Railway Technology.

5. DRIVE SYSTEMS FOR ELECTRIC VEHICLE APPLICATIONS.

There are many examples of hybrid-electric and pure-electric powered vehicles currently available. Many are in the form of research and development or concept vehicles, but there are a small number becoming commercially available. Much research has been conducted into the EV/HEV concept, and the one thing that is clear upon examining the state of the industry today, is that nobody has yet found an optimum solution.

With HEV's, there are two basic approaches that have been adopted, that of the series HEV and the parallel HEV. Series hybrids are where all the power from an internal combustion engine (ICE) is converted into electrical energy for use by the motor(s) and battery. The parallel hybrids are where the power from an IC engine is coupled both to the vehicle drive wheels and to an electric generator/motor. With this approach the electric propulsion motor also acts as a generator to provide regenerative braking, and to charge the batteries from the ICE when required.

With both series and parallel designs the provision of clutches means that the vehicle may be operated in the pure-electric form (with the ICE shut down) for limited periods.

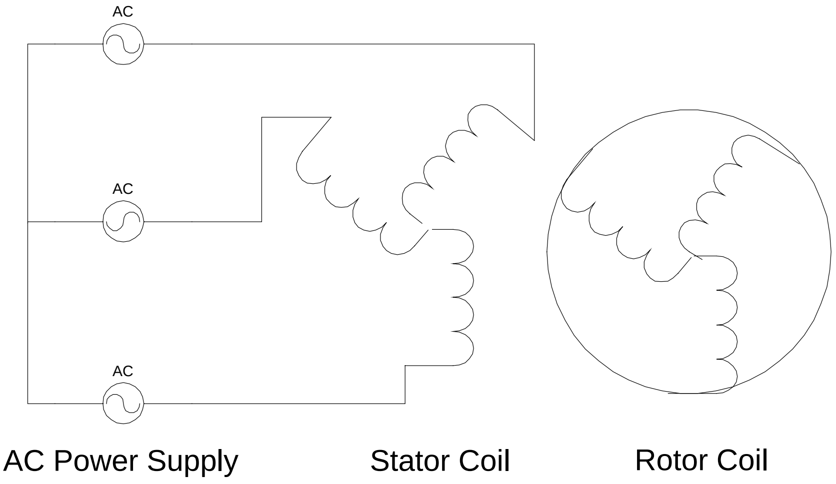
As already explained, there are two main breeds of this type of vehicle, the pure electric (EV) and the hybrid-electric vehicle (HEV). However, the variety of technologies found on different platform vehicles is diverse. In the descriptions that follow, brief technical details of each technology are given along with an indication (where available) of practical applications including dates and time scales.

5.1. AC Induction Motor

The AC induction motor rotates due to the interaction of the magnetic fields in the rotor and stator. The stator windings are connected to a single or three-phase supply, and by applying a voltage across them, a rotating magnetic field is formed. The rotor has layers of conductive strands along its periphery, which are short-circuited to form conductive loops. The rotating magnetic field of the stator induces a current into the conductive loops of the rotor, causing a force to act on the current carrying conductors, which results in a torque. See Figure 1 for a schematic diagram of the AC induction motor.

These motors are simple in construction, as the current in the rotor does not have to be supplied by a commutator (as in the DC motor) and are maintenance free. The absence of brush friction enables higher rates of rotation, hence a higher output. Speed variations of induction motors are achieved by varying the frequency of the applied voltage, through the use of an inverter and other control electronics. The semiconductors used in the inverter will ultimately limit the maximum rotation speed of the motor, however the development of power semiconductors which offer fast switching and low resistance have expanded the applications of this type of motor.

Figure 1. AC Induction Motor

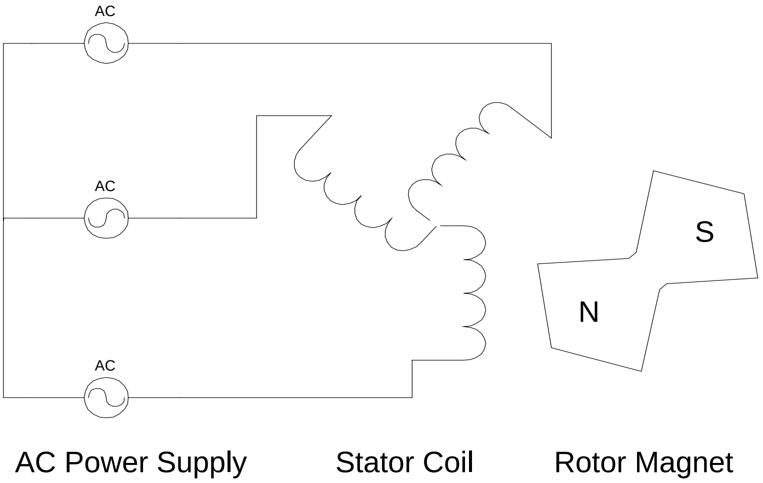


5.2. AC Synchronous Motor (Brushless DC Motor)

This motor has a stator very similar to that of an AC induction motor. The windings are placed in slots throughout the periphery and produce a magnetic field on the permanent magnets of the motor. The quantity of windings and slots are largely determined by the number of phases (usually 3 or 1) and the number of poles (usually 2 or 4). The stator produces a rotating magnetic field that is proportional to the frequency supplied. The rotor turns at the magnetic poles with a motion synchronous to the stator magnetic field. See Figure 2 for a schematic diagram of the AC synchronous motor.

Again, this motor has no brushes to limit rotation speed. Speed variations of these motors are again achieved by varying the frequency of the applied voltage, through the use of an inverter and other control electronics.

Figure 2. AC Permanent Magnet Motor



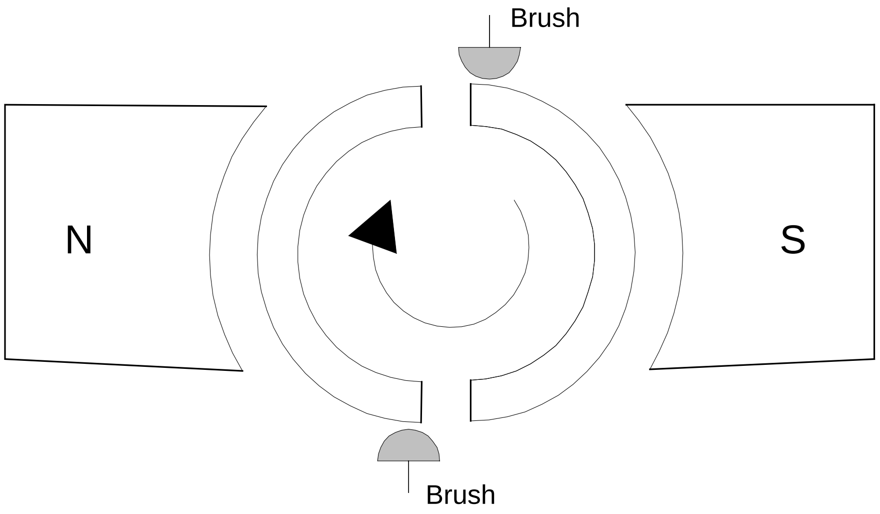
5.3. DC Brushed Motor

The stator of a brushed motor has poles made up of permanent magnets or DC excited magnets, which produce a static magnetic field. The brushed motor with permanent magnets is called the permanent magnet DC motor, and the ones with excited magnets are called series, shunt or compound DC motors depending on how they are configured.

The rotor of a DC brushed motor has current carrying windings. Current is passed to these windings via a commutator and copper brushes. Motion is achieved from the force acting on a current carrying conductor when placed in a magnetic field. See Figure 3 for a schematic diagram of the DC brushed motor.

DC motors can be directly connected to a DC supply, but torque and velocity control is lost. Using PWM, linear or SCR amplifiers for example, can achieve precise control over torque and velocity.

Figure 3. DC Brushed Motor

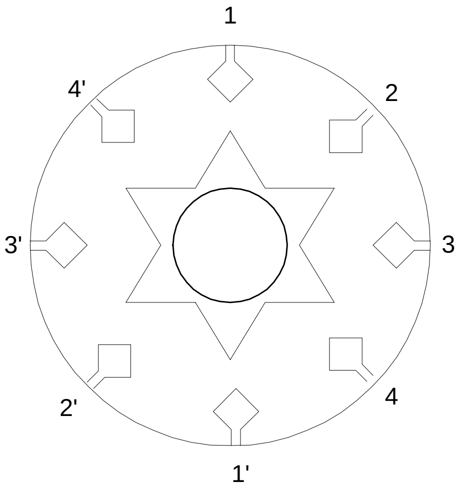


5.4. Switched Reluctance Motor (SRM)

Both the stator and the rotor have protruding poles. Poles 1 and 1' (see Figure 4) are wired in series and energised at the same time. The rotor has no permanent magnets or windings, thus when one of the four phases of the stator is energised, the closest set of poles in the rotor (made up of reluctance magnets) are pulled into alignment. By turning off phase 1 and energising phase 2, the rotor will rotate to align the rotor poles closest to phase 2.

A four-phase converter capable of accepting feedback is used to energise the coils in order to control the SRM.

Figure 4. Switched Reluctance Motor



6. POWER SUPPLIES

6.1. Batteries

Batteries have a large influence in the development of EV's. There are numerous types currently available, or under development. Below is a list currently favoured by most leading EV manufacturers

- Lead-Acid (Solectria)
- Nickel-Cadmium (Citroen, Peugeot and Renault)
- Nickel-Metal Hydride (Toyota)
- Sodium-Nickel Chloride (Mercedes-Benz)

Many companies are also researching into lithium based batteries, particularly lithium-polymer and lithium-ion, as these are seen as the next step in the development of batteries. Table 1 provides a comprehensive summary of the battery types and some key features.

Table 1. A summary of battery types, and some key features.

Battery Type	Energy Density Wh/kg	Power Density W/kg	Operating Temperature (Deg C)	Cycle Life	Commercial Availability
Lead Acid	35-50	150-400	Ambient	500-1000	Now
Advanced Lead Acid	60	200-450	Ambient	2000	Now
Nickel Cadmium	40-60	80-150	Ambient	800	Now
Nickel Metal Hydride	70-95	200-350	Ambient	750-1200+	Now
Nickel Iron	50-60	80-150	Ambient	1500-2000	Now
Nickel Zinc	55-75	170-260	Ambient	300	Now
Sodium Sulphur	150-240	230	350	800+	Now
Sodium Nickel Chloride	90-120	130-160	300	1200+	Now
Iron Air	80-120	90	-	500+	Prototypes
Lithium Ion	80-130	200-300	-	1000+	Now
Lithium-Iron Sulphide	100-130	150-250	450	1000	Prototypes
Lithium Polymer	155	315	120	300	Prototypes
Aluminium Air	200-300	160	Ambient	-	Prototypes
Zinc Air	100-220	30-80	Ambient	600+	Prototypes
Zinc Bromide	70-85	90-110	-	500-2000	Prototypes
Vanadium Redox	20-30	110	75-85	-	Prototypes
Molten Salt	110	125	350	-	Prototypes

Some of the latest batteries are highly complex devices that are hardly recognisable as batteries. For example, some of the more advanced cell systems require auxiliary systems for air circulation and air cleaning, while others need to operate at high pressures.

6.2. Ultracapacitors (Supercapacitors)

Energy storage has always been a problem for EV's, and an even greater problem for HEV's. In a purely electric vehicle, energy is usually stored in batteries, and then used to power the vehicle; once depleted the batteries are recharged. In an HEV, energy is constantly being stored and used, and the repeated charging and discharging puts a tremendous strain on the batteries, reducing their lifetime.

Ultracapacitors that are now becoming available can eliminate many of the battery related problems for HEV's. The electrical energy stored in a ultracapacitor is over 100 times that of conventional capacitors. The surface area of the conducting plates are directly related to the level of charge generated. It is this property that much research is being conducted into, with a view to raising the levels of capacitance. For example, carbon electrodes have been produced with surface areas of 2,000m^2/gram.

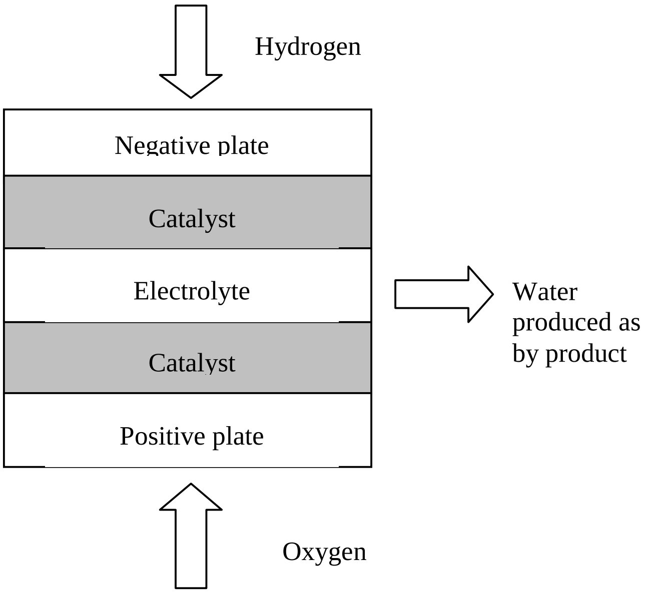
It is predicted that the addition of the ultracapacitor to the EV and HEV will enable batteries to be smaller, more efficient and provide longer-range capabilities. The ultracapacitor will be used to load-level the battery when it is subjected to high-load conditions, i.e. during acceleration. The ultracapacitor could also be used with ICE's to pre-heat the catalytic converter. Its properties also lend itself to regenerative braking.

6.3. Fuel Cells

Fuel cells, unlike conventional batteries, are not energy storage devices and thus require a constant supply of fuel. This in essence makes them an ideal candidate for automotive application, as any fuel cell powered vehicle is limited in range only by its fuel storage capacity.

Unlike an IC engine no combustion takes place in the cell, the electricity is produced by chemical reaction. A cell consists of two electrodes separated by an electrolyte. Hydrogen is fed into the fuel cells negative plate, which splits the hydrogen into a proton and electron. The proton passes threw the electrolyte whilst the electron is redirected and used in the external circuit. The oxygen (usually from air) enters the cell at the positive plate and reacts with the electrons forming water. Figure 5 shows a simple fuel cell.

Figure 5. Simple fuel cell schematic



6.4. Types of Fuel Cell

There are a number of fuel cells, which are under various levels of development. Below is an overview of the main fuel cell types, which could be used to power vehicles.

6.4.1. Solid Polymer

This type of fuel cell uses a solid polymer as its electrolyte, and is the fuel cell, which is currently undergoing the most research and development. Its advantages include a solid electrolyte and high power density at comparatively low temperatures.

Daimler-Benz plans to be the first motor manufacturer to produce a viable fuel cell vehicle, and claims future production of 40,000 engines in 2004.

Other companies investing in this type of fuel cell include, Toyota, Chrysler, Ford, General Motors (who are also promising a vehicle by 2004), Honda, Mazda, Mitsubishi, Peugeot, Renault, and Rover.

6.4.2. Alkaline

Although most of the vehicle manufactures have opted for the solid polymer fuel cell (SPFC) alkaline fuel cells (AFC) are being used in road going vehicles. One such vehicle was introduced in 1998 as a London Taxi. Zevco, a Belgium company that manufacture alkaline fuel cells, produced the vehicle. Mass production of these fuel cell vehicles is, however, still some way off.

6.4.3. Phosphoric Acid

These cells are too large to be used for light motor vehicles, and the electrolyte is extremely corrosive being made of Phosphoric acid. They may, however, be suitable for heavy vehicles. Table 2 lists a few fuel cells and their principle applications.

Table 2. Fuel Cell Applications.

	Electrolyte	**Application**
Alkaline Fuel Cell	Potassium Hydroxide	Transport.
Solid Oxide Fuel Cell	Zirconium and Yttrium Oxides	Power generation.
Proton Exchange Membrane/ Solid Polymer Fuel cell	Poly-Perfluoro Sulfonic Acid	Transport
Direct Methanol Fuel Cell	Poly Perfluoro Sulfonic Acid	Transport

Although fuel cell vehicles currently are little more than show vehicles, industry is striving through research to reduce the size whilst increasing the efficiency of the cells. Toyota is currently working on a hybrid system that uses a fuel cell along with an additional battery to help boost acceleration. The use of such a battery fuel cell combination enables a smaller cell to be used. The vehicle also utilises regenerative braking to extend the vehicles range by effectively topping up the battery charge during braking. Daimler-Benz has developed a bus (Nebus) which is in service in Germany and uses a 250 kW cell. Due to the size of fuel cell require at present a train has not yet been developed. However, Alstom Transport in France have suggested that a Light Rail Vehicle could be a possibility by 2008 (International Rail Journal April 2000). McDermott and BMX Technologies are also working, together with Ballard, to produce a fuel cell which will be able to power an all-electric ship. Siemens in Germany are also developing a cell to power a submarine.

6.4.4. Fuel Cell Summary

Fuel cell packs produce electrical power in a similar way to standard batteries and as such they are unlikely to be a source of electromagnetic interference. However, there is a possibility of emissions from the electronic control systems and electric drive motors. Because of the rarity of fuel cell vehicles one was not available for inspection and measurement. It must be assumed then that the various companies involved in the research and manufacture of such vehicles have taken steps to minimise the electromagnetic emissions in order to comply with European regulations.

6.5. Flywheel Batteries

Research is being undertaken into the feasibility of using flywheels to power an electric vehicle. The flywheel battery is basically a high-speed flywheel supported by low friction magnetic bearings. The flywheel is spun to around 60,000 revolutions per minute in a sealed evacuated chamber. The flywheel is charged or spun using an integral motor generator. Once the unit is charged the motor is used as a generator which supplies electrical power to the vehicles drive motor. During overrun and braking the flywheel is again recharged through the motor generator using regenerative braking. The flywheel battery has the advantage over the electro-chemical battery in that it does not degrade over time due to charging. However, there are safety issues concerning the flywheel and its containment in the event of failure or accident damage.

6.5.1. Flywheel Batteries Summary

Flywheel systems currently under research have a peak power of 40 kW and an energy storage capacity of 300 Whr but are rather bulky weighting 100 kg and being enclosed in a cylinder 0.6 meters long and 0.25 metres round. The electromagnetic emissions from such a system would largely depending on the control system. The use of choppers and power line ripples from regenerative braking could cause some interference.

6.6. Gas Turbine-Electric

6.6.1. Micro Turbine system

The design of the micro turbine is based on a radial gas turbine engine with some internal modifications to reduce emission and increase the efficiency of the engine. The maximum turbine shaft speed is approximately 96,000 rpm. The rotating shaft is couple to the permanent magnet generator which produces variable voltage and variable frequency A.C power which is dependent on engine speed. This is then converted to D.C to charge the vehicle batteries or power the traction motors.

A hybrid shuttle bus fitted with a Capstone 24 kW Micro Turbine system turbine has been in service in the USA since 1997 and has accumulated over 23,000 miles. This system uses two 70 kW motors and a 324V, 192 Ahr PbA battery. The batteries power the drive motors on this particular vehicle with the turbine used to recharge the batteries. Other possible systems could use power straight from the turbine alternator to drive the traction motors threw inverters. Such a system could also use battery power whilst travelling in city centres, shutting the turbine down to reduce emissions and use regenerative braking to extend the vehicles range.

7. CHARGING SYSTEM TECHNOLOGY FOR ELECTRIC VEHICLES

Basically there are two technologies that are being developed for charging electric vehicles, conductive and inductive. Much effort is being devoted to the development of the vehicle systems, and to the infrastructure that will support the mass deployment of electric vehicles, as this practically has to be in place before large volume sales of EV's become a reality. The industry has to solve the two-technology debate in order to standardise on what is the best system for use. A brief summary of the state of development (1998) is given below.

Note: The three charging levels detailed are for North America.

7.1. Inductive

General Motors developed the inductive charging technology for EV's, and have been joined by Toyota and Nissan in adopting this system for their vehicles.

The inductive charging system is based on transformer technology common in the utility industry and other applications where environmental conditions, such as underwater oil well operations, dictate the need for a safe non-metallic power transfer technology.

The basic principle behind inductive charging is that the two halves of the inductive coupler are the primary and secondary coils of a transformer. When the charge coupler (primary) is inserted into the vehicle inlet (secondary), power can be transferred magnetically. With no metal to metal contact, the system is safe to use in all environmental conditions (i.e. rain, sleet and snow). The charger converts 60 Hz utility power to high-frequency AC power (hundreds of kHz). The higher frequency is necessary to reduce the size and mass of the on-vehicle portion of the transformer. See Figure 6 for a diagram of an inductive charging system.

Inductive charging technology is covered in a Society of Automobile Engineering (SAE) recommended practice document. SAE J1773 'Electric Vehicle Inductive Charge Coupling Recommended Practice'. This will greatly aid the standardisation of manufacturers systems.

There are three levels of charging detailed in the SAE document:

- Level 1: This charging method allows an EV to be charged by the most popular grounded receptacle. Level 1 AC supply specification is: 120 VAC Nominal, 60Hz, 15A, single phase.

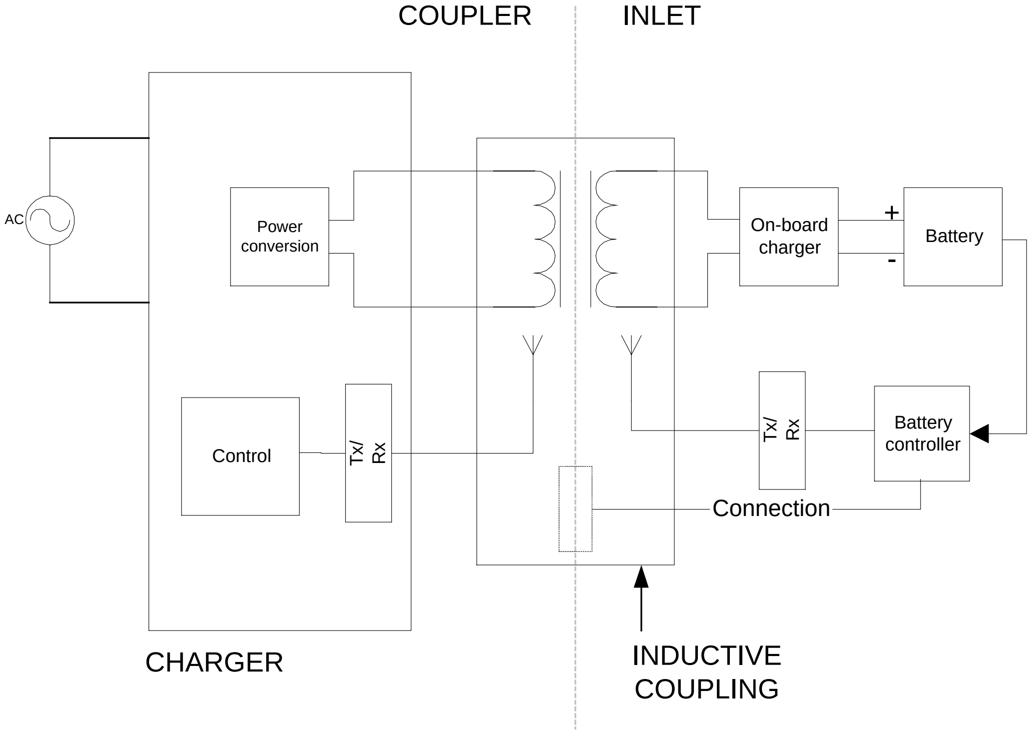
- Level 2: This charging method utilised dedicated charging equipment in both private and public locations. Level 2 AC supply specification is: 208 and 240 VAC nominal, 60Hz, 40A, single phase.

- Level 3: This charging method allows EV's to be charged at commercial "fast-charge" facilities. Level 3 AC supply specification is: 25 kW to 160 kW, 208 to 600 VAC nominal, 60Hz, 3-phase.

The communications between the charger and the vehicle will support SAE J1850 compatible digital communication. The specification for the communication medium is: Frequency: 915MHz ±10MHz, modulation: AM (on/off keying), maximum tx/rx distance: 25mm, transmit power: 1 mW ±0.5 mW, receive sensitivity: -26 dBm ±10 dBm, data rate: 10.4 kbits/sec.

The EMC requirement as stated in 4.3.2 of the SAE document states: 'the EMC requirements of the vehicle inlet under all power levels will meet radiated and conductive requirements of GM9100P and SAE J551'.

Figure 6. Inductive Charging System



7.2. Conductive

Ford, Chrysler and Honda are supporting the conductive charging technology. Conductive charging systems are based on the standard metallic contact plugs found on most home appliances. It is a butt-contact device where two flat metallic surfaces are butted together to complete the power transfer connection. Retractable plastic shields protect the contacts on the off-vehicle conductive charger handle. Figure 7 shows a diagram of a conductive charging system.

Conductive charging technology is covered in a Society of Automobile Engineering (SAE) recommended practice document. SAE J1772 'Electric Vehicle Conductive Charge Coupler Recommended Practice'. This will greatly aid the standardisation of manufacturers systems.

There are three levels of charging detailed in the SAE document:

- Level 1: A charging method that allows an electric vehicle to be connected to the most common grounded receptacle. The vehicle will be fitted with an on-board charger capable of accepting energy from the existing supply network. Level 1 AC supply specification is: 120 VAC nominal, 15A, single phase.

- Level 2: A charging method that utilises dedicated vehicle supply equipment in either private or public locations. The vehicle will be fitted with an on-board charger capable of accepting energy from an electric-vehicle specific AC supply network. Level 2 AC supply specification is: 208 to 240 VAC nominal, 40A, single phase.

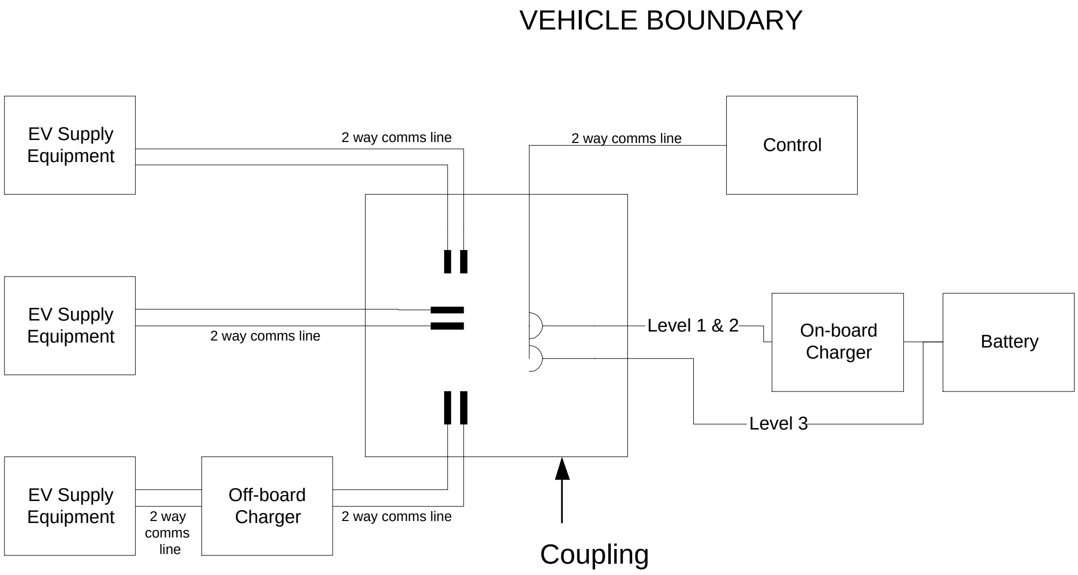
- Level 3: A charging method that utilises dedicated electric vehicle supply equipment to provide DC energy from an appropriate off-board charger to the electric vehicle. The maximum power supplied for level 3 charging equipment should be capable of replenishing more than half of the capacity of an EV battery in as few as 10 minutes. Level 3 AC supply specification is: 600 VDC maximum, 400A.

The coupler must be capable of providing bi-directional serial data communication for the transfer of information between the vehicle and the supply. The serial data communication shall be SAE J1850 type 1 and/or 2 physical layers using the three low-voltage, low-current contacts provided. Serial data communication is not required for level 1 charging, optional for level 2, and mandatory for level 3.

Paragraph 5.1.4 (EMC) of the SAE document states that under current interpretation, electric vehicles and their charging systems are exempt from FCC regulation. CFR 47 part 15.03 provides the admonition "…, it is strongly recommended that the manufacturer of an exempted device endeavour to have the device meet the specific technical standards of this part." It is worth noting that this statement does not appear in SAE J1773.

Paragraph 5.1.4.1 (Electromagnetic Emissions) of the SAE document states that during charging, the system shall meet the requirements specified in SAE J551-5.

Figure 7. Conductive Charging System



8. ELECTRONIC SYSTEMS FOR VEHICLES

8.1. Anti-Lock Brakes.

Current ABS systems employ wheel speed sensors that detect the rate at which the road wheel is decelerating. This information is then processed in an electronic control unit (ECU) which determines if there is a risk of wheel lock. If the wheel is locked or is about to lock, the system reduces the pressure to the locking wheel’s brake to prevent it locking and the resulting loss of vehicle steering and/or directional control. This system is common on most vehicles and is mandatory on HGV's and coaches.

Future systems could also utilise the system to brake the vehicle when a dangerous situation is detected ahead, such as a pedestrian or animal which runs suddenly into the road. Such systems would utilise forward-looking sensors capable of detecting the environment. These sensors could comprise a combination of Infrared and Microwave technologies. The information from the sensor would be sent on a high-speed bus to the control system and together with information from other vehicle mounted sensors would make a judgement on the situation and the best way to activate the brakes.

Such a system could also be used to control the braking force if, for instance, the sensor in front of the vehicle detected an object and the driver was not applying the brake sufficiently to stop before impacting with the object. The system could also be used to hold the brakes on if a pedestrian is crossing close to the front of a stationary HGV in traffic and the driver attempts to pull away without noticing their presence. This would require sensors to detected and differentiate humans from inanimate objects and would probably result in a system that detects the environment around the entire circumference of the vehicle.

Since the ABS system is a safety critical system it comprises built in redundancy and watchdog circuits to increase the units reliability and to act as a self-monitoring system. The ECU operates on the vehicle voltage and has a voltage stabiliser to smooth the power supply. This unit is also used to shut the system down in the event of a supply voltage being above or below the tolerance limits. The signals from the wheel sensors are AC waveforms that increase in frequency with speed. These signals are in the region of 100mV. The output voltages to the actuators are more typically system voltage.

8.2. Traction Control.

Current traction control systems monitor wheel spin by comparing the speed of individual road wheels. This information is taken from the same wheel speed sensors that are used by the ABS system. The system uses either one or a combination of a reduction of engine power and the application of the spinning wheel’s brake to increase the vehicle’s traction. Most modern systems are linked with the vehicles anti-lock brake system utilising the wheel speed sensors to detect wheel spin and the ABS pump and valves to apply the brake of the spinning wheel. The fuel injectors are prevented from injecting fuel and thus producing an engine misfire achieving the reduction in engine power. Some vehicles also include a system that has no direct mechanical link between the accelerator pedal and the throttle valve on a spark ignition engine or control lever on a diesel engine which are operated using an ECU controlled electric motor. This then allows the engine power to be controlled by the traction control unit ECU which can close the throttle or control lever appropriately and thus reduce engine power.

The ECU's of such systems are similar in design as those used in ABS systems employing redundancy and watchdog circuits to increase system reliability.

Future applications could utilise a forward-looking sensor of the type previously described to detect a bend or hazard in the road. The system would then reduce the engine power or apply the brakes to slow the vehicle if the driver did not take appropriate action. Sensors in the vehicle, such as yaw sensors and accelerometers, could also be used to predict a roll over situation and reduce the engine power or brake the vehicle to a safe speed. This would be of great benefit to HGV drivers. The vehicle's speed could also be reduced if the driver negotiated a bend at a speed deemed by the system to be dangerous. For instance, a stationary car encountered mid-way around the bend or the vehicle was about to slide on a change of road surface detected by the sensors.

8.3. Cruise Control/Speed Limiters.

Current systems allow the driver to select a speed that is then maintained. Road speed is sensed using road speed sensors i.e. speedometer pulse or the ABS sensors, the cruise control ECU then monitors the speed adjusting the throttle automatically to maintain that speed. Automatic system deactivation is provided as soon as any input from the driver via brake or system controls is detected.

There are also current systems that can maintain a constant distance to an object in front of the vehicle. These use sensors fitted to the front of the vehicle such as a laser or radar device. The driver can, with this type of system, select a distance from the car in front that he or she wants to maintain. The system then calculates the distance (beam time of flight) from the vehicle in front by use of information supplied by the forward-looking sensor. The vehicles speed is then increased or reduced with reference to the speed of the vehicle being followed using the throttle or brakes.

Other applications could include intelligent systems. Such systems could adjust the vehicle speed to suit the road conditions, reducing the vehicle speed in adverse road surface or environmental conditions. This type of system would greatly increase vehicle occupant, pedestrian and other road user safety. Linking the system with Global positioning systems (GPS) or roadside transponders could prevent the driver from exceeding the speed limit set for that road. Research is currently looking into the feasibility of such intelligent speed limiting systems.

8.4. Supplementary Restraint Systems

Current systems use sensors that detect the vehicle crashing during the first stages of the impact. The system uses accelerometers, usually two at the front of the vehicle and one in the central area to sense the rate of vehicle de-acceleration. Information from these sensors is then passed to an ECU, which calculates whether the vehicle is crashing. If the ECU detects a crash it fires pyrotechnic devices which in turn inflate air bags and pre-tension seat belts. For safety a signal representing an impact must be received from each sensor before the airbags are deployed.

Research is currently looking at the possibility of using sensor systems that detect an impact prior to it happening. These sensors will be able to detect whether the vehicle is about to impact with an object such as a car, a large object such as a tree or HGV, or whether the object is a pedestrian. Such sensors would also allow more time to set up the safety systems. In the case of a pedestrian or other unprotected road user, the deployment of airbags fitted to the front of the vehicle would reduce the risk of serious injury. Figure 8 shows an actual test carried out a TRL. Internal sensors could detect the height, weight, position, and possibly the sex and age of the vehicle occupants and set up the restraint systems to best suit the person. The airbags in such systems could have dual pyrotechnic charges of different sizes, to give three deployment rates, using either one or both charges. The driver and passengers' seat could be moved back, to reduce the risk of being impaled on the steering column, or injuries sustained by objects intruding into the passenger compartment. Sensors could detect the position of the occupants to see if the deployment of air bags would be dangerous and prevent the deployment. Such a situation would be if the driver were very close to the steering wheel. Air bags could also be switched off if a child was sitting in the front passenger seat and could be injured by the deploying airbag.

Figure 8. Actual test undertaken by TRL Ltd showing external pedestrian protection device concepts.

8.5. Steering.

Current systems use hydraulics, pneumatics or electric motors to reduce the effort needed by the driver to turn the steering wheel. In the case of hydraulics or pneumatics initial movement of the steering opens valves that operate rams assisting the driver to move the steering. Electrical systems use electronic sensors to detect the driver’s inputs and electric motors to assist the movement of the steering. Electronic steering is commonly fitted to vehicles used by disabled people where the steering is controlled by a joystick. Because of the better driver feed-back from the system and the reduction in size of the electronic systems, more manufacturers are fitting this type of system.

Adwest have a second-generation system that utilises Surface Acoustic Wave (SAW) sensors to measure steering torque. These sensors are based on a sliver of piezo-electric quartz, which produce a frequency in the region of 200MHz depending on the torque.

All of these systems are steering assist systems and do not remove the mechanical link between the steering wheel and the steering actuator system, i.e. steering rack or steering box.

Future systems could form part of a collision avoidance system to perform evasive manoeuvres to avoid road accidents, and could also be used as part of a robotic driver system. The removal of the steering column and replacing it with an electronic steer-by-wire system would remove the risk to the driver of being impaled on the steering column during an impact. Such a system would remove any mechanical link between the steering wheel and the steering actuator, and an ECU would monitor steering input and control electric motors which would then move the steering. This system could allow the steering device to be an integral part of the driver’s seat and the seat could be moved away from the dashboard (under the control of an active safety system) reducing the risk of injury to the driver in the event of a frontal impact.

8.6. Drive Train.

The modern motor vehicles engine incorporates management systems to increase fuel efficiency and reduce emissions. These engines are dynamically controlled by an ECU that has a full dynamic map of engine parameters stored into its memory. Signals are received from various sensors in and around the engine enabling the system to monitor the load requirements to provide the maximum performance and fuel economy, and lowest possible exhaust emissions. Such closed loop systems perform these calculations many times a second.

Electronically controlled gearboxes and four wheel drive systems are also becoming more commonly used. These work together with the engine systems to give optimum performance. The gear changes are matched more precisely to the engine load and speed, and road speed is also taken into account. Intelligent four-wheel drive systems can vary the torque transmitted to individual wheels, to enhance handling and off road performance.

Future systems could be coupled into a robotic driver system, utilising the engine and gearbox control units to achieve a reduction in emissions and fuel consumption. There is also the possibility of placing a control unit along with the sensors and actuators at each wheel, these would be integrated using a high-speed bus system.

8.6.1. Electronic Stability Control (ESC)

These are systems that are an extension of the ABS and traction control (TC) systems that provide enhanced control of the lateral dynamics of vehicles. Information on the drivers intended course is measured using various sensors. This information is then used by the system to estimate the available coefficient of friction.

The following are used to detect the vehicles’ stability: steering angle sensor, vehicle speed sensor, and lateral acceleration. Signals from these sensors are used to calculate whether the vehicle is nearing or has exceeded its dynamic threshold. If this is the case the system intervenes by the application of the vehicle brakes in an attempt to regain stability. A single wheel can be braked to apply a yaw moment in the opposite direction as the vehicle yaw in order to retain the vehicle on its intended course.

8.7. Active Suspension

Current systems monitor vehicle ride height and re-adjusts it using a pump to increase pressure in suspension dampers, or airsprings. The height of the vehicle is monitored using sensors and adjustment is made by the ECU. The driver can also make adjustments to the suspension characteristics. Settings such as increasing the ride height on off road vehicles increasing the distance between the vehicle underside and the ground when driving over rough terrain. Making the suspension stiffer reduces body roll improving the vehicles handling. Softening the suspension gives the occupants a more comfortable ride. The damping rate can also be electronically adjusted to best match the suspension deflection and the undulations of the road surface and thus tuning the suspension for increased vehicle handling and stability.

One system proposes the use of magneto-rehological (MR) fluid based actuators and associated sensor and control technologies to improve the ride and handling qualities of a vehicle. The principle behind this technology is that an applied magnetic field causes a change in the yield stress of the MR fluid. By designing shock absorbers and suspension struts to accommodate this technology, semi-active control of a vehicle suspension system has been achieved. Magnetic coil powers of 20W have been quoted. There are other systems that use electro-rehological (ER) fluid based actuators that work on a similar principle. These systems lend themselves to integration with ESC (Electronic Stability Control), ABS (Anti-Lock Brakes), and TC (Traction Control) systems.

Future suspension systems could include forward-looking sensors, which could detect the road ahead and adjust the suspension according to the road conditions. For example, the suspension could be stiffened just before the entrance to a bend to give good performance threw the bend, and softened after exit to increase comfort to the occupants. Furthermore, vehicles could be made to "lean" into corners to improve comfort and handling. The suspension could also be automatically lowered when travelling at speed to reduce aerodynamic drag and improve fuel consumption.

8.8. Bluetooth

The Bluetooth standard was initially conceived by Nokia, Ericsson, IBM, Intel and Toshiba as a means of interconnecting a number of consumer devices using a low-cost and low-power radio network, enabling these devices to be synchronised conveniently and removing the need for interconnecting wires.

The wireless link uses the Industrial Scientific and Medical (ISM) band at 2.45 GHz, which enables products to be exempt from individual licensing requirements, but will still require certification to meet FCC Part 15 regulations and the Radio and Telecommunication Terminal equipment (RTTE) directive in Europe.

Bluetooth uses a frequency-hopping scheme (1600 hops per second) over a width of 80 MHz in the majority of countries, however in France and Spain this has been restricted to

22 MHz due to existing frequency allocations. Output powers range from 1mW (0dBm) to 100mW (+20dBm).

8.9. Keyless Entry/Passive Start And Entry Systems (PASE)

The upcoming transponder generation offers special diagnosis functions enabling authorised groups to gain information about the history of the immobiliser system when reading secret information in the key. In addition, special integrated circuits will offer additional functions such as keyless entry. The logical development of these types of systems in the automotive security and RFID (Radio Frequency Identification Device) technology has lead to multi-antenna structures enclosed in a battery buffered identification device (e.g. keyfob, credit card etc).

These new systems will continue to use a regular RF transmitter with buttons on it, and still have an RF receiver inside the vehicle. However, in addition the vehicle will have 125kHz LF (Low Frequency) antennas installed (inside and out), which together with an LF receiver in the key will add a new link to the existing RF one. This new RF link will replace the need to operate a key button to send a coded RF signal to the vehicle, and will instead be used to request this signal when necessary (lock, unlock, start). To trigger this RF code request, switches or sensors at the door handle and inside the vehicle are used.

8.10. Smart Card Systems

The use of smart cards is increasingly becoming more popular, although their use has been somewhat limited to the high street bank or mobile phone. Smart cards could, in the future, be used to relay occupant information to the vehicle. Relevant information such as gender, weight, height and age could be stored on the card and transmitted to the vehicle as the occupant entered. The vehicle would sense where the occupant was sitting and tune the active safety systems in that region for that particular person. A person’s name, address and medical details could also be stored on the card, and in the event of an accident these details could be transmitted to the emergency services giving them valuable information about the occupants as they travel to the accident site.

8.11. Transponder/GPS Systems

Transponders and global positioning systems (GPS) are widely used in the aviation and marine industry, and only recently has global positioning systems been fitted to vehicles at the higher end of the market.

As yet transponders have not been fitted to vehicles. Transponders transmit and receive information using radio frequencies. A great deal of information about the vehicle that they are fitted to could be transmitted to other vehicles in the vicinity also fitted with the system. Such information could include the type of vehicle, the weight of the vehicle, the vehicle’s speed, and in the case of a HGV the type of load carried. If the system was linked into a GPS system additional information could also be transmitted such as closing speed, bearing, range, and the estimated time to impact. On receiving this information the other vehicle would transmit similar information and the vehicles active safety systems would be set up accordingly.

8.12. Lane Guidance

Research into the guidance of vehicles is underway in Japan. The system uses a low frequency transmitter imbedded in the road surface at approximately 5 metre intervals and two vehicle-mounted receivers. The road transmitter was chosen for its ability to penetrate snow-covered roads and thus after researching different technologies an electromagnetic wave type was chosen. The receivers are mounted one each side of the front of the vehicle and measure the difference in signal strength between sensors, thus detecting vehicle deviation from the lane centre. The emission field of the transmitter has been measured as being dome shaped with a height of 40 centimetres and diameter of 20 centimetres. It is also proposed that the transmitter could transmit extra information about the traffic or road conditions ahead and could also be used as danger signals and route guides.

The use of electromagnetic fields in the above mentioned transmitters could possibly cause problems with electronic systems currently fitted to vehicles. Any interference with such systems could potentially be hazardous if the brake or steering systems are effected. The potential for disruption of the magnetic field around the transmitter by metallic objects is also a source of possible problems. Such disruption of the field could cause the vehicle to deviate from the intended course.

8.13. Electronic Braking Systems

The first generation electronic braking system is already available on production vehicles, and is essentially electronic brake actuation which consists of an electronic brake-circuit pressure sensor and ECU interface. This system then retains the hydraulic braking system familiar on modern vehicles.

In an emergency braking situation, the driver presses the brake pedal hard trying to stop as quickly as possible, which results in a sharp increase of brake pressure that the ECU recognises as an emergency. Should the driver then ease the pressure enough for the ABS system to stop cycling, the ECU restores full braking force.

The next step for the technology is brake-by-wire, utilising and electronic pedal force transmitter/feedback device integrated with an ECU. The braking force is likely to be supplied by an electric motor driving the friction-pad clamping device via gears and clutches etc to provide a fast and electronically controlled response.

The EBS can be interfaced via a communications bus (e.g. CAN) to other vehicle systems, and in particular applications for HGV's are already being tested. These include the integration of the engine management system, a transmission-gear ratio selection and clutch operation controller, an electronic controller of the auxiliary braking provided by a vehicle retarder (a useful feature on long descents), an effective compressed air supply management system for both tractor and trailer braking systems, the dynamic vehicle stability controller (which helps to eliminate jack-knifing), and the air suspension management system. Adaptive cruise control can also be incorporated.

8.14. Vehicle Battery Powerline Communication

Battery powerline communication (PLC) would be of great advantage to the automotive industry, as the wiring harness is already the second heaviest component after the engine and anything that can be done to reduce this weight is received with interest. The main idea behind PLC is that every electronic system requires power, and if there is the ability for it to pass data down the powerline, an extra communication bus is not required, thus saving weight.

The vehicle powerline is often very noisy, and of low impedance that changes every time a load is switched in or out. Only with recent semiconductor developments has it been possible to implement digital communications in such a hostile environment.

A variety of systems are in the research and development stage, and one such system is proposing the use of multiple carrier frequencies, and matching frequencies to applications. For example low frequency (1K-1KBPS) for mechatronics, medium speed (10K-1MBPS) for telematics and high-speed (1-100MBPS) for mutimedia.

Fundamentally, the system modulates the power line with the low-level data signals, and incorporates a high-level of error correction. Little more information was available at the time of writing.

Many of these are very similar to the J1850 and CAN bus that is mentioned, and many directly integrate to the J1850 and CAN bus architecture, therefore a brief description of the J1850 bus is given below.

The system described in the SAE standard details a Class-B data communications network interface. Class-B data communications is described as: A system whereby data (e.g. parametric data values) is transferred between nodes to eliminate redundant sensors and other system elements. The nodes in this form of a multiplex system typically already existed as stand-alone modules in a conventionally wired vehicle.

There are two implementations detailed that use 10.4 KBPS, and the other 41.6 KBPS. The first type incorporates Variable Pulse-Width Modulation (VPW); the second incorporates Pulse-Width Modulation (PWM) bit encoding.

The first implementation utilises a single wire medium, whilst the second utilises a parallel wire pair, or a twisted pair medium.

There is a full set of EMC requirements described in SAE J1850, paragraph 8.10; therefore it is unlikely that if these are adhered to, this type of system will cause any EMC problems.

8.15. 42 Volt Vehicle Electrical Architecture

The drive to equip vehicles with a 42V system to replace the existing 12V system is embedded in improved efficiency (a potential 20% reduction in average energy consumption), improved reliability of electric over belt driven devices (for example), and as an enabler for new features.

The new 42V systems will gradually appear on vehicles from 2002 onwards, with increasing market uptake by 2004. They will first emerge as dual 42V/12V mixed architecture making the slow transition to a pure 42V system. Below is a summary of some advantages of employing a 42V system.

- Engine Start: This is likely to remain via an electromagnetic motor, and could be optimised via 42V technology to reduce starting time from over 1second of the 12V system, to below 0.5seconds resulting in lower pollution and better fuel economy.

- Electrical Energy Generation: Currently proposed systems include having a 14V and a 42V alternator, a single 42V alternator and generating 14V via DC-DC converters, and a dual wound 14V/42V alternator. There is also the possibility of employing an integrated starter-alternator (ISA, or starternator), which could be directly mounted on the crankshaft and will improve starting time, thus making automatic engine start/stop in traffic (for example) a possibility. This ISA can also electronically provide engine damping, thus removing the need for a crankshaft flywheel.

- Lighting: Producing 42V filament lamps is difficult as they are longer and thinner than their 12V counterparts, hence two options are proposed keeping the existing 12V lamps. The first is to run the lighting system from a DC-DC converter, whilst the second (cheaper) option involves using pulsed control of the 42V rail (one system proposed utilises 8.3ms slow rise-time PWM). The use of LED, high intensity discharge (HID) and neon technology have also been proposed.

- Small Motors: Rewinding small motors for 42V applications will increase their size and cost, also arcing and brush wear become issues. Research is being conducted currently on this problem, and one approach involves the PWM of the power rail as discussed for lighting.

Other systems become possible with a 42V vehicle electrical architecture because the available power from the current 12V systems has reached its maximum. Such systems offer reduced on-engine loading by the removal of engine driven belt devices, potential weight savings, and improved reliability and ease of servicing.

Heating systems are likely to be one of the first beneficiaries of a 42V system, as these can be made to react faster by operating at a higher current, or made with thinner wire (embedded window heaters).

A further advantage of 42V systems is the ability to operate at the same power level for a lower current, an example (for heating systems) is a 300W heated rear window. Using 12V it draws 25A, while using 42V it draws just 8A.

Some other systems that become a reality with the move to 42V are listed below:

- Electric air conditioning compressor
- Electric and electro-hydraulic brakes
- Electromechanical valve train (electronic power valve system)
- Electric water pump
- Electric oil pump
- More efficient electric power steering
- Electrically heated catalytic converter
- Passenger compartment electrical heating system
- More efficient electric starting

8.16. Terrestrial Trunked Radio (TETRA).

Terrestrial Trunked Radio (TETRA) is the modern digital Private Mobile Radio (PRM) and Public Access Mobile Radio (PAMR) technology for police, ambulance and fire services, security services, utilities, military, public access, fleet management, transport services, closed user groups, factory site services, mining, etc.

With support of the European Commission and the ETSI members, the TETRA standard has been developed over a number of years by the co-operation of manufacturers, users, operators and other experts, with emphasis on ensuring the standard will support the needs of emergency services throughout Europe and beyond. The standard builds upon the lessons and techniques of previous analogue trunked radio systems and the successful development of GSM during the 1980s. The work started in 1990 and the first standards were ready in 1995.

TETRA offers fast call set-up time, addressing the critical needs of many user segments, excellent group communication support, Direct mode operation between radios, packet data and circuit data transfer services, frequency economy and excellent security features. TETRA uses Time Division Multiple Access (TDMA) technology with 4 user channels on one radio carrier and 25 kHz spacing between carriers. This makes it inherently efficient in the way that it uses the frequency spectrum. For emergency systems in Europe the frequency bands 380-383 MHz and 390-393 MHz have been allocated for use by a single harmonised digital land mobile systems. Additionally, whole or appropriate parts of the bands 383-395 MHz and 393-395 MHz can be utilised should the bandwidth be required.

For civil systems in Europe the frequency bands 385-389,9 MHz and 395-397,9 MHz, 410-420 MHz and 420-430 MHz, 450-460 MHz and 460-470 MHz, 870-876 MHz and 915-921 MHz have been allocated for TETRA.

TETRA trunking facility provides a pooling of all radio channels that are then allocated on demand to individual users, in both voice and data modes. By the provision of national networks, country-wide roaming can be supported, the user being in constant seamless communications with his colleagues. TETRA supports point-to-point, and point-to-multipoint communications both by the use of the TETRA infrastructure and by the use of Direct Mode without infrastructure.

8.17. GSM and DCS Systems

Digital modulation in communication systems can offer many advantages over analogue systems. One of the primary benefits is the increase in capacity that can be gained by sending the data in a digital format. Further benefits come in the form of security and encryption, ISDN interconnection possibility, reduced fraud (common on analogue systems) and the implementation of a Pan-European System.

The two common systems that have emerged are GSM 900 (Global System for Mobile Communications), and more recently DCS 1800 (Digital Cellular System). DCS is a direct ascendant from GSM, and offers direct integration into this system (as seen in dual-band digital mobile phones). They will be familiar to everybody in the form of the mobile-phone communications media, but other applications are being found as well, such as TETRA and the roadside beacon infrastructure (to include a road-traffic advisor and remote speed control).

Table 3 describes and compares the main technical points of both GSM 900 and DCS 1800.

Table 3. A summary of the GSM 900 and DCS 1800 systems.

	GSM 900	DCS 1800
Geography	Europe	Europe
In-Service Date	1991	1992-1993
Frequency Range	935-960 MHz 890-915 MHz	1.7-1.9 GHz
Data Structure	TDMA	TDMA
Channels per Frequency	8-16	8-16
Modulation	0.3 GMSK	0.3 GMSK
Speech Codec	REL-LTP 13 kBits/sec	REL-LTP 13 kBits/sec
Mobile Output Power	3.7mW to 20W	250mW to 2W
System Spectrum Allocation	50 MHz	75 MHz
Modulation Data Rate	270.833 kBits	270.833 kBits
Channel Spacing	200 kHz	200 kHz
Number of Channels	124 frequency channels with 8 timeslots per channel (1000)	3000-6000

9. RAILWAY TECHNOLOGY

Due to the extended service life of trains and the small market in terms of turn over of vehicles, the industry has been slow to introduce new technology. This is apparent, but to a lesser extent, in the heavy goods and passenger carriage market sectors, which also have, relative to the car and light commercial vehicle market, a slow turn over of vehicles and small market share. This can be seen in the amount of investment in new electronic technology that is clearly biased toward the car industry with the heavy commercial and train markets benefiting from little investment in new research and technology.

9.1. Current Technology on British Electrically Powered Trains

The following is a list of technology currently employed on British mainline stock. The latest Class 357 (Electrostar) that is currently being introduced is also included.

- 25kV 50Hz AC supply, via mainline overhead cables and pantograph pickup
- 750V DC third rail supply

(Some trains are dual-voltage i.e. the Class 319)

- DC Motors (see section 5)
- 3-phase asynchronous AC motors (see section 5)

- Camshaft Resistance Control, a method of controlling the DC motor by varying the voltage and current thorough it. This is achieved by progressively switching different resistors in or out of the motor circuit by the use of a profiled camshaft to switch the resistors in the correct sequence

- Transformers are used to reduce the 25kV AC to a working voltage for the locomotive or multiple electrical unit.

- Tap Changer, a device fitted to early AC stock to select appropriate taps on the transformer winding in order to provide a range of voltages for AC motor control.

- Fixed output transformer, is a recent device with a fixed output voltage, voltage control achieved electronically.

- GTO (Gate Turn Off) inverter, a circuit that uses GTO thyristors (a thyristor that can be switched off as well as on) to turn DC into AC for motor speed control. As the speed of the motor is determined by the frequency of AC supplied, the inverter output frequency needs to vary over a wide range (typically 0 - 200 Hz). Consequently the inverter design incorporates complex switching strategies where the frequency is changed in stages as the train speeds up ("electronic gears").

- GTO Force Commutated Bridges are fitted to ensure that there is no lag between the voltage and current supplied. In a force commutated bridge, the GTO thyristors have both switch-on and switch-off controlled via a pulse width modulated switching pattern, to ensure current is brought into phase with voltage. This can result in lower electricity consumption.

- Chopper, a device to provide variable DC voltage from the DC supply to eliminate the need for resistance control of DC motors. It works by switching the input voltage on and off i.e. PWM - the longer the mark-space ratio, the higher the output voltage. Choppers are usually operated at fixed frequency (300Hz in the UK).

- IGBT (Insulated Gate Bipolar Transistor) is the latest generation of power semiconductor, and these devices can be switched much faster than their GTO predecessors (up to 2kHz). The higher switching rate eliminates the "gears" in inverter circuits and simplifies control electronics. These are employed in the force commutated bridge and inverter circuits of the Class 332 Heathrow Express units, the Class 357 (Electrostar) and the Class 334 units.

- Rheostatic braking is employed to dissipate energy generated by the motors (that can be made to act as generators under braking) in a brake resistor. This method gives long-term savings in brake pad wear.

- Regenerative braking is used to return energy to the supply system during braking. On the AC powered units, regen-braking has only recently become possible with the advent of force commutated bridges. The basics of regen-braking involve turning the motors into generators when they are not required to provide forward motion, and instead use the forward motion to generate electricity.

It is also worth mentioning that the French TGV trains run from a dual ±25kV system (50kV peak), and that future expansion of the Channel Tunnel system could mean that

French trains will be running on the British railway system and visa-versa using dual standard systems.

One problem has already been highlighted (and solved) with the French system in a location where the main A1 Autoroute runs close to the rail system, and failures in electronic equipment had been linked to electromagnetic emissions from the rail network.

The problem was overcome by load-sharing between the two pantographs fitted to the train (prior to this, only one was normally used).

The details are contained in the EMCATT Report, Section 4/6 "Electromagnetic Disturbances due to Electric Railways and Power Lines", Sept 1995. (Simmons, Nano and Demoulin).

9.2. Magnetically Levitated Trains (MAGLEV)

Since the early 1970’s research into magnetically levitated trains has been undertaken by a number of different countries, most noticeably Germany and Japan. In the past few years such technology has become a real commercial viability, with slow speed trains used at Birmingham airport.

Maglev trains are levitated, guided and propelled using electro-magnetic force. The propulsion system is basically a synchronous long stator drive, with the stator positioned along the guideway, or track, and the secondary element being the train itself. Two sets of three-phase stator packs, are usually mounted one each side of the guideway. These packs are supplied with alternating current from variable frequency inverters, which sets up a travelling magnetic wave along the length of the guideway. The superconductor magnets fitted to the train react with this magnetic wave and propel the train, with the frequency fed to the stator pack controlling the speed of the vehicle along the guideway. To enable multiple trains to run on the same track with small headway’s the guideway is separated into lengths from 360 to 3,000 metres allowing different frequencies on separate sections of the guideway.

Separate mounted coils along the sides of the guideway handle levitation and guidance of the train. When the vehicle passes over these coils an electromagnetic force is produce by induction that levitates the vehicle, this induction also supplies the vehicle with power without the need for contacts. The coils are also utilised for guidance; each being electrically connected providing an electromagnetic guidance force that increases in strength with vehicle speed.

Problems with high magnet fields in the interior of earlier Japanese trains required that the magnets be moved to the ends of the carriage, where previously they had been fitted along the entire length. The magnet fields within the passenger compartments of the train was believed to be strong enough to interfere with heart pacemakers and wipe magnetic strips on credit cards.

Measurements on the magnetic field around the guideway, carried out at the Japanese National Railways test track at Yamanashi, found that at ground level under a section of track elevated to eight metres a reading of 0.5 gauss was obtained.

9.2.1. Maglev Summary

It can be assumed that the use of high powered synchronous long stator drives and the associated magnet fields which surrounds them, that there will be electromagnet emissions to some degree with this type of transport system. These emissions are more significant with the varying frequencies on the different sections of track. On the German system the stator packs are positioned at 0.238 metre intervals, which gives a switching frequency of 466.8 Hz at a train speed of 400 km/h, and 583.6 Hz at 500 km/h. The Japanese system uses a 1.35 metre pitch for its stator packs which would give 82.3 Hz at 400 km/h and 102.9 Hz at 500 km/h.

10. IMPLICATIONS

Research by TRL and others has shown that motor vehicles respond as broad band receivers up to about 400 MHz but above this frequency behave as 'lossy' systems. It is likely that the converse will also apply and they will behave as poor transmitters above about 400 MHz. However, we need to be aware of the electronic systems operating on the vehicles and the frequencies and powers associated with them. In theory any oscillating signal can generate an electromagnetic field. However the majority of current and future electronic control systems will be of low power so that potential electromagnetic emissions from these types of device are likely to be low. The problems are likely to come from high power switching circuits and high power data communications. Digital systems with their fast edge signals need to be particularly addressed as these types of waveform are likely to penetrate electronic circuits in a similar way that transient disturbances can affect their operation. In these cases the fast rising edged signals can often break through filter circuits causing potential failures and false outputs. These effects can be minimised by good electronic circuit design.

Similar arguments can be applied to other forms of transport, for example railways. However, in this case high power switching systems and drive motors are common place. In addition the railway network includes the power distribution and signalling infrastructure which is another potential source of emissions.

The radio spectrum for the UK is changing and currently the main broadcast transmissions are 88 MHz -107MHz for FM radio, 150 kHz – 260 kHz for AM radio, 470 MHz – 854 MHz for terrestrial television, the 900 MHz and 1.8 GHz bands for mobile telephones, the 11 GHz band for satellite broadcasts and the TETRA network between 410 MHz and 430 MHz. In addition there are a wide range of low power systems used for a variety of purposes including paging systems, car alarms and amateur radio. In the future the current trend to use digital systems at high frequencies, greater than 1 GHz, and low powers, less than 5 W, will continue. This is likely to result in fewer problems of electromagnetic compatibility between systems. It is planned to terminate the current analogue UHF television service within a few years, which will free up the UHF band for other purposes. Digital services have now been proven and provide significant improvements in both sound and visual performance.

These changes should benefit the vehicle designer but it is important to consider the potential effects of new vehicle systems on the radio spectrum to ensure that transmissions are unaffected by the new designs. In the future inter-vehicle and roadside communications will grow considerably. Systems for remote vehicle speed control and automatic road tolling will utilise roadside beacons, cellular radio and satellite links; prototype automatic tolling systems have been demonstrated at TRL using a frequency of 5.8 GHz.

A large number of new electronic systems for vehicles will emerge over the next few years. These will include improved designs of current systems such as ABS and engine management as well as advanced active safety systems such as collision avoidance. The following sections describe some of the most important systems and their potential sources of electromagnetic disturbances.

10.1. Power Supplies

10.1.1. Fuel Cells

Most of the world's leading vehicle manufacturers are developing fuel cell powered vehicles. It is believed that this technology will ultimately become the major motive power for passenger cars.

The following list gives the major components likely to generate electromagnetic disturbances:

- Control system microprocessor
- Pressure control valves
- Chopper voltage regulation
- Induction from high currents

It is unlikely that the microprocessor control systems will generate significant electromagnetic disturbances to affect the radio spectrum but as clock frequencies increase, then potential signals that could resonate with RF transmissions should be avoided. The main problem with these systems is likely to be generated by the high power switching circuits likely to be found in the voltage regulation and output control circuits. It is essential that these signals are adequately suppressed as part of the electronic design.

10.1.2. Flywheel Batteries

Flywheel batteries have been demonstrated by several manufacturers and some prototype vehicles have already been tested. However, it is believed that fuel cells will be preferred as they have fewer technical difficulties to overcome; in particular, the high speed rotational; forces of the flywheels needed to generate the current. As with fuel cells, the main potential problems for electromagnetic compatibility are likely to come from high power switching circuits. In addition, the use of AC alternators will potentially generate large electromagnetic fields unless adequately screened.

The following list summarises the major sources of potential electromagnetic disturbances:

- AC ripple from the generator
- Recharge emissions from motors during regenerative braking
- Switching transients from change-over relays
- Voltage regulators
- Induction from high currents

10.1.3. Multi-rail Systems

Over the next few years vehicle power supplies will develop using multi-rail systems. The current 12 volt systems for passenger cars and light vehicles and 24 volt systems for heavy commercial vehicles will be supplemented by a 42 volt rail. This is intended to allow lower currents whilst maintaining and increasing power levels. Subsystems may also require different voltage levels, for example gas discharge headlamps that need 90 volts to energise the lamps. These additional power rails will require changes in alternator design and the use of appropriate converters to generate the necessary voltages.
The following list shows some of the important sources of electromagnetic disturbances:

- Relay switching transients
- DC-DC converters
- Switching transients between 12/42V
- Emissions from high-output alternators
- PWM control of light circuit
- Induced voltages from wiring
- Increased number of electric pumps and motors (EPAS, water, oil, air conditioning etc)

10.1.4. Gas Turbines

Gas turbines are unlikely to find their way into the smaller road vehicles where other technologies are more practical. However, they offer potential advantages for larger vehicles and railway traction. The major factors relating to electromagnetic compatibility arise from high current generators and high power electrical switching circuits.

The following list the major potential sources:

- AC ripple from generator
- Fuel pump
- ECU module
- Rectifiers
- Switching transients from change-over relays

10.1.5. Charging Systems

Charging systems fall into two categories:

- Inductive
- Direct connection

Both systems use an electronic charge controller, which, if correctly designed, should not generate significant levels of RF emissions. However, the frequency and power levels used for inductive coupling need to be chosen carefully so as not to affect the RF spectrum. Tests of the emissions of such an inductive charging system showed significant levels in the RF emissions as described below.

10.2. Data Communications

10.2.1. Data Communication Systems

The next few years will see dramatic changes in mobile communications systems for transport. Improvements in safety will involve data requirements from radio or satellite sources for a variety of applications:

- Railway signalling
- Railway train location and control
- Road transport safety systems such as rollover control and collision avoidance
- Remote speed limit enforcement
- Automatic road tolling
- Remote vehicle weighing and monitoring
- Route guidance

Most of these systems will use digital systems operating in the UHF bands and at higher frequencies above 1 GHz, but using relatively low power levels, typically below 5 W and often less than 1 W in some applications.

The main factors likely to influence electromagnetic compatibility include:

- ECU clock speed
- Fast rise times of digital waveforms
- Noise on powerline (powerline communication systems)

10.2.2. Smart Cards

Smart cards are likely to be introduced for a wide range of applications including ignition keys, load identification and driver recognition. It is unlikely that these systems will generate significant electromagnetic disturbances. The most likely source of emissions will come from the data transfer where data rates and voltage levels will need to be controlled. However, good electronic and system design should reduce disturbances to insignificant levels

10.2.3. Mobile Radio

Mobile radio systems fitted to vehicles are changing rapidly. Systems have moved away from the medium power, 20-25 Watt systems that have been used by the emergency services and private mobile radio users to new equipment using lower powers, less than 10 Watts, and operating in the UHF band and above.

These systems have now progressed from the original analogue designs to sophisticated digital systems. For example GSM (Global System for Mobile communications) which operates in the 900 MHz band and DCS (Digital Communications System) which operates at 1.8 GHz. Vehicle mounted systems operate at up to 22 Watts for GSM and 4 Watts for DCS. The actual power level depends upon the propagation conditions and is adjusted automatically by the equipment. The Trans European Trunked Radio system (TETRA) is the agreed standard for a new generation of digital land mobile communications, which operates between 410 MHz and 430 MHz in the UK.

The requirements of the Automotive EMC Directive combined with guidelines for the installation and operation of mobile transmitters, agreed jointly by the DETR and the Radiocommunications Agency, should ensure the safe operation of these systems in vehicles.

10.3. Active Safety Systems

10.3.1. Anti-lock Braking Systems and Traction Control

These systems have been available on road vehicles for many years and have undergone a process of continuous development. The latest systems are highly effective and include complex algorithms capable of responding to a range of driving conditions. In practice there have been few problems of electromagnetic compatibility and the behaviour of the systems is well understood.

Potentially the sources of electromagnetic disturbances will be generated by:

- AC from wheel sensors (very low level)
- ECU clock
- Pressure pump
- Modulator valves
- Relays

In practice, as is the case with many electronic systems, it is the high power elements of the circuit where the problems are most likely to occur. However, there is no evidence of problems with these systems affecting the radio spectrum.

10.3.2. Collision Avoidance and Vehicle Guidance

There has been much research in recent years on collision avoidance and vehicle guidance systems. In the next few years these systems will be introduced into motor vehicles. Demonstration vehicles have been produced by most of the world's major vehicle manufacturers. The systems proposed use the three following technologies to provide data on the vehicle position:

- Radar
- Laser
- Video camera

In addition it will be necessary in some cases for communication with roadside beacons, satellites and other vehicles to provide information for the on-vehicle system.

All of these systems will make use of digital communications, which will require appropriate design so as not to affect the RF spectrum. Whilst the radar systems proposed will utilise the 24 GHz and 77 GHz bands which should be significantly higher than broadcast transmissions. These intentional radio systems will be controlled by radio regulations. In practice it is believed that the modest powers of the systems used and low power electronics will not pose a significant threat. There are already passenger cars available with radar systems to measure the headway for automatic cruise control: Jaguar and Mercedes Benz are examples.

10.3.3. Powertrain Control

As with ABS and traction control, electronic engine management and transmission control are well known technologies and are found in large numbers of road vehicles. In practice there has been little evidence of problems affecting the radio spectrum

10.4. Body Systems

Body systems include a number of applications including:

- Active Suspension
- Climate control
- Seat position
- Mirror position
- Automatic windscreen wiping
- Automatic headlamp illumination
- Automatic dipping of the rear view mirrors
- Wiring looms

In each of these except for wiring looms the potential sources of electromagnetic disturbances are:

- Modulator valves
- Pump
- Motors
- Relays

As with most of the other systems described so far the major problems of electromagnetic compatibility are likely to arise from high power switching circuits, electrically operated control valves and electric motors. The electrical performance of these devices is well understood and it is unlikely that significant electromagnetic compatibility problems will occur.

In the case of wiring looms a different situation is present. The wiring loom itself can act as a transmitting antenna capable of tuning to a particular wavelength. For motor vehicles and railway locomotives the wavelengths are such that there should be few problems at frequencies above about 400 MHz. At lower frequencies careful system design should provide adequate protection. Wiring looms will become much simpler in the future with the development of multiplexed wiring systems using only a few cables. These systems will require complex data transmission over the vehicle bus with appropriate transmitter and receiver nodes at each junction. Such systems are already used in some high end vehicles using a system know as CAN , computer area network, which has similarities to datacommunication rings found in computer installations. The signals transmitted on these data buses will comprise complex digital signals to ensure data integrity.

The use of multiplexed ring wiring systems may cause generation of electromagnetic disturbances but the levels are likely to be low in terms of affecting other electronic control systems. However they may affect radio receivers, particularly if fitted to the same vehicle. In practice multiplexed wiring systems need to be implemented using either ‘twisted pair’ cable or screened cable which should not only reduce the level of radiated emissions but also improve the immunity to external sources. The routing of the cable around the vehicle is also important to ensure correct operation.

10.5. Motive Power

The most significant factors affecting the electromagnetic compatibility of motive power systems are given below:

10.5.1. AC Motors

These motors are excited by pure sine waves, and as they contain slightly non-linear magnetic circuits they emit harmonics of their driving frequency. Also, "cogging" frequencies will be evident which are related to the number of poles and the rotational speed of the motor. All of these are low frequencies, and are usually only a problem when motor loading is a significant proportion of the supply capacity.

10.5.2. DC Commutator Motors

These are excited by a pure DC voltage, and produce sparks around their commutators caused by the rotor winding fields collapsing as they become disconnected in-turn. These sparks emit broadband frequencies from the commutator switching frequency to well over 1 GHz.

10.5.3. Switched Reluctance Motors

The AC drive waveform will be the main emission frequency.

10.5.4. Adjustable Speed DC and AC ("Inverter") Drives and Stepper Motors

These are all naturally electrically "noisy" due to the high-power rapidly changing waveforms they use. These type of drives can have significant emissions up to 1,000 times their internal switching rate, which is usually 20 to 100 kHz, resulting in emission frequencies extending up as far as 100 MHz in some cases. DC drives and stepper motors are not usually as bad due to their (generally) lower switching rates of about 50 Hz to 5 kHz.

Larger power drives tend to use higher-power semiconductors, which tend to switch more slowly, hence the upper frequency at which switching harmonics cause significant emissions is also lower. All motors and their cables also emit electromagnetic fields relating to their excitation voltages and currents.

10.6. Railways

Electromagnetic disturbances generated by trains depend upon several factors, the type of locomotive, its speed, the type of power supply system, the operating voltage and the distance from the track and catenary. Railway systems also include a complex infra structure of power distribution and signalling. EMC requirements for railways are now covered by appropriate regulations to limit emissions, based upon CISPR recommended limits, and provide a minimum level of immunity.

The main factors affecting railway locomotives are:

- Pantograph
- Motors
- Camshaft resistance control
- Transformers
- GTO Thyristors
- Choppers
- IGBT controlled systems
- Rheostatic braking
- Regenerative braking

The major problems are likely to occur from the high power motor drives and switching circuits. Current UK electric locomotives operate either on a 600 V DC rail or 25 kV AC system. These systems are well understood and potential electromagnetic compatibility problems should be under control.

A special branch of locomotive operates using magnetic levitation. These systems have been demonstrated all over the world but only a few systems have actually been built. The main factors affecting the electromagnetic compatibility include:

- Emissions from the levitation magnets
- Variable supply frequencies to drive the system
- Generators
- Power pickup from induction

11. EMISSIONS TESTS

11.1. Test Procedure.

All tests apart from those conducted on the train were carried out in accordance with the Automotive EMC Directive 95/54/EC. The site used was a 30-metre radius clear, flat area of the TRL test track free from electromagnetic reflecting surfaces. The antennae were positioned in the centre of this circle with the measuring equipment 10 metres away. Figure 9 shows a plan of the test site.

Measurements of peak level were undertaken, as this is the best method to characterise the types of signal likely to cause problems to - and be emitted from - the sensitive electronic systems being reviewed in this report. Other methods such as quasi-peak effectively serve to filter the signals, thus making detection of fast rise-time digital signals or transients difficult.

A background measurement was taken before each vehicle was tested in both horizontal and vertical polarisations. The vehicle was then moved into the test area at a distance of 10 metres and a full spectrum measurement between 20 Hz and 18 GHz was made.

Each vehicle was operational during the tests, this involved the hybrid's engine being run at a constant 1500 rpm in accordance with the Directive, and the ignition switch being fully over on the electric vehicle throughout the tests to ensure all auxiliary and control systems were running. Emissions measurements were also carried out with the electric vehicle on its battery charging cycle. The HGV's engine and auxiliary systems were turned off for the test, as the contribution to the electromagnetic emissions from the data bus alone was required.

The HGV was measured at a 10m and 3m distance from the antennae. The 10m distance providing good low-reflection performance from the test vehicle, but also lower signal-to-noise ratio of any measurement. The 3m distance however, provided a good signal-to-noise ratio, but was subjected to potential reflections from the test vehicle.

The type of tests conducted on the multiple electrical unit were not covered by any standard, however, as far as practically possible the tests were carried out using established methodology to ensure reliable results. The tests on the train were conducted using a spectrum analyser covering from 10 kHz to 1 GHz. The antennas for the tests were elevated to half the carriage height, and all tests were repeated 3 times in both polarisations. Figure 10 shows the position of the antennas in the carriage.

Measurements in both vertical and horizontal polarisations were carried out in the driving carriage and the pantograph carriage. In the pantograph carriage, the antennae were approximately 1 metre away from the pantograph access panel. The antennae location was the same in each carriage, and the local layout was the same, the only difference being at the far end of the carriage (where there was a toilet and space for luggage in the pantograph carriage, as opposed to seating in the driving carriage).

The tests were conducted at night (0030-0300 hrs) along a return journey from the Soho Depot (West Bromwich) to Rugby station, via Stafford station. As it was dark, no comments can be made about the location of any of the tests, except that the train was moving at the time.

A further in-carriage mobile-phone test was carried out over a narrower frequency band (500MHz - 1GHz). This test involved a phone-call being placed between two mobile phones situated 5m from the antennae, for both horizontal and vertical polarisations (of the measuring antennae, the mobile phone antennae were orientated as they would be in use).

Due to the ever-changing background in a moving train and the large amount of activity and high voltage power lines in the depot, a background measurement would have been of limited value, so one was not carried out.

The data from the measurements was downloaded to laptop computers for later analysis, one computer being used for each test receiver. The weather was dry and sunny for the daytime tests, and dry and clear for the night train test with no precipitation during or before any test. All data was printed out in the form of graphs and are included in Annex B.

Figure 9. Plan view of test site

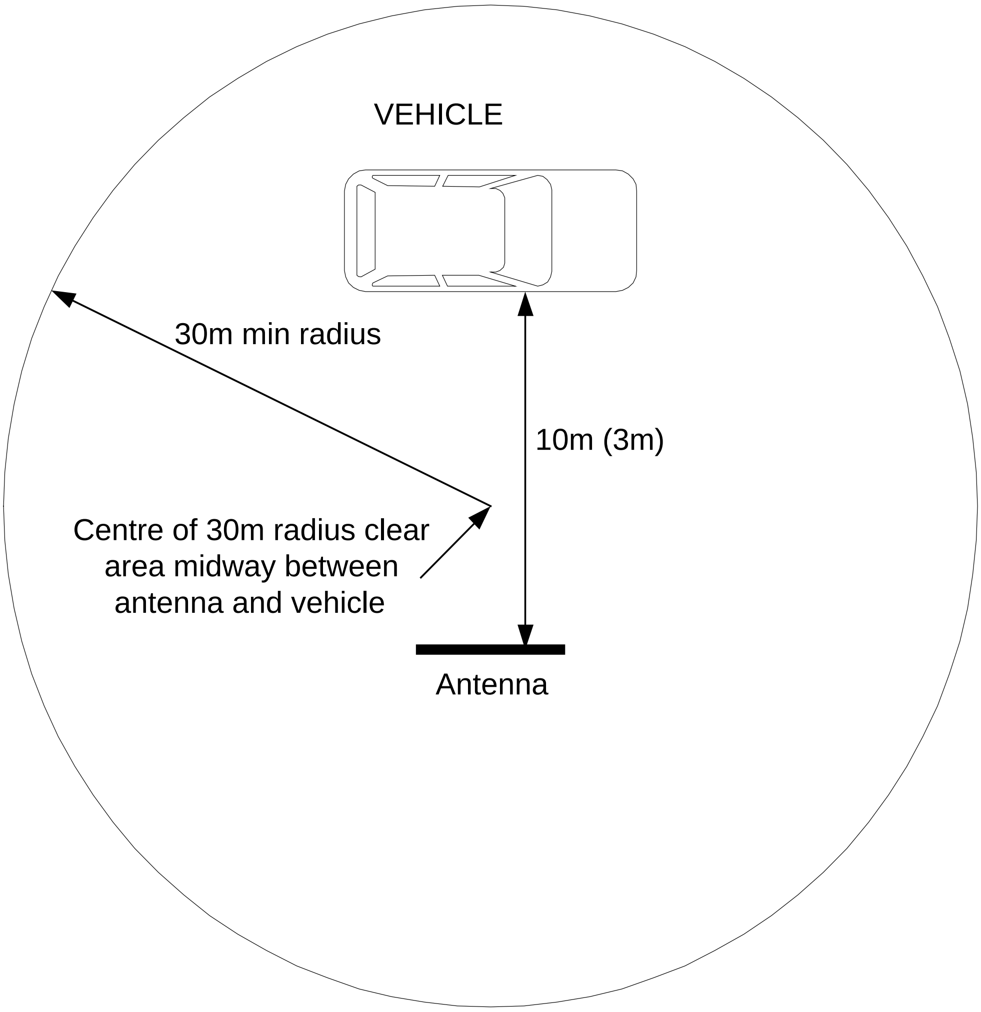
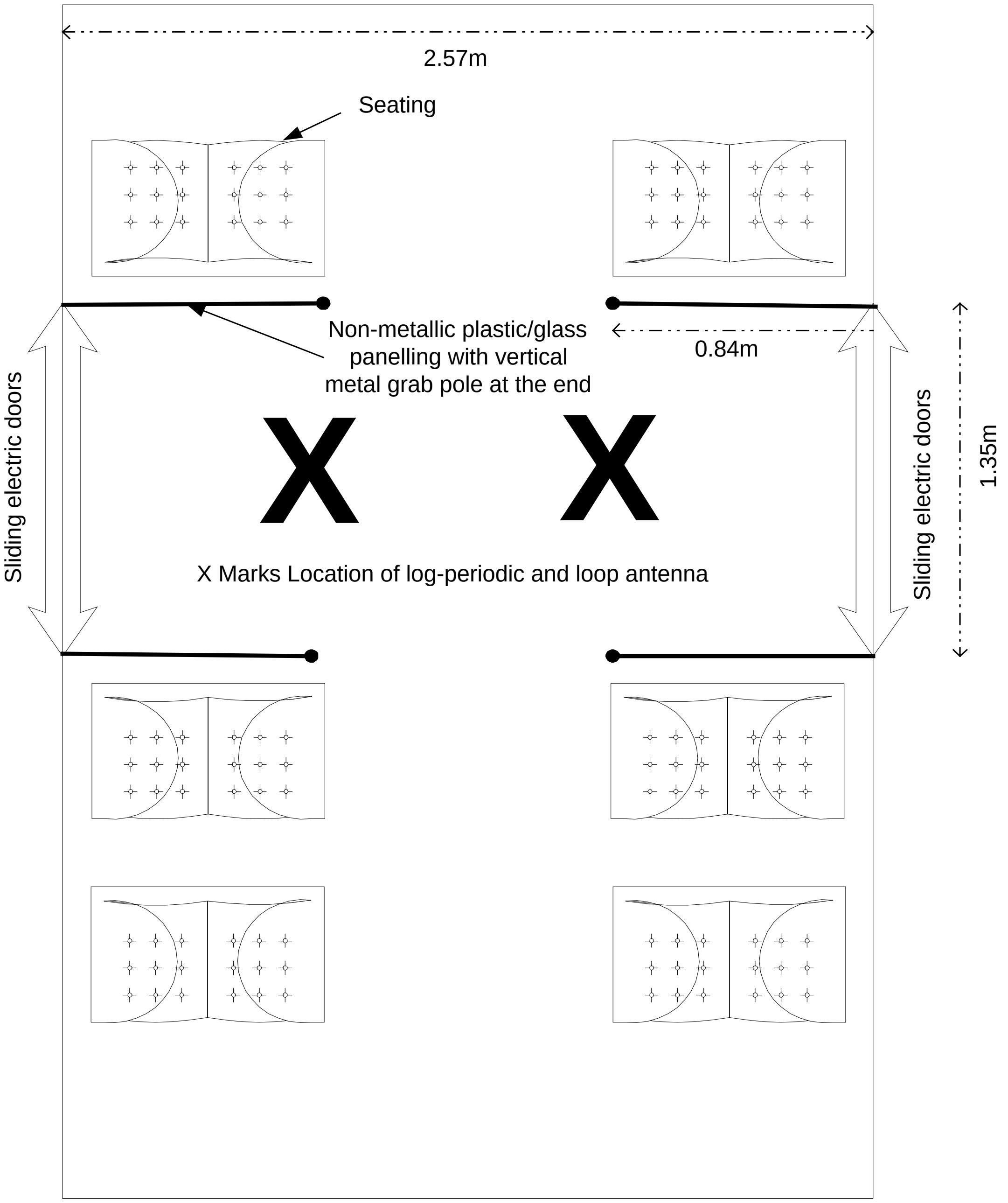


Figure 10. Plan view of a section of the carriage showing the antennae positions



Further key dimensions/details for the train carriage were:

- Total carriage length 22.27m
- The carriage was 2.25m high
- There was a double parallel row of fluorescent strip lights running down the centre of the ceiling
- There were a total of 20 rows of double or triple width seating, giving a total of 98 seats in the carriage.

11.2. Test Equipment.

The testing was split into two sections. Both of the cars and the HGV were tested at TRL using the equipment listed at Annex A.1. For portability reasons, a different set of measuring equipment was used for the train testing, which is listed at Annex A.2. The equipment was all fully calibrated and traceable to national standards.

11.3. Vehicle Measurements Analysis Of Test Results

The full set of test results appear in annex B. The graphs that are presented here represent only those that warranted further investigation. Table 4 also provides a summary of the findings, and clearly indicates the measurement results that exceeded the CISPR limits. Both table 4 and the CISPR limits are presented after the results for the electric train.

11.3.1. Annotations That Appear on the Data Graphs

- (H) = Horizontal polarisation
- (V) = Vertical polarisation
- Where no polarisation is indicated, the measurement was conducted using a loop antenna
- Background (1) = The background electromagnetic spectrum measured prior to the test
- Background (2) = The background electromagnetic spectrum measured after to the test
- Test (1, 2, 3 …) = On the train, a number of repeats of the same test was carried out as there were many influences and variations observed during the journey.

11.3.2. Description of Data Graph Features

Many of the main features to be seen on the graphs are from the various allocated bands of the radio spectrum. A few of the major ones are listed here:

- 87.5 to 108 MHz FM Radio Broadcasting
- 117.975 to 137 MHz Aeronautical ("Air Band")
- 144 to 146 MHz Amateur Radio Band
- 217.5 to 230 MHz Digital Audio Broadcasting
- 230 to 280 Military Air Band
- 450 to 470 MHz Emergency Services
- 470 to 590 MHz TV Broadcasting Band IV
- 598 to 854 MHz TV Broadcasting Band V
- 890 to 915 MHz GSM (Mobile Phones)
- 935 to 960 MHz GSM (Mobile Phones)

11.3.2.1. Electric Vehicle Measurement Results

The graph at Figure 11 shows a broad band vertically polarised emission with a peak level of 36 dBuV/m between 55 and 70 MHz. The emissions were measured whilst the vehicle was being charged and are within the CISPR broadband emissions level between 62 MHz and 67 MHz. Defined as being 54 dBuV/m for this frequency range.

Figures 12 and 13, also measured whilst the vehicle was charging, show broad band emissions between 420 and 430 MHz with a peak level of 62 dBuV/m in vertical polarisation and 66 dBuV/m in horizontal polarisation. The CISPR limit in this frequency range is 65 dBuV/m. These emissions are in the frequency region which are allocated to TETRA and private business radio (PBR). Such radio systems are used in supermarkets, which are likely candidates for the installation of electric vehicle charging units, in their existing fuel stations.

Figure 11. Electric Vehicle Charging (V)

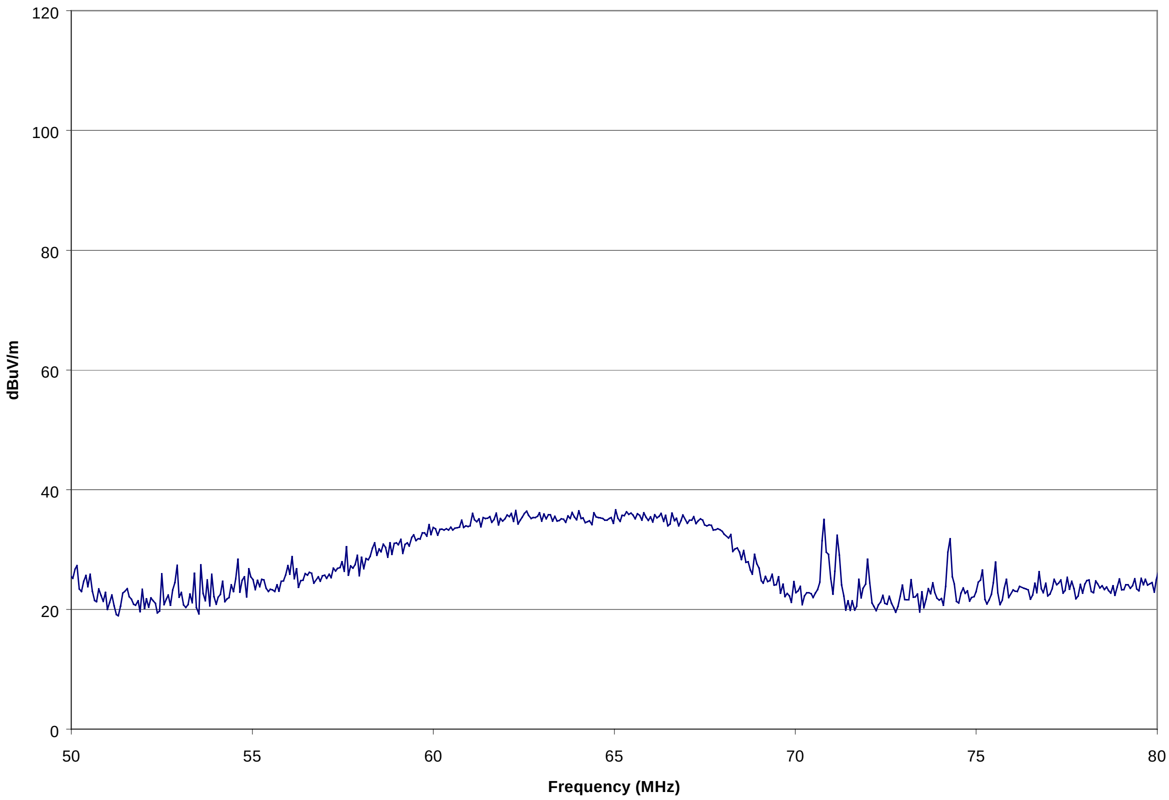


Figure 12. Electric Vehicle Charging (H)

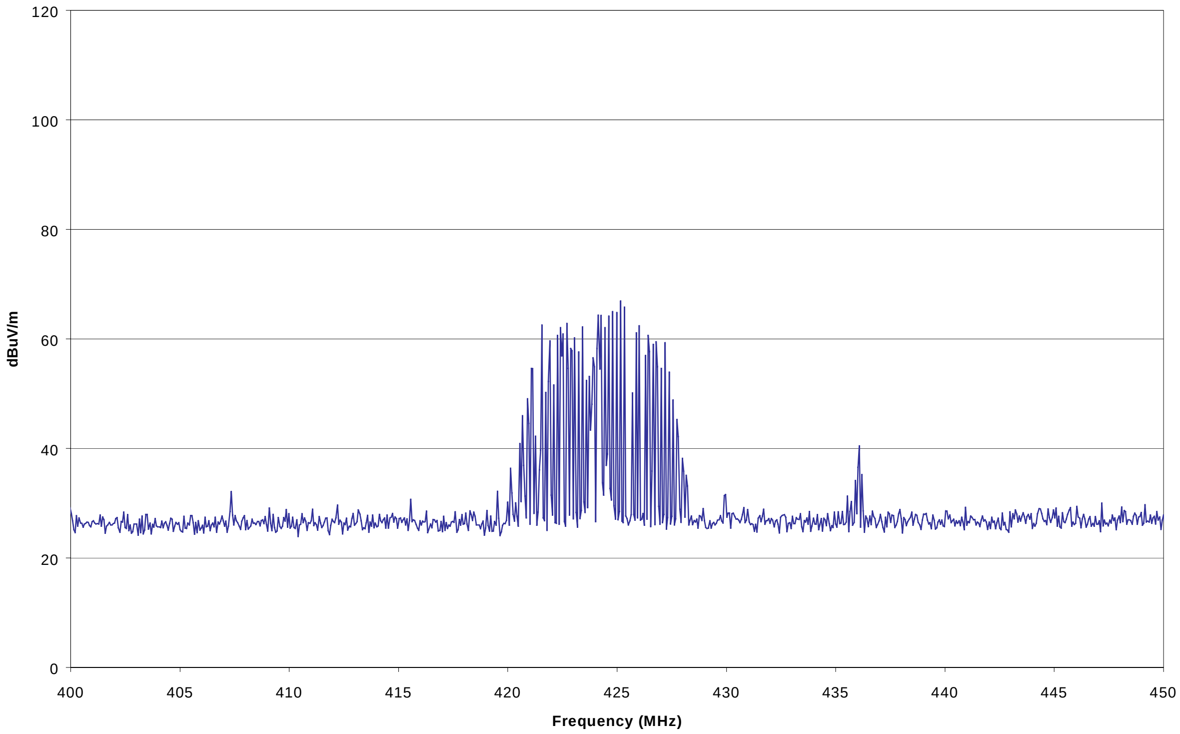
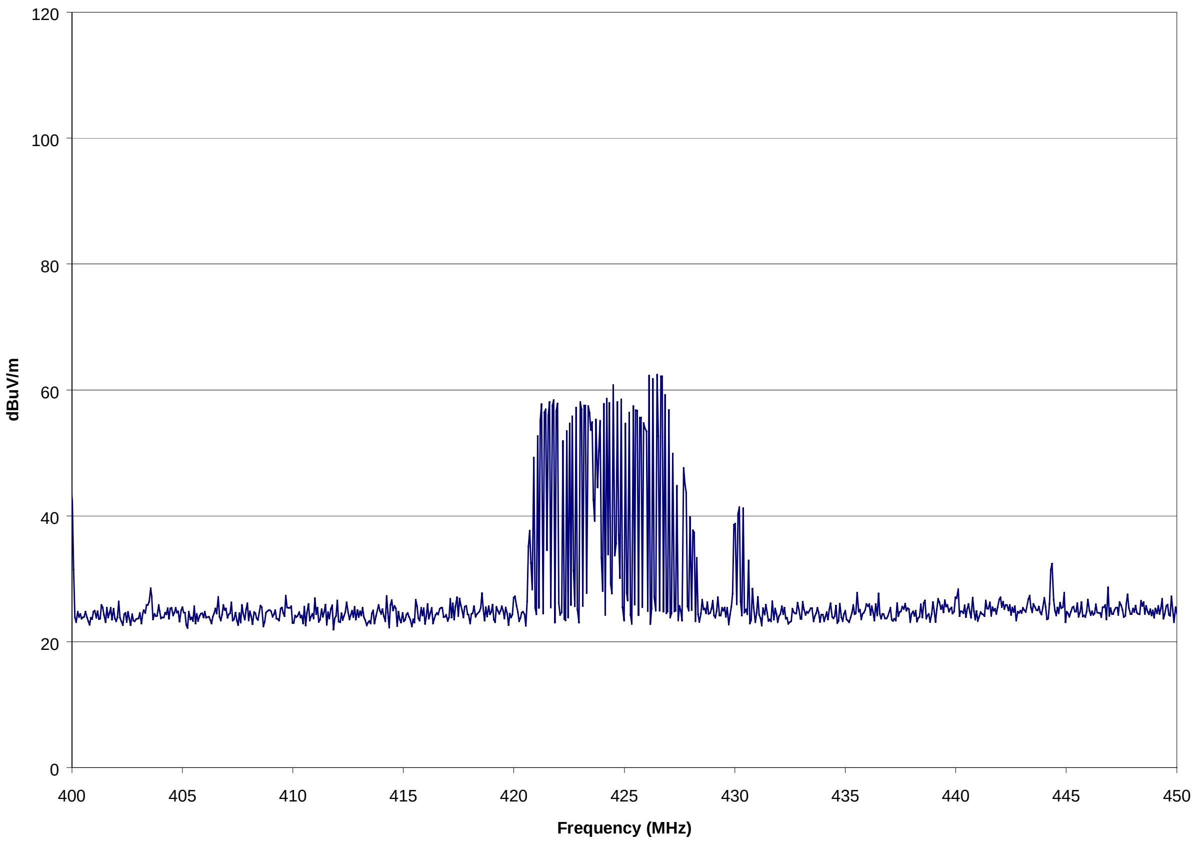


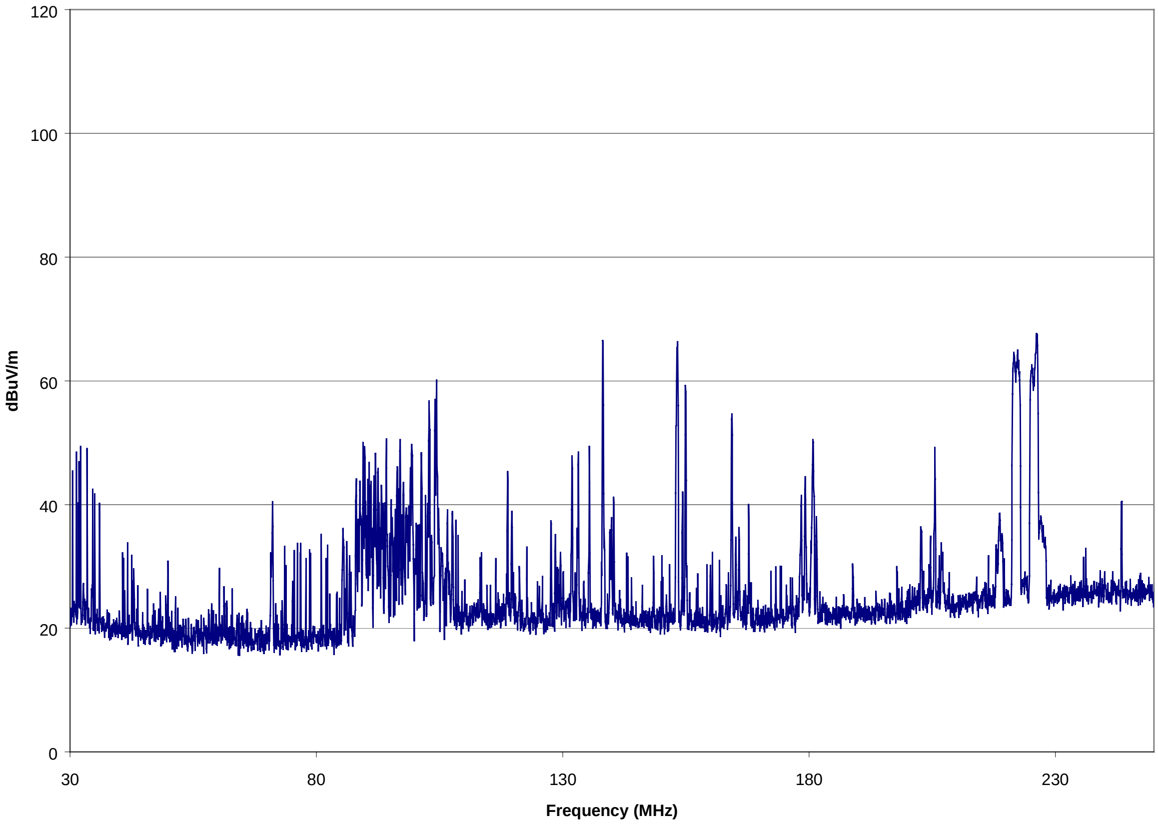
Figure 13. Electric Vehicle Charging (V)



11.3.2.2. Hybrid Vehicle Measurement Results

Figure 14 shows several narrow band emissions ranging from 30 MHz to 243 MHz which vary in intensity from 32 dBuV/m to 49 dBuV/m and were measured with the vehicle engine held at 1500 rpm. All emissions measured exceed CISPR levels by between 8 dB at 78 MHz to 25 dB at 33.480 MHz. The emissions are in the frequency ranges of fixed mobiles including hospital pagers, aeronautical, emergency positioning radio beacons (EPRB), and programme making and special event (PMSE) channels.

Figure 14. Hybrid Vehicle @ 1500 rpm (V)



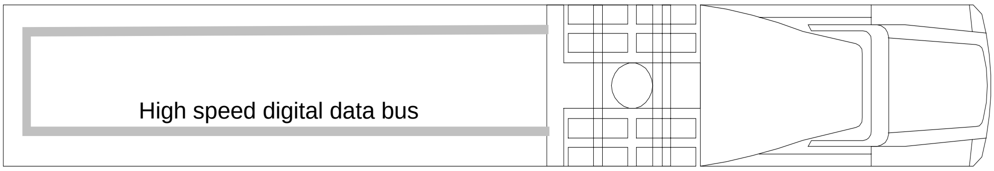
11.3.3. Articulated HGV With High-Speed Digital Data Bus.

A DAF tractor unit was coupled with a 3-axle trailer unit. To simulate a possible future data-bus system, a length of unshielded twisted pair cable was run from a point outside an aft of the lorry cab and through the main I-beam structure of the trailer (Figure 15). The cable then followed the main I-beam down the right-hand side of the trailer, forming a loop just aft of the last axle, and then followed the left-hand structural I-beam back towards the cab.

The twisted pair conformed to the cable specification for a high-speed CAN-BUS as detailed in SAE J2284, and was terminated with two 0.1% tolerance 120Ω resistors in parallel, also as detailed in SAE J2284. The output impedance of the driving function generator was 50Ω.

The data signal was provided by a Rhode & Schwarz multifunction signal generator. The data consisted of a 1 MHz carrier, modulated with a 1 kHz bit rate, and a 100 Hz packet rate to simulate the type of format used on digital communication buses. Total peak voltage of the signal was 1V, as it was felt that excessive radiation from the data-bus might occur, causing an infringement of the regulations concerning transmission of RF, had higher peak voltages been used.

Figure 15. Schematic of the HGV and data-bus



11.3.3.1. HGV Measurement Results

The data bus was routed along the inside of the main structural I-Beam on the trailer, this would serve to provide a high level of shielding. In future applications, if such a routing was not followed, further increases in the emission levels are likely to be observed.

Figure 16 shows the emission from the databus system fitted to the HGV as described previously which can be seen clearly at 1 MHz at a level of 9 dBuV/m with the vehicle at a distance of 10 metres away from the antenna. The level of the emission increased to 22 dBuV/m at a distance of 3 metres, which can be seen in Figure 17. However CISPR levels do not cover emissions as low as 1 MHz as they start at 30 MHz.

The results presented are for the peak bus voltage of 1V. However it is likely that real systems will use higher voltages, e.g. 12 volts. This rise in voltage would cause a corresponding rise in the level of emissions. The measured level at 3 metres was 21 dB for a 1 volt signal, if the data signal is increased to 12 volts it is possible that a rise in emissions of approximately 20 dB could be seen. A frequency of 1 MHz is not likely to effect major broadcast transmissions but the data frequencies and any harmonics should be chosen to avoid interference. The use of screened cables could also eliminate or reduce the emission levels from such systems.

Figure 16. 10m HGV Data Bus Test.

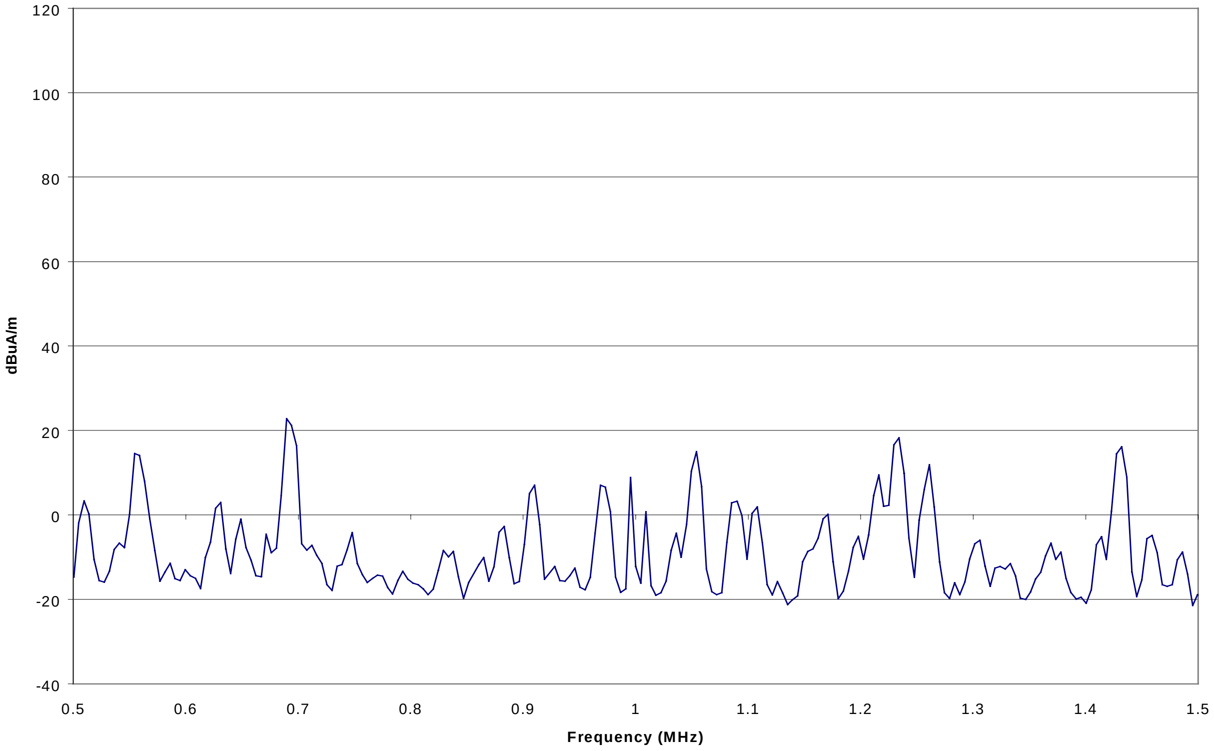
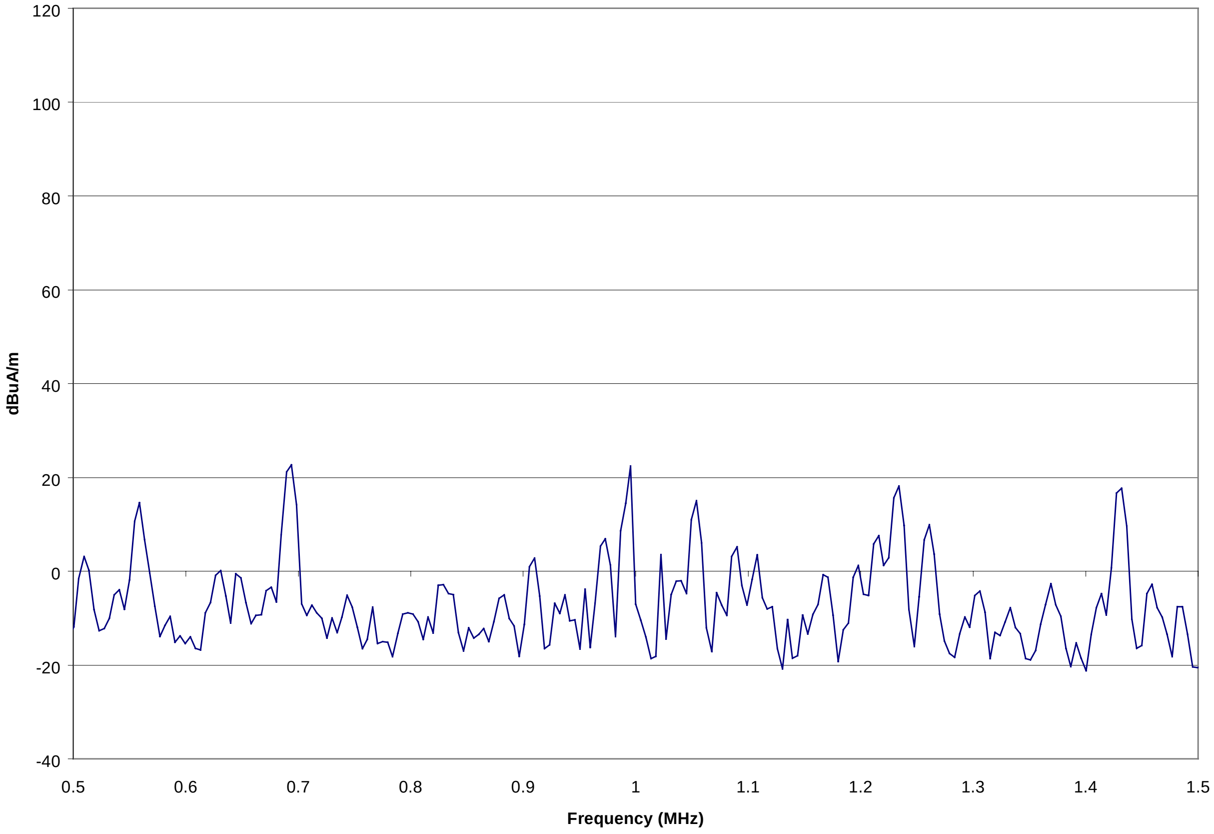


Figure 17. 3m HGV Data Bus Test



11.3.4. Multiple Electrical Unit Train

The Multiple Electrical Unit (MEU) that was characterised as part of the measurement phase of this report consisted of three carriages, one driving carriage at each end coupled to a pantograph carriage (power pickup) in the middle. The electric train has the following technology on-board:

- 25kV 50Hz AC supply, via mainline overhead cables and pantograph pickup
- Fixed output transformer, with electronic voltage control
- 3-phase asynchronous AC motors
- GTO (Gate Turn Off) inverter, a circuit that uses GTO thyristors to turn ADC into AC for motor speed control. As the speed of the motor is determined by the frequency of AC supplied, the inverter output frequency needs to vary over a wide range (typically 0 - 200 Hz). Consequently the inverter design incorporates complex switching strategies where the frequency is changed in stages as the train speeds up.
- GTO Force Commutated Bridges are fitted to ensure that there is no lag between the voltage and current supplied. In a force commutated bridge, the GTO thyristors have both switch-on and switch-off controlled via a pulse width modulated switching pattern, to ensure current is brought into phase with voltage. This can result in lower electricity consumption.
- Rheostatic braking is employed to dissipate energy generated by the motors (these can be made to act as generators under braking) in a brake resistor. This method gives long-term savings in brake pad wear.
- Regenerative braking is used to return energy to the supply system during braking. On the AC powered units, regen-braking has only recently become possible with the advent of force commutated bridges. The basics of regen-braking involve turning the motors into generators when they are not required to provide forward motion, and instead use the forward motion to generate electricity.

11.3.4.1. Electric Train Measurement Results

Due to the complicated nature of the changing environment when the train carriage was in motion, the three results sets taken for each frequency band and polarisation have been averaged, and comparisons made between the driving carriage and pantograph carriage only. No reference has been made to any background measurement, and a large amount of the spurious frequencies listed in Table 4 can be related to well known sources such as television broadcast etc.

Figure 18 shows the measurements taken inside a moving train driving carriage. The emissions ranged from 481 MHz to 582 MHz and were all horizontally polarised. The levels ranged form 31 dBuV/m to 37 dBuV/m with the highest level at 561.075 MHz, and is likely to be a television broadcast. Figure 19 shows measurements taken at the same location in the driving carriage but differed in that the polarisation was in the vertical plane. The measured frequencies were broadly similar to that measured with horizontal polarisation but were generally higher in level, with the highest measured peak at 949.075 MHz at a level of 53 dBuV/m and is likely to be a mobile phone signal.

Figure 20 shows the measurements taken inside the pantograph carriage using horizontal polarisation. There were three spot frequencies of concern. The first at 602.3 MHz at a level of 32 dB. The two frequencies at 699.3 MHz and 704.15 MHz had levels of 44 and 41 dB respectively. These frequencies are in the UHF range and could possibly effect television broadcasts.

To establish the effect of passengers using mobile telephones whilst travelling in the train carriage, measurements were taken during a telephone call made between two phones inside the carriage. The peaks at 891.25 MHz (69 dBuV/m), 903.75 MHz (69 dBuV/m) and 906.25 MHz (72 dBuV/m) are clearly illustrated in Figure 21.

Figure 18. Average of Measurements Inside Driving Carriage (H).

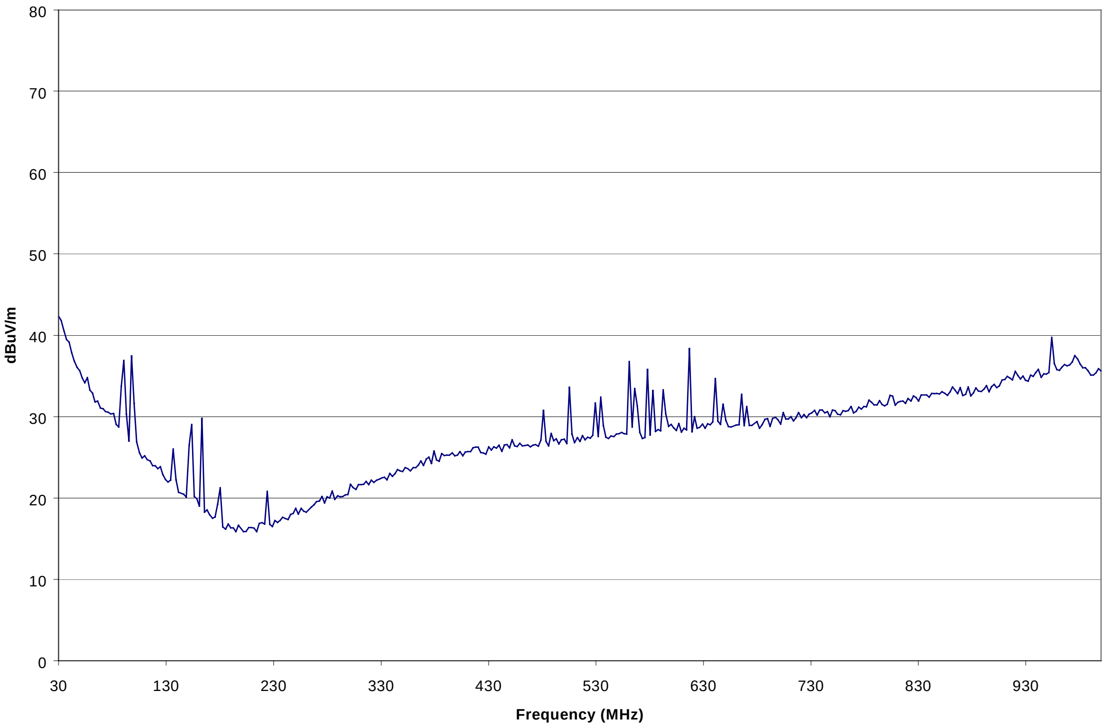


Figure 19. Average of Measurements Inside Driving Carriage (V).

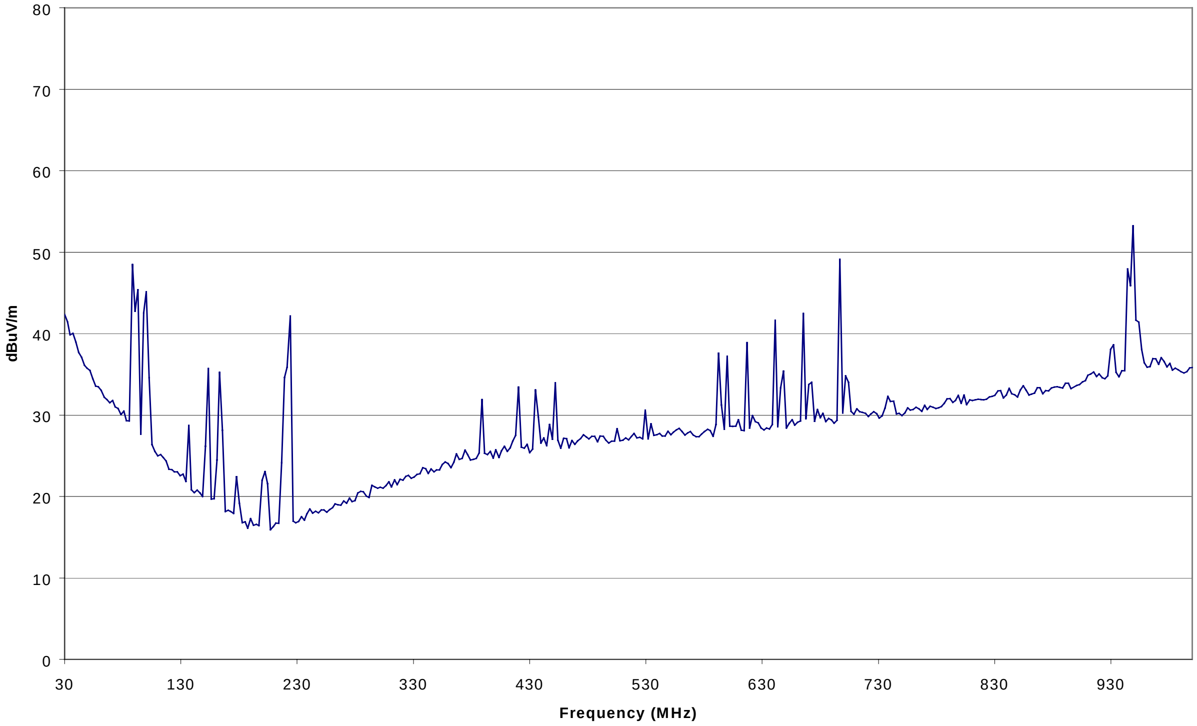


Figure 20. Average of Measurements Inside Pantograph Carriage (H).

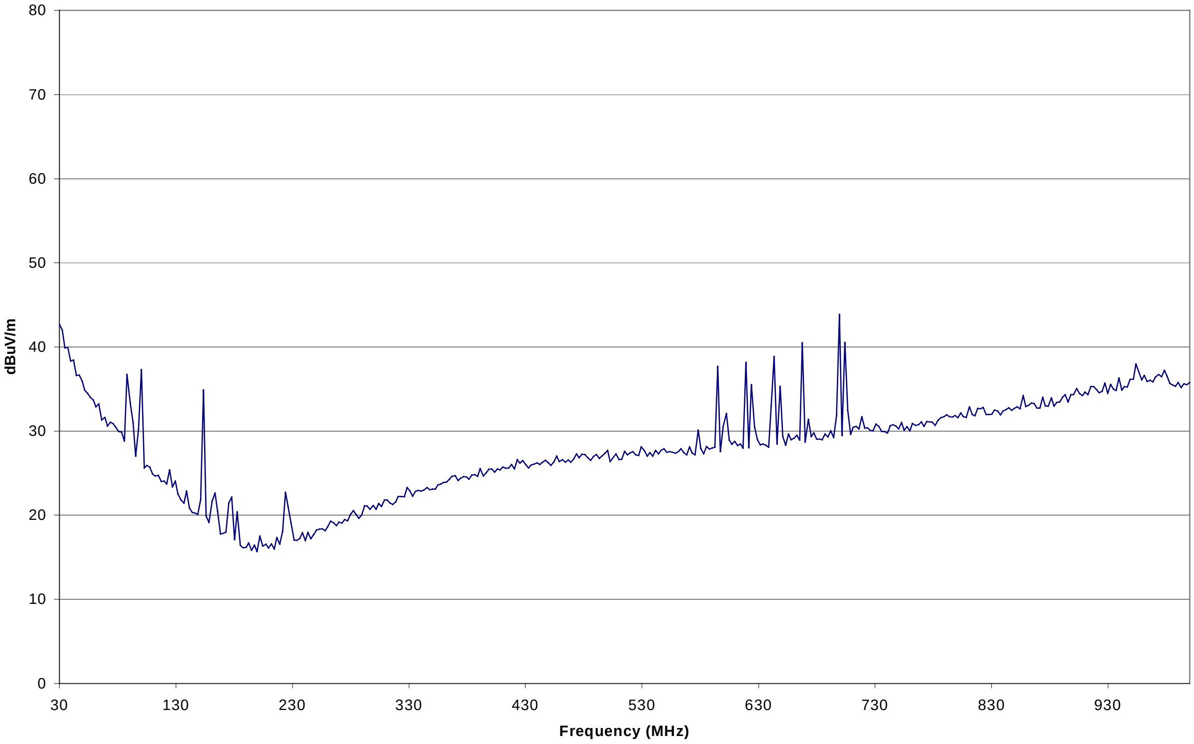


Figure 21. Mobile Phone Call in Pantograph Carriage (H).

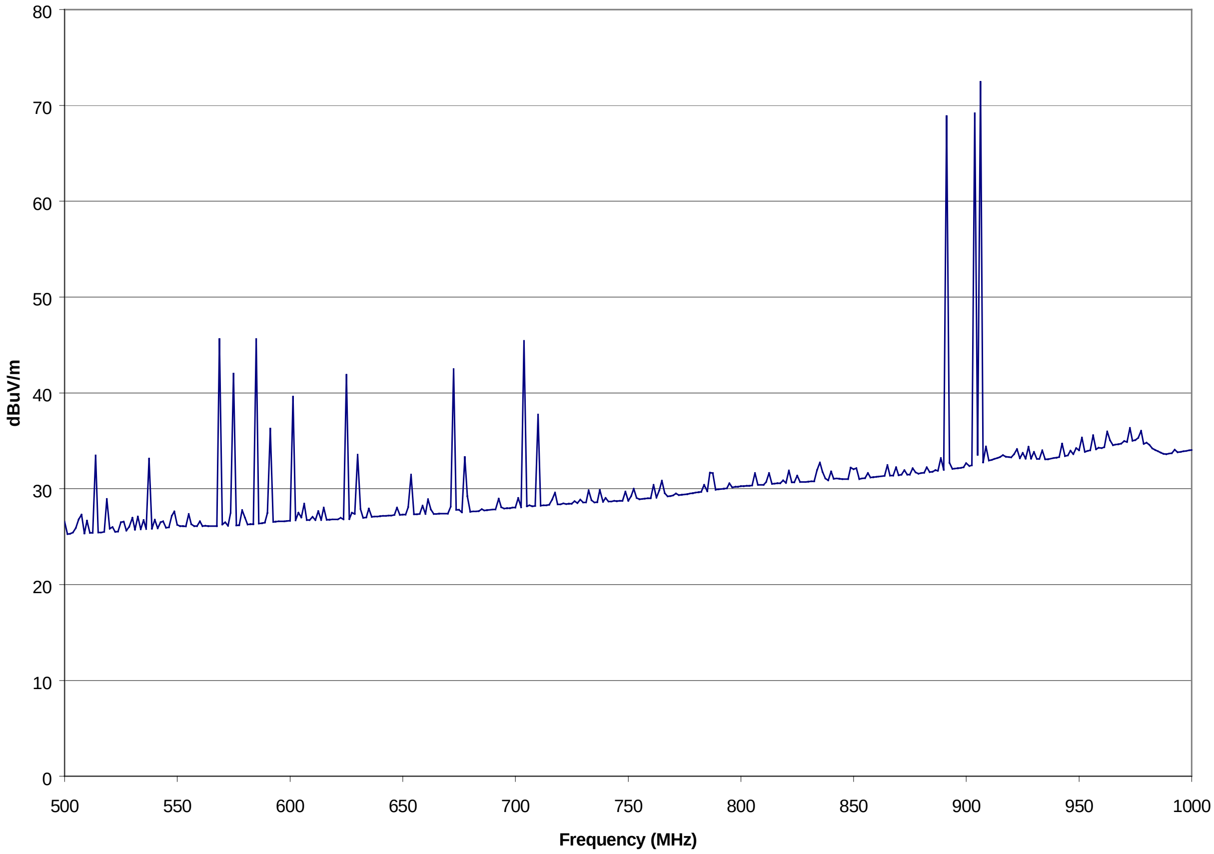


Table 4. Potential Emission Frequencies and Polarisation's From Test Vehicles

Electric Vehicle	**Peak Level dBuV/m**
55-70 MHz (V) (charging)	*36*
71.22 MHz (H) (charging)	*36*
420-430 MHz (V&H) (charging)	*62/**66***
Hybrid Vehicle	
30-33 (V) MHz	***49***
78 (V) MHz	***32***
81 (V)MHz	***35***
82 (V)MHz	***33***
133.14 (V)MHz	***36***
135.42 (V)MHz	***49***
243.42 (V) MHz	***40***
HGV	
1 MHz at 3m	22
1 MHz at 10m	9
Electric Train	
Driving Carriage	
136.7 MHz (V)	29
420.425 MHz (V)	33
434.975 MHz (V)	33
451.95 MHz (V)	33
481.05 MHz (H)	31
505.3 MHz (H)	34
529.55 MHz (H)	32
534.4 MHz (H)	32
561.075 MHz (H)	37
565.925 MHz (H)	33
582.9 MHz (H)	33
932.1 MHz (V)	39
949.075 MHz (V)	53
Pantograph Carriage	
602.3 MHz (H)	32
699.3 MHz (H)	44
704.15 MHz (H)	41
891.25 MHz (mobile phone test)	69
903.75 MHz (mobile phone test)	69
906.25 MHz (mobile phone test)	72

The numbers in bold italic for the electric vehicles and the HGV exceed CISPR levels.

11.4. CISPR Vehicle Narrowband Reference Limits

Below are three graphs (Figures 22 to 24) that show the CISPR Vehicle Narrowband Reference Limits, which define emission limits from 30 MHz to 1 GHz. Three graphs are presented with scales to match the data presented in this report to allow clear comparison.

Figure 22. CISPR Vehicle Narrowband Reference Limits.

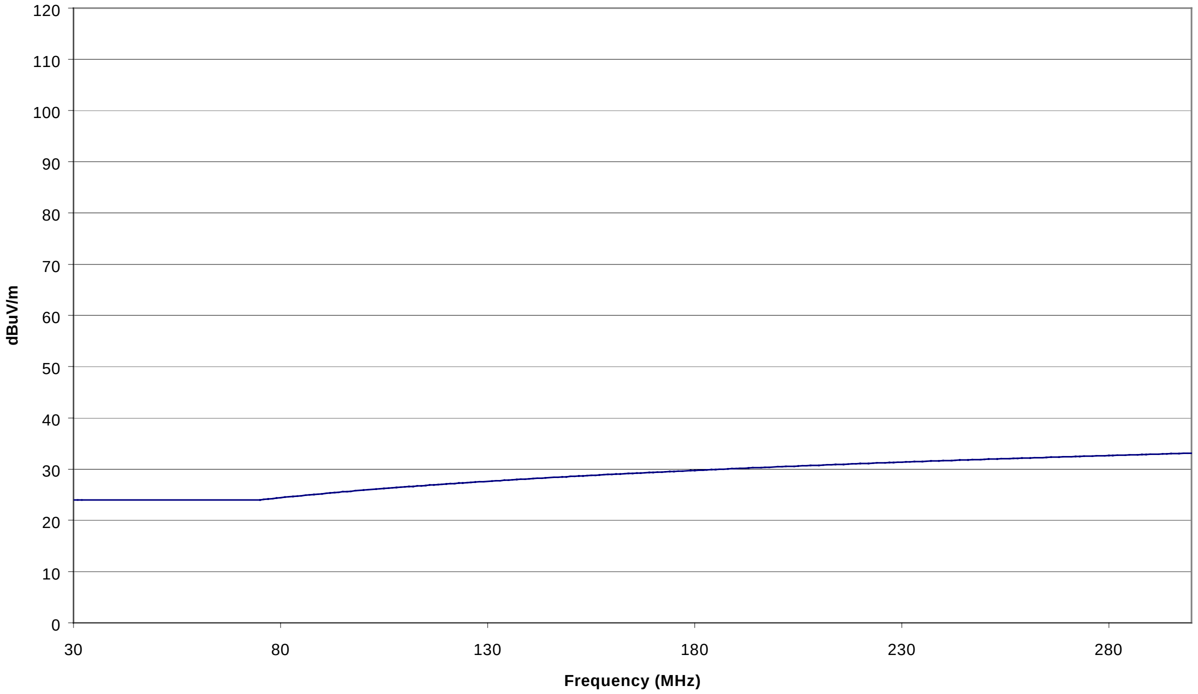


Figure 23. CISPR Vehicle Narrowband Reference Limits.

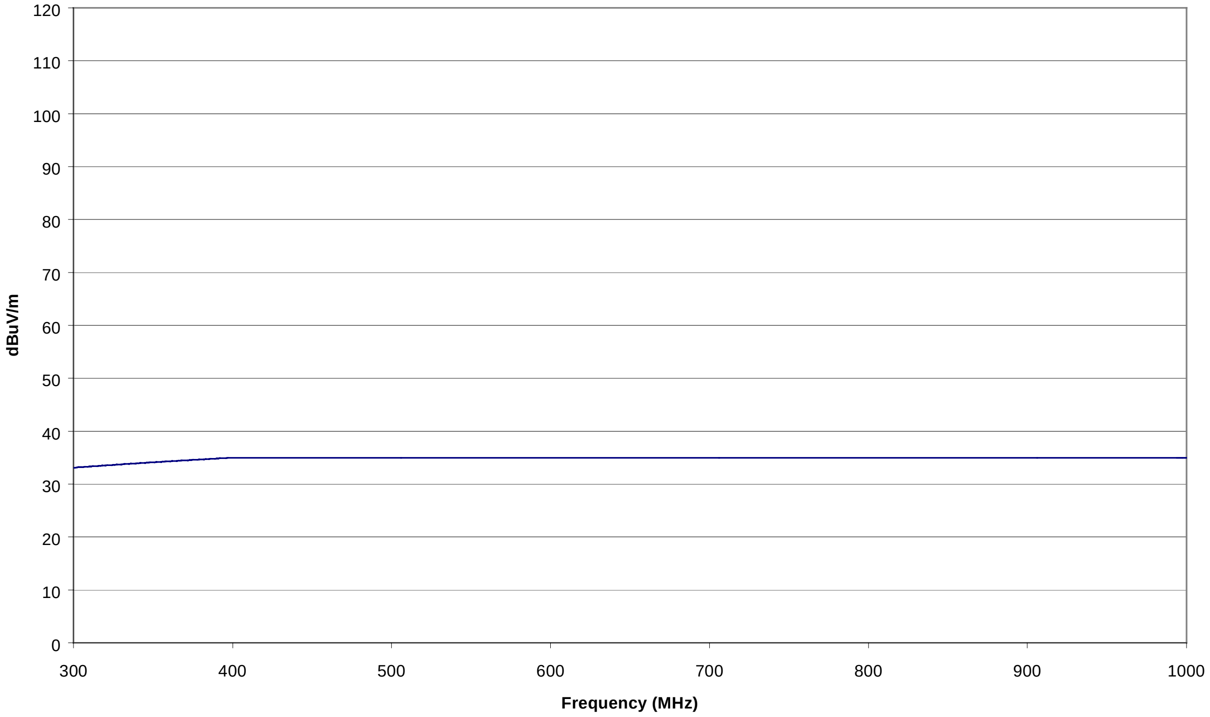
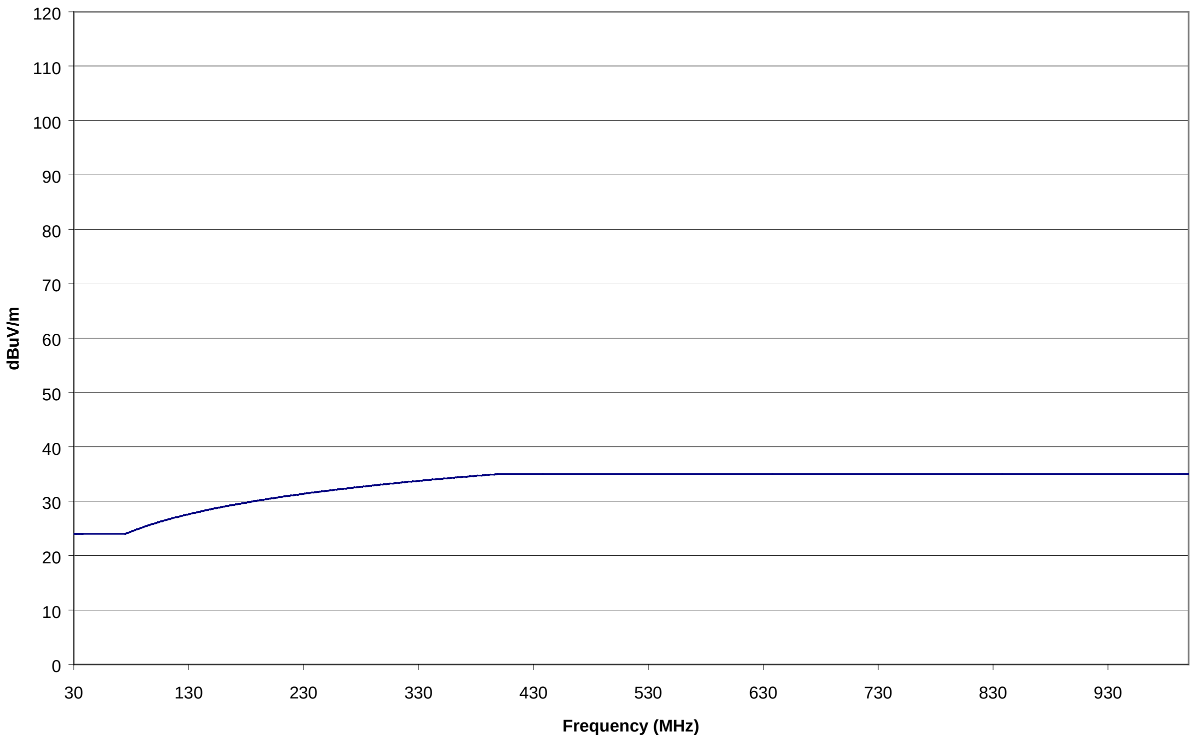


Figure 24. CISPR Vehicle Narrowband Reference Limits.



12. RELEVANT STANDARDS AND DIRECTIVES

12.1. European Communities Directive 95/54/EC

The Automotive EMC Directive 95/54/EC, covers both immunity and emissions requirements of electromagnetic compatibility. The emissions part of the Directive is largely based on CISPR Standard 12. The emissions tests required are separated into two main sections. The first relates to whole vehicle tests, the second set are individual tests of vehicle sub-assemblies. Both the sections are further broken down into narrow and broad band emissions and immunity tests.

The manufacturer of the vehicle or system to be tested is required to compile a list describing all projected variations and combinations of relevant vehicle electrical/electronic systems, body styles, variations in body materials, general wiring arrangements, engine variations, left and right hand and wheel base variations. A representative vehicle is then selected from this list for testing.

12.1.1. Broadband Vehicle Test.

The broadband emissions test is intended to measure the emissions produced by spark ignition systems. The test can be carried out with the vehicle at either three or ten metres away from the antenna, with the vehicle to antenna distance chosen by the test house.

Immediately before and after the test an ambient reading is taken. In each case the background noise should be at least 10 dB below the reference limits for the specific test.

The vehicle is brought into the test area and the engine is run at 1,500 rpm for multi-cylinder engines and 2,500 rpm for single cylinder engines. Measurements are taken over the frequency range spanning 30 MHz to 1 GHz. The emissions can be measured using quasi-peak or peak detectors, although the reference limits quoted apply to quasi-peak and would require conversion if measured in peak.

12.1.1.1. Reference Limits

Ten Metre Test

34 dBµV/m	30 MHz to 75 MHz.
34 to 45 dBµV/m	75 MHz to 400 MHz increasing logarithmically.
45 dBµV/m	400 MHz to 1 GHz.

Three Metre Test

44 dBµV/m	30 MHz to 75 MHz.
44 to 55 dBµV/m	75 MHz to 400 MHz increasing logarithmically.
55 dBµV/m	400 MHz to 1 GHz.

The test is carried out using both horizontal and vertical polarisation with the vehicle passing the test if all emissions are 2 dB (20%) below the reference limit.

12.1.2. Narrowband Vehicle Test.

The narrowband emissions test is also carried out at either three or ten metres distance between the vehicle and the antenna. The vehicle emissions measurements are carried out in the same way as the broadband test. However, a short initial step test can be carried out eliminating the need for the complete test. This test involves the FM frequency range of 88 MHz to 108 MHz being scanned. If the reference limits set for this frequency range are not exceeded, the full test need not be carried out.

The ambient noise is again measured before and after the test with any signals required to be at least 10 dB below the reference limits. The vehicle is brought into the test area and the emissions measured over the frequency range from 30 MHz to 1 GHz. The vehicle’s ignition is switched on but the engine is not run during the test. The emissions can be measured using quasi-peak or peak detectors, although the reference limits quoted apply to quasi-peak and would require conversion if measured in peak.

12.1.2.1. Reference Limits

Ten Metre Test

24 dBµV/m	30 MHz to 75 MHz.
24 to 35 dBµV/m	75 MHz to 400 MHz increasing logarithmically.
35 dBµV/m	400 MHz to 1 GHz.

Three Metre Test

34 dBµV/m	30 MHz to 75 MHz.
34 to 45 dBµV/m	75 MHz to 400 MHz increasing logarithmically.
45 dBµV/m	400 MHz to 1 GHz.

The test is carried out using both horizontal and vertical polarisation with the vehicle passing the test if all emissions are 2 dB (20%) below the reference limit.

12.1.3. Broadband Electrical/ Electronic Sub-assembly Test.

This test is intended to measure the broadband emissions from electrical/electronic sub-assemblies which may be subsequently fitted to vehicles which have passed the whole vehicle tested described above. The test is carried out with the unit operating, preferably with the wiring harness intended for use in the vehicle. The unit is powered via a 5 uH/50Ω artificial network electrically bonded to the ground plane. Both horizontal and vertical antenna polarisation’s are used during the test with a unit to antenna distance of one metre. The ambient measurement is the same for that of the whole vehicle test. Measurements are taken though the 30 MHz to 1 GHz frequency range.

The emissions can be measured using quasi-peak or peak detectors, although the reference limits quoted apply to quasi-peak and would require conversion if measured in peak.

12.1.3.1. Reference Limits

64 to 54 dBµV/m	30 MHz to 75 MHz. decreasing logarithmically.
54 to 65 dBµV/m	75 MHz to 400 MHz increasing logarithmically.
65 dBµV/m	400 MHz to 1 GHz.

The electrical/ electronic sub assembly passes the test if all emissions are 2 dB (20%) below the reference limit.

12.1.4. Narrowband Electrical/ Electronic Sub-assembly Test.

The test is the same as the broadband test for electrical/electronic sub-assembles with the extra provision of a short test. The short test is carried out using either horizontal or vertical antenna polarisation’s. The frequency range from 30 MHz to 1 GHz is scanned using a spectrum analyser to aid in the detection of peak emissions. These peaks can then be used to assist in the choice of frequencies to be used in the full test. If the emissions are 10 dB below the reference limit during this initial test the unit is deemed to comply with directive for that frequency band.

The full test is carried out with a unit to antenna distance of one metre and is carried out using both vertical and horizontal antenna polarisation’s and measurements taken across the band of frequencies from 30 MHz to 1 GHz.

12.1.4.1. Reference Limits

54 to 44 dBµV/m	30 MHz to 75 MHz. decreasing logarithmically.
44 to 55 dBµV/m	75 MHz to 400 MHz increasing logarithmically.
55 dBµV/m	400 MHz to 1 GHz.

The electrical/ electronic sub assembly passes the test if all emissions are 2 dB (20%) below the reference limit.

12.1.5. Exemptions.

A vehicle or electrical/electronic system, which does not include an electronic oscillator with an operating frequency greater than 9 kHz, is deemed to have complied with the narrowband emissions test.

12.1.5.1. Electrostatic Discharge.

For a vehicle fitted with tyres, the chassis can be considered to be an electrically isolated structure. Significant electrostatic forces in relation to the vehicle’s external environment only occur at the moment of occupant entry or exit from the vehicle. As the vehicle is stationary at these moments, no type approval test from electrostatic discharge is deemed necessary.

12.1.5.2. Conducted Transients.

Since during normal driving, no external electrical connections are made to vehicles, no conduced transients are generated in relation to the external environment. The responsibility of ensuring that equipment can tolerate the conducted transients within a vehicle, e.g. due to load switching and interaction between systems lie with the manufacturer. No type approval test for conducted transients is deemed necessary.

12.2. CISPR 25 Limits and Methods of Measurement of Radio Disturbance Characteristics for the Protection of Receivers Used On-Board Vehicles.

This standard concerns the interference relating to motor vehicles and internal combustion engines, and is designed to protect receivers from disturbances produced by conducted and radiated emissions arising from vehicles.

The standard covers the frequency band from 150 kHz to 1 GHz and establishes a test method to measure electromagnetic emissions from a vehicle’s electrical system, and the testing of on-board components and modules independently of the vehicle. It also sets limits for electromagnetic emissions from components and vehicle electrical systems to prevent disturbance to on board receivers.

12.2.1. Measurement of Emissions Received by an Antenna on the Same Vehicle

This test is to ascertain the disturbances from vehicle systems against a maximum permissible level measured at the vehicle mounted antenna between a frequency range of 150 kHz to 1 GHz.

The emissions from different sources are likely to be different and as such the limits themselves are given for long and short duration disturbances. A long duration disturbance source could be an ignition system or blower motor, and a short duration disturbance a washer pump motor or power seat. A full list of the limits is given in the CISPR 25 standard, table 5 page 41 and includes measurements made using quasi-peak and peak detectors which range from 9 to 15 dBuV quasi-peak, and 19 to 28 dBuV peak depending on the emission frequency.

12.2.2. Measurement of Vehicle Components and Modules.

The measurements for this test are carried out between the frequency range from 150 kHz to 1 GHz. It is the measure of disturbances applied by electrical equipment within the vehicle, to the vehicle's on-board power supply. This includes disturbances coupled from the wiring to the vehicle's antenna. The section describes methods of safeguarding radio reception in the same vehicle in which the disturbance arises.

The procedure is split into two main groups, the first being a voltage measurement at all power leads. Where the equipment under test (EUT) has its ground return though its casing, the measurement is made relative to the case or ground lead as close to the EUT as possible. Where the equipment under test is fitted with a remote ground return line, the voltage is measured on each of the supply and return lead relative to the ground plane.

The second measurement uses a current probe to measure emissions in the power line. The current is measured at four different positions on the harness of the EUT to assure that the maximum level is measured as follows:

- 50 mm from the EUT connector.
- 500 mm from the EUT connector.
- 1,000 mm from the EUT connector.
- 50 mm from the artificial mains network (AN).

The limits for these tests are given in the CISPR 25 standard pages 57 and 59 and are split into classes. A class is a performance level agreed upon by the purchaser and the supplier and is documented in the test plan.

A summary of the limits for broadband conducted disturbances are as follows:

- Between 61 and 113 dBµV peak and 48 to 100 dBµV quasi-peak for class one.
- Between 55 and 103 dBµV peak and 42 to 90 dBµV quasi-peak for class two.
- Between 49 and 93 dBµV peak and 36 to 80 dBµV quasi-peak for class three.
- Between 43 and 83 dBµV peak and 30 to 70 dBµV quasi-peak for class four.
- Between 37 and 73 dBµV peak and 24 to 60 dBµV quasi-peak for class five.

A summary of the limits for narrowband conducted disturbances are as follows:

- Between 42 and 90 dBµV peak for class one.
- Between 36 and 80 dBµV peak for class two.
- Between 30 and 70 dBµV peak for class three.
- Between 24 and 60 dBµV peak for class four.
- Between 18 and 50 dBµV peak for class five.

The above levels are dependent on frequency.

12.2.3. Radiated Emissions from Component/Module.

These test measurements must be carried out in an absorber lined shielded enclosure to eliminate environmental interference. The test measures radiated emissions from vehicle components.

The measurements are made in the frequency range from 150 kHz to 1 GHz with a bandwidth of 120 kHz, and the antenna in both the horizontal and vertical polarisation's above 30 MHz. The equipment under test is subjected to a typical loading so that the maximum emissions occur during measurement. The equipment's surface which emits the greatest R.F. emissions is situated closest to the antenna during measurements. If this surface changes with frequency then measurements are made in orthogonal planes. The limits set for this test are listed in the CISPR 25 standard on page 69 of the document.

A summary of the limits for broadband radiated disturbances from components are as follows:

- Between 49 and 96 dBµV peak and 36 to 83 dBµV quasi-peak for class one.
- Between 43 and 86 dBµV peak and 30 to 73 dBµV quasi-peak for class two.
- Between 37 and 76 dBµV peak and 24 to 63 dBµV quasi-peak for class three.
- Between 31 and 66 dBµV peak and 18 to 53 dBµV quasi-peak for class four.
- Between 25 and 56 dBµV peak and 12 to 43 dBµV quasi-peak for class five.

A summary of the limits for narrowband conducted disturbances are as follows:

- Between 36 and 61 dBµV peak for class one.
- Between 30 and 51 dBµV peak for class two.
- Between 24 and 41 dBµV peak for class three.
- Between 18 and 31 dBµV peak for class four.
- Between 12 and 21 dBµV peak for class five.

The above levels are dependent on frequency.

12.3. CISPR 12 1996: LIMITS AND METHODS OF MEASUREMENT OF RADIO DISTURBANCE CHARACTERISTICS OF VEHICLES, MOTORBOATS, AND SPARK-IGNITED ENGINE-DRIVEN DEVICES.

The limits in this standard are designed to provide protection for broadcast receivers in the frequency range 30 MHz to 1000 MHz when used in a residential environment, and applies to the emission of broadband and narrowband electromagnetic energy.

The standard does not apply to aircraft, traction systems (railway, tramway and trolley bus), or to incomplete vehicles.

Broadband emission limits L [dBμV/m], at frequency f (MHz), measured at 10m distance.

Bandwidth	30-75 MHz	75-400 MHz	400-1000 MHz	Measurement type
120 kHz	L = 34	L = 34 + 15.13 lg(f/75)	L = 45	Quasi-peak
120 kHz	L = 54	L = 54 + 15.13 lg(f/75)	L = 65	Peak
1 MHz	L = 72	L = 72 + 15.13 lg(f/75)	L = 83	Peak

Narrowband emission levels are summarised below, and apply to peak and quasi-peak measurements. Vehicles that meet the narrowband emission requirements of CISPR 25, section 2 shall be deemed to be in compliance with the narrowband requirements of this standard and no further testing is necessary. For measurements at 3m, 10 dB shall be added to the limit.

30 MHz - 230 MHz	30 dBμV/m
230 MHz - 1000 MHz	37 dBμV/m

All measurement equipment shall comply with CISPR 16-1, and the measurements largely follow the requirements of CISPR 16-1.

Minimum scan times and bandwidths for the measurement equipment are defined in the standard.

Methods of checking for compliance with CISPR requirements are detailed in the standard.

12.4. CISPR 26 1995: RADIO INTERFERENCE FROM ELECTRIC TRACTION SYSTEMS

This standard deals specifically with railway systems.

The standard identifies sources of electromagnetic disturbances from electric traction systems and discusses the physical aspects of the disturbances. Tables of reference are provided detailing typical amplitudes of disturbances against their source. Means of propagation are also discussed.

Measurement methods:

The frequency bands applied by this standard are 9 kHz - 300 MHz for rolling stock, and 9 kHz - 30 MHz for feeder sub-stations, traction network, interlocking and signalling equipment.

Depending on the situation of the measurement antennae, there are two different test methods described in the standard.

1) Stationary method, where the antennae is placed 10m from the closest line conductor of the traction network. The E-Field will be measured in both horizontal and vertical planes.

The test method calls for a 25m radius from the test location to be clear of trees, bushes, neighbouring electric power lines etc.

2) Moving car method, where the antennae is placed on a vehicle or test car following the tested vehicle. It is not presented as a standard test, but is discussed in the standard.

The measurement apparatus and methods used for checking compliance with limits shall conform to CISPR 16-1.

CISPR 26 states that where possible peak detectors should be used, and the results converted to quasi-peak levels. The frequency bands and bandwidths for measurement also conform to CISPR 16.

The provision of using less accurate test equipment than that detailed in CISPR 16 is made in CISPR 26.

The choice of measurement frequency shall be in accordance with the general CISPR regulations, unless it is a prototype vehicle, in which case it shall be verified whether characteristic frequency bands exist at which higher disturbance levels might occur. This is essential for vehicles having pulsed starting and braking systems.

Use of the selected frequency measurement will depend on the test site. A survey must be made to identify existing radio signals; frequencies may then have to be changed to avoid these background radio signals. Then 5 frequencies per decade are required to be measured, and a search for the noise maxima in the 9 kHz to 150 kHz band must be made prior to frequency selection. Above this frequency, further searches are not required.

The speed of the measured test vehicle and the testing of regenerative braking will be the same as that described in EN 50121.

For stationary measurements, at least 6 measurements are to be taken at the nominated frequencies, one for each pass of the vehicle. If a change of direction of travel yields significantly different results, the readings shall be taken for the direction of the highest reading. Then, the average of the 6 readings is to be taken.

Emission limits:

The limits refer to protection limits of the radio and television broadcast bands, and nominal useable field strengths are quoted for each band, transmitter type and location. Protection ratios are also given, and these are summarised below:

AM Radio (LF, MF and HF Ground Wave)	30 dB (26 dB for Region 2)
FM Radio ± 75 kHz deviation (mono)	36 dB
FM Radio ± 75 kHz deviation (stereo)	45 dB
FM Radio ± 50 kHz deviation (mono)	39 dB
FM Radio ± 50 kHz deviation (stereo)	49 dB
TV Vision 625 line (PAL)	45 dB
TV Audio (FM)	As for FM Radio

Protection boundaries (corridors) are detailed in the standard, and vary according to the type of rail system, the largest being 10m from the centre of the track.

12.5. ENV 50121 1996: RAILWAY APPLICATIONS - ELECTROMAGNETIC COMPATIBILITY

The set of railway EMC product-specific European Pre-standards is intended to permit compliance with the General EMC Directive 89/336. It consists of 5 parts as described below.

The set of Pre-standards specifies the limits for EM emission of the railway as a whole to the outside world, and of the EM emission and immunity for equipment operating within the railway but which must be compatible with the emission limits set for the railway as a whole. The frequency covered by the Pre-standards is in the range of DC to 400 GHz, however testing is limited to frequencies not exceeding 1 GHz. The limits for EMC phenomena are set so that the railway as a whole satisfies the EC Directive 89/336 on electromagnetic compatibility, and so that EMC is achieved between the various parts of the railway.

12.5.1. Part 1: General

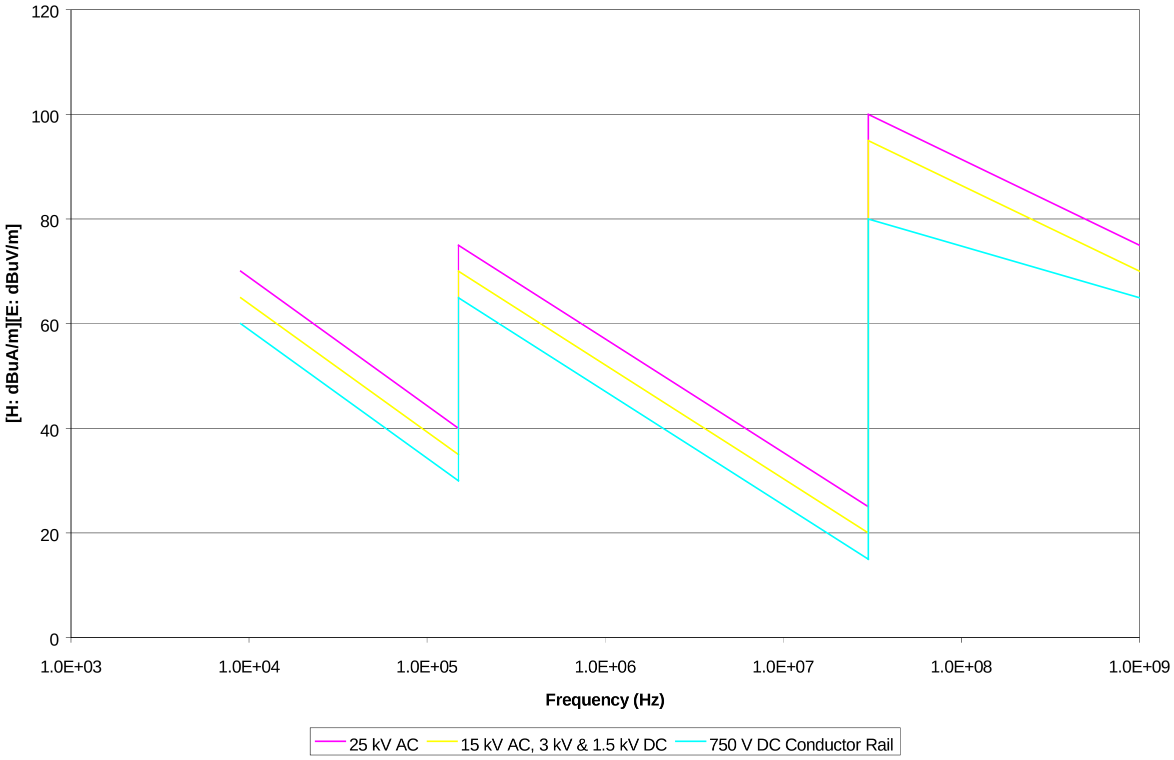
This part gives a description of the electromagnetic behaviour of a railway; it specifies the performance criteria for the whole set. A management process to achieve EMC at the interface between the railway infrastructure and trains is provided.

12.5.2. Part 2: Emission of the Whole Railway System to the Outside World

This part sets the emission limits from the railway to the outside world at radio frequencies. It defines the applied test methods and gives information on typical field strength values from DC to radio frequency (more typically 9 kHz to 1 GHz).
The emission limits in the frequency range are given in Figure 25. The method of measurement has been adapted from CISPR 16-1, but there are fundamental differences. The main points are summarised below:

- Peak measurements are made
- The frequency bands and bandwidths are in accordance with CISPR 16
- 5 frequencies must be measured per decade
- It is desirable, but not mandatory to conduct a search in the 9 kHz - 150 kHz bandwidth prior to choosing the 5 frequencies
- 9 kHz - 30 MHz the H-Field is measured
- 30 MHz - 1 GHz the E-Field is measured
- The measuring antennae should be located 10m from the track centreline
- The vertical E-Field is measured only, horizontal measurement may be specifically requested
- The tests should be conducted at speeds of more than 90% of the maximum service speed
- Tests should be conducted during the use of regenerative braking, and the applied brake power should be at least 80% of the rated maximum

Figure 25. Emission Limits (Peak 80/80)



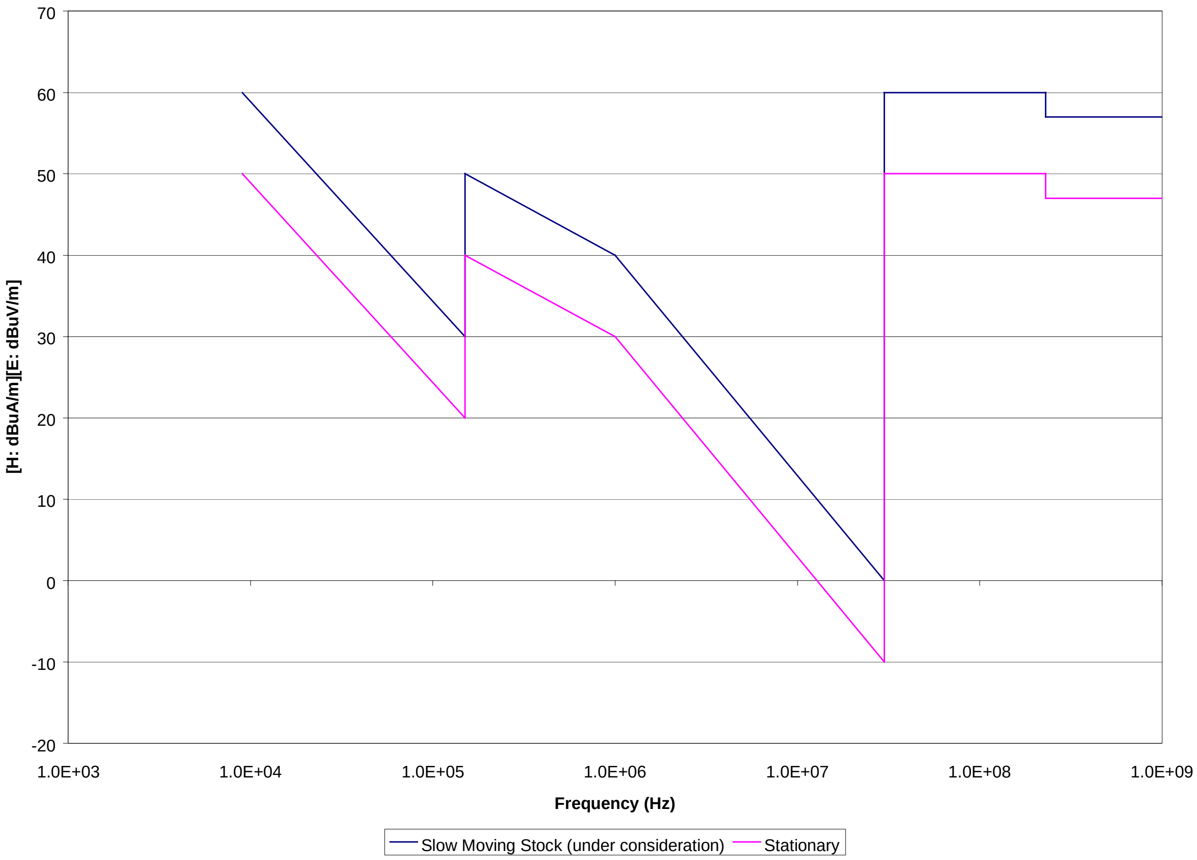
12.5.3. Part 3-1: Rolling Stock - Train and Complete Vehicle

This part specifies the emission and immunity requirements for all types of rolling stock. It covers traction stock and trainsets, as well as independent hauled stock. The scope of this part of the Pre-standard ends at the interface of the stock with its respective energy inputs and outputs.

It is worth noting that the standard does not include interference with digital telecommunication lines such as PCM, ISDN etc, but does cover analogue lines
The emission tests follow the same measurement procedure as in part-2, with the proviso that frequency scanning be used instead of spot frequencies. .

The emission levels are given in Figure 26, however the limit curve given for slow moving stock is currently under consideration and the corresponding values are only indicative. (For the slow moving test, the recommended speeds are 20 km/h for urban vehicles and 60 km/h for mainline vehicles).

Figure 26. Emission Limits For All Types Of Railway Vehicles.



12.5.4. Part 3-2: Rolling Stock- Apparatus

This part applies to emission and immunity aspects of EMC for electrical and electronic apparatus intended for use on railway rolling stock, in relation to conducted and radiated disturbances.

The Pre-standard does not apply to transient emissions when starting or stopping the apparatus.

There are no test requirements as part of this Pre-standard to test for emissions (or immunity) of the main circuit breaker, traction transformer or traction motor.

Radiated electromagnetic emissions are only measured for the equipment enclosure. The limits are summarised below, and EN 55011 is referred to for the test method (this standard deals with industrial, scientific and medical equipment)

30 MHz - 230 MHz	40 dBµV/m QP measured at 10m
230 MHz - 1 GHz	47 dBµV/m QP measured at 10m

12.5.6. Part 4: Emission and Immunity of the Signalling and Telecommunications Apparatus

This part specifies limits for electromagnetic emission and immunity for signalling and telecommunications apparatus.

The reference test method for radiated electromagnetic emissions is described in EN 55022 (limits and methods of radio interference characteristics of information technology equipment). The limit levels are summarised below:

30 MHz - 230 MHz	40 dBµV/m QP measured at 10m
230 MHz - 1 GHz	47 dBµV/m QP measured at 10m

12.5.7. Part 5: Fixed Power Supply Installations

This part applies to emission and immunity aspects of EMC for electrical and electronic apparatus and components intended for use in railway fixed installations associated with power supplies. This includes the power feed to the apparatus, the apparatus itself with its protective control circuits, conductors at railway system voltage but not carrying current (e.g. overhead contact lines), trackside items such as feeder lines, switching stations, power autotransformers, booster transformers, substation power switchgear and power switchgear to other longitudinal and local supplies.

The emission limits for substations are summarised below, For measurements above 30 MHz, only the vertical polarisation is evaluated.

9 kHz	55 dBµA/m QP, measured at 3m
≤150 kHz	45 dBµA/m QP, measured at 3m
>150 kHz	50 dBµA/m QP, measured at 3m
≤30 MHz	20 dBµA/m QP, measured at 3m

>30 MHz	55 dBµV/m QP, measured at 3m
1 GHz	35 dBµV/m QP, measured at 3m

The values being endpoints of straight lines on dB/log(f) plots

The measurements are conducted 3m from the fence of the substation, or if no fence exists 10m from the apparatus.

The emission limits from railway feeder lines are summarised below:

30 MHz - 230 MHz	40 dBµV/m QP, vertical polarisation, measured at 10m
230 MHz - 1 GHz	47 dBµV/m QP, vertical polarisation, measured at 10m

The emissions from substations at power frequencies and harmonics up to 9 kHz, when measured 3m from the fence of the substation, the RMS value of the magnetic field gradient in any axis shall not exceed 50A/m.

The emission limits for equipment operating at less than 1000V RMS are summarised below:

9 kHz	55 dBµA/m QP, measured at 3m
≤150 kHz	45 dBµA/m QP, measured at 3m
>150 kHz	50 dBµA/m QP, measured at 3m
≤30 MHz	20 dBµA/m QP, measured at 3m
>30 MHz	55 dBµV/m QP, vertical polarisation, measured at 3m
1 GHz	35 dBµV/m QP, vertical polarisation, measured at 3m

The values being endpoints of straight lines on dB/log(f) plots

There are no limits specified within the general space inside the boundary of the substation.

For apparatus which is underground, measurements shall be made at the surface of the ground above the apparatus as described in this part of the Pre-standard in the frequency range 9 kHz to 150 kHz, and the limits given for the emissions at radio frequencies from sub-stations shall be applied.

There are no limits for emissions into the active space of the underground railway due to the complexities of obtaining measurements in the confined space and the lack of a precise method of relating the measured values to the degree of disturbance which other apparatus would suffer.

12.6. SAE (SOCIETY OF AUTOMOTIVE ENGINEERS - USA) RELEVANT STANDARDS

12.6.1. SAE J551-1 1996: Performance Levels and Methods of Measurement of Electromagnetic Compatibility of Vehicles and Devices

In summary, this document details emissions tests over the range 60 Hz to 18 GHz, but only sets limits for emissions in the same bands as the CISPR requirements. The table below summarises this information:

SAE J551 Part	Test Type	Frequency Range	Test Distance	Comparable Standard
2 (see note 1)	Broadband	30 MHz to 1 GHz	10m and 3m	CISPR 12
	Narrowband	150 kHz to 1 GHz	10m and 3m	CISPR 12
4 (see note 2)	Broad and Narrow	150 kHz to 1 GHz	N/A	CISPR 25
5 (see 7.2)	Broad and Narrow	150 kHz to 30 MHz	1m or 3m	None

Note 1: SAE J551 Part 2: Limits and methods of measurement of radio disturbance characteristics of vehicles, motorboats and spark-ignited engine-driven devices. (SAE Standard)

Note 2: SAE J551 Part 4: Test limits and methods of measurement of radio disturbance characteristics of vehicles and devices, broadband and narrowband, 150 kHz to 1 GHz. (SAE Standard)

12.6.2. SAE J 551-5 1997: Performance Levels and Methods of Measurement of Magnetic and Electric Field Strength from Electric Vehicles, Broadband, 9 kHz to 30 MHz.

This SAE recommended practice was initially included as an appendix to the historical broadband radiated noise test. It was published separately in June 1995, and is now in use in the industry as the standard method for electromagnetic emission testing of electric vehicles in the USA.

Conducted and radiated emissions measurements of battery charging systems that use an induction power coupling device are not covered by this part.

The measurement of electromagnetic disturbances for frequencies from 30 MHz to 1 GHz and narrowband electromagnetic disturbances for frequencies from 150 kHz to 30 MHz are covered in SAE J 551-2.

The table below summarises the emission limits:

Frequency	Level dB(µV/m/kHz)
9 kHz to 4.77 MHz	99.9 - 20 $\log_{10}$(freq.(MHz)/0.009)
4.77 MHz to 15.92 MHz	154.4 - 40 $\log_{10}$(freq.(MHz)/0.009)
15.92 MHz to 20 MHz	89.4 - 20l og_{10}(freq.(MHz)/0.009)
20 MHz to 30 MHz	22.5

Frequency	Level dB(µA/m/kHz)
9 kHz to 4.77 MHz	48.4 - 20 $\log_{10}$(freq.(MHz)/0.009)
4.77 MHz to 15.92 MHz	102.9 - 40 $\log_{10}$(freq.(MHz)/0.009)
15.92 MHz to 20 MHz	37.9 - 20l og_{10}(freq.(MHz)/0.009)
20 MHz to 30 MHz	-29.0

The measurement instrumentation shall conform to CISPR 16-1, and the band definitions are also in accordance with CISPR 16-1.

The test site shall conform to the requirements of SAE J551-2 (CISPR 12).

The preliminary scan test procedure requires the drive wheels to be elevated using insulated jack stands. However, if operating the vehicle in the unloaded state would cause damage to the propulsion system or result in lower radiated emissions, a dynamometer may be used.

The vehicle should then be taken to a steady-state speed of 25mph (40km/h) in top gear. The measurements should be taken in the vertical plane for the E-Field, and all three planed for the H-Field. All four sides of the vehicle should be characterised.
The direction of the highest emission from the vehicle will be obtained from these results. With the antennae positioned and oriented in the direction of this maximum received signal, the tests should be repeated for 10 mph (16 km/h) and 40 mph (64 km/h) in order to determine the speed that produces the highest emission.

The frequency band shall be divided up into a minimum of 11 bands with approximately one band per frequency octave. Each band is to be scanned to determine the radiated field strength as a function of frequency. Spot frequency measurements are not recommended, but shall be considered sufficient provided that a minimum of two frequencies per octave are measured, and that the ratio of successive frequencies is not greater than 1.6. A range of frequency bands is included in the document.

Measurements of on-board chargers shall be made at the maximum trickle charge level, but with the vehicle propulsion system de-energised. If the vehicle is designed to be charged from more than one power line voltage, then measurements shall be made at each line voltage. The required test frequency range shall be swept.

If a digital control or switching circuit utilises a frequency that exceeds 1.705 MHz, then radiated emission tests of the charging system are also required. The measurements shall be made in accordance with SAE J 551-2 using the narrowband radiated emissions limit in the frequency range 30 MHz to 1 GHz.

12.6.3. SAE J 1772 1996: Electric Vehicle Conductive Charge Coupler

In respect of electromagnetic emissions, this recommended practice states: "During charging, the system shall meet the requirements specified in SAE J 551-5".

12.6.4. SAE J 1773 1995: Electric Vehicle Inductive Charge Coupling

In respect of electromagnetic emissions, this recommended practice states: "EMC requirements of the vehicle inlet under all power levels will meet radiated and conductive requirements of SAE J 551".

13. RECOMMENDATIONS FOR REGULATIONS AND STANDARDS

13.1. Frequency Range

Current regulations and standards are based upon CISPR 12, which specifies emissions tests over the range 30 MHz to 1GHz. Measurements are confined to electric fields as magnetic fields are unlikely to have significant effects. Specific regulations, such as ENV 50121 for railways, proposes emissions tests from 9kHz to 1 GHz but frequencies below 150 kHz are not mandatory. This regulation also proposes magnetic field measurements between 9kHz and 30 MHz. The Automotive EMC Directive, 95/54/EC, is also vague in the specification of the required test frequencies and can give the impression that only 13 spot frequencies need to be tested. However, most competent bodies understand this and simply demonstrate 13 spot frequencies to the Testing Authority although the system under test has undergone a full examination over the entire frequency range.

There are already discussions relating to extending the upper frequency limit, for example to 18 GHz, and even higher frequencies and 400 GHz has also been suggested. It is true that the number of sources is increasing and the frequencies at which they operate are now beyond the current frequency limits. Examples include, cruise control radar systems for vehicles operating at 24 GHz or 77 GHz, electronic road tolling operating at 5.8 GHz and satellite broadcasting in the 11 GHz band.

It is easy enough to argue the case to extend the frequency range of emissions tests, and for that matter immunity as well, but there are practical and logistical factors that need to be taken into consideration. First of all how many frequencies should be tested? Secondly the cost of the test equipment will rise if broadband coverage of very high frequencies, for example greater than 18 GHz, is deemed necessary. We also need to take into account the performance of the measuring equipment as discussed below.

It is recommended that the emissions test frequencies are extended to cover new sources but a continuous sweep is unsuitable. Therefore we propose that the Approvals Authority agrees a range of frequencies, these may be spot frequencies or bands, where protection is important. The obvious transmissions being the terrestrial radio and television broadcasts, satellite broadcasts and mobile communications bands. This concept is already proposed in some regulations such as CISPR 26. This approach will target the critical frequencies and will allow testing to be carried out in a reasonable time scale.

Whilst most of the emissions measurements consider the electric field, it is worth including magnetic field measurements as described in ENV 50121. There is a trend to use electric and hybrid motor drives in road vehicles, which can generate significant magnetic fields. Whilst these fields may diminish rapidly with distance, there is potential for generating disturbances on the vehicle itself which could affect radio communications equipment.

13.2. Emissions Limits

Current emissions limits are based upon CISPR 12. These are fixed at frequencies between 30-75 MHz rising logarithmically to a different fixed level at frequencies above 400 MHz; different levels are provided for different bandwidths. In addition, different levels are specified for narrow band and broad band signals to cover transmissions with a single frequency source or broadband ‘noise’ type signals.

The results from the emissions tests as proposed by CISPR 12 may be described as average, peak or quasi-peak measurements; quasi-peak is simply a type of filter intended to simulate the front end of radio and television receivers. It is important to ensure that these measurements accurately follow the current and future trends in radio communications. It must also be remembered that many designs of electronic circuit, and certainly those of the future, will utilise digital circuits. These designs will be sensitive to fast rising signals and so an average or quasi-peak measurement will not be adequate. In these cases a peak measurement should be used.

The current test levels proposed would appear adequate for current systems and future systems of a similar type. However, the required levels of emissions for systems operating at frequencies over 1 GHz need to be considered. It would not appear unreasonable to simply extend the current frequency range alone whilst retaining the same limits. Alternatively, on the basis that the Approvals Authority will agree the frequencies needed to be protected, it is appropriate to call upon the Approvals authority to recommend the limits of emissions at the specific frequencies. Recommended levels have already been agreed for UHF television and FM radio.

The question of digital signals is a complex one and needs to be addressed separately. Typically digital signals comprise complex modulation of the carrier wave using a range of techniques. A simple example would have packets of data at about 200 Hz containing 128 bits of data. This type of data is also likely to be encrypted using appropriate coding techniques. When deciding the limits for digital signals it is important to consider the form of the modulation and properties of the waveform. Digital systems may also be capable of error tolerance, built into the coding and decoding process. This should be considered when deciding upon limits for emissions.

13.3. Test Methods

Traditionally emissions measurements are carried out using a radio receiver or spectrum analyser. The radio receiver approach is generally more accurate but scans the frequency range taking measurements at each pre-determined spot frequency. This can take a long time depending upon the number of spot frequencies selected. On the other hand the spectrum analyser can take a broad band scan but is less accurate as a result. However, this can be improved by reducing the bandwidth of the analyser and measuring over the range in stages. Hence there is a trade-off in accuracy against measuring speed. Either approach is capable of providing satisfactory results.

The test location for road vehicles is currently defined as a 30 metre radius circle which is clear from reflecting surfaces; a smaller 15 metre radius is specified for the testing of sub-assemblies. There is debate as to the use of screened anechoic chambers for emissions tests. This author is of the opinion that such chambers are acceptable provided their resonance and mode generation characteristics are acceptable to the Approval Authority and are fully understood and documented.

Emissions tests can be performed using an antenna to vehicle spacing of either 3 or 10 metres. The 10-metre separation is preferred, as interactions with the vehicle are lower but the effect of background sources may be higher; this is a function of the test site. It is important to remember that the acceptance angle of the receiving antenna used for the measurements needs to be considered when measuring the emissions from large vehicles. It may be necessary to take measurements at a number of locations around the vehicle to ensure full coverage is achieved.

Regulations for railways specify a ‘tunnel’ outside which emissions will be limited in line with CISPR standards. However, it is possible that radio communications equipment will be operated within this ‘tunnel’ and may be affected by electromagnetic disturbances. It is also possible that offices and houses could lie within the 10-m corridor. Examples of potential victims are mobile communications equipment used inside the train and trackside communications. This aspect of the electromagnetic performance needs examination.

13.4. Transport Applications

In the future there will be a trend to move to electric and hybrid powered road vehicles as well as other technologies such as fuel cell and flywheel batteries. These systems have the potential to generate large transient switching waveforms involving high currents of several hundred amps. This could cause significant disturbances to the RF spectrum unless adequately controlled. The use of high power electric motors is also likely to generate significant electric and magnetic fields at power frequencies, which also need to be controlled.

Measurements by TRL of the emissions from an electric car showed that significant emissions, in excess of the CISPR limits, were generated at 81 MHz, 135 MHz and between 30 and 33 MHz. This shows the potential for generating RF emissions. It is recommended that other electric vehicles be tested to examine their performance.

It is also important to test ancillary equipment which may be part of the vehicle system but may not be physically part of the vehicle, for example the charging system for electric vehicles. Measurements made by TRL showed that the charging system for an electric vehicle which used an inductive charging system generated electromagnetic disturbances in excess of the CISPR limits between 420 and 430 MHz. This is alarming as this band is used for the UK TETRA system. It is important that these ancillary pieces of equipment are tested to appropriate requirements.

In the future many road vehicles will be equipped with safety devices such as collision avoidance systems, occupant protection and pedestrian protection. Vehicle manufacturers are already demonstrating examples of all these systems. A similar scenario exists for railway stock, for example the automatic train protection system. These systems will contain electronic and electrical systems capable of generating electromagnetic disturbances. There will be a high level of digital techniques used in the designs and regulations will need to take all these aspects into account.

Part of this development will include the use of multiplexed wiring systems running around both road vehicles and trains to provide communications between the different electronic systems. These systems are already in use, for example the ‘CAN’ bus used in road vehicles. The wiring systems used for these communications have the potential to generate significant electromagnetic emissions and measurements by TRL have shown that levels in excess of the CISPR limits can be generated depending upon the peak to peak voltages used in the data transmission. These tests were carried out using the ‘twisted pair’ wiring scheme proposed in the ‘CAN’ specification. It is recommended that this approach is re-examined and the use of alternative cabling systems considered, for example the use of screened cables instead of the ‘twisted pair’ approach.

Trends in passenger transport are likely to grow in the development of electric tramways. Whether these use rail pickups or overhead cables, it will be necessary to address the potential disturbances from the power pick up systems. However, railway experience should enable these tramway systems to operate satisfactorily.

14. RECOMMENDATIONS FOR FUTURE WORK

As a result of this programme of research we have identified a number of topics which we believe are worthy of further research:

1. Perform a series of more detailed emissions tests on the vehicles used for this study to determine the precise source of the emissions that were found to exceed the current regulations.

2. Carry out a programme of tests on a number of electric/hybrid vehicles to measure the emissions characteristics of a wider range of units including their charging systems.

3. Carry out an up to date survey of the electromagnetic sources in the UK.

4. Perform a series of emissions on a vehicle fitted with a collision avoidance/automatic cruise control radar system.

We would hope to involve vehicle manufacturers in some of this work, in particular in identifying possible problems with particular vehicles.

15. CONCLUSIONS

This project has provided a world wide review of current and future technology for electrically powered public and private transport, examined the potential effects of these technologies on the RF spectrum, conducted practical emissions measurements on a variety of systems, and reviewed current EMC emissions regulations. Implications of the developments in technology have been examined and recommendations made to ensure the radiofrequency spectrum will be adequately protected.

There will be considerable growth in the radiocommunications network including systems on vehicles using radio waves for a range of applications including inter-vehicle communications, highly accurate global positioning and radar for active cruise control and collision avoidance.

Four sets of EMC tests for emissions have been completed on an electric car, a hybrid car, an articulated heavy goods vehicles fitted with a datacommunications ring and a railway locomotive. In some cases the levels of radiofrequency emissions exceeded current regulations.

The results from the tests showed that the levels of emissions were below the current Automotive EMC Directive reference levels for the HGV. However, the electric vehicle potentially exceeded these levels, and tests showed that the charging circuit for the electric vehicle produced radiated emissions in excess of these limits which could affect the radio spectrum. CISPR have, however, recently agreed that CISPR 11, regarding Industrial, Scientific and Medical (ISM) radio-frequency equipment, will apply to electric vehicles whilst they are being charged.

A number of problems were also encountered with the hybrid petrol/electric vehicle. These were frequencies near hospital pagers and emergency location beacons. It will be necessary to reduce these emissions to ensure safe reliable operation of all the potential systems affected.

In the future large numbers of electric motors will be found as the main source of motive power in pure electric vehicles and hybrids. These have the potential to generate stray electromagnetic emissions. However, these vehicles will be required to meet the Automotive EMC Directive, which should satisfactorily control their emissions and immunity response.

In the next few years high power switching circuits will be used on vehicles for motor control. Such systems already exist on railway locomotives. These systems have the potential to generate significant transient disturbances. However, it is possible that special electronic circuit design and wiring loom construction will overcome many of the problems.

There is a trend in mobile communications systems to use higher frequencies, UHF and above, and lower powers, typically 10-Watts maximum. It is believed that these new systems are unlikely to pose a threat to other electronic systems.

Many new systems for road and rail transport will utilise datacommunications networks. Frequencies are available for these systems but their use needs to be monitored to ensure that adequate electromagnetic compatibility is achieved.

Data communications systems will continue to use digital techniques with their associated fast edged signals. These types of waveform can affect electronic circuits more seriously than amplitude or frequency modulated signals. It is important to ensure that these types of digital systems are monitored to ensure they do not cause problems with other electronic circuits.

Whilst the majority of vehicle based systems are unlikely to cause problems of electromagnetic compatibility with other systems outside the vehicle, it is important to consider the other electronic systems fitted to the source vehicle. It is possible that vehicle communications could be affected by on-vehicle emissions although good design and installation should be able to overcome most of the problems.

Systems for collision avoidance, lane detection and automatic cruise control systems will make use of radar, laser and video camera systems to enable the vehicle to ‘see’ in front and detect objects. These systems will also use inter-vehicle communications as well as possible use of roadside beacons and satellite systems. The electromagnetic compatibility of these systems needs to monitored and controlled.

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ANNEX A. TEST EQUIPMENT

A.1. Test Equipment (Cars and HGV).

Electro-Metrics Limited Interference Analyser 16 Hz - 50 kHz. Model EMC-11 Mk IV.

Rohde and Schwarz EMI Test Receiver 9 kHz - 2750 MHz. Model ESCS 30.

Electro-Metrics Limited Interference Analyser. 0.5 GHz - 18 GHz. Model EMC-60 Mk IV.

Magnetic Loop Antenna. Type ALP-10/11. 20 Hz - 50 KHz.

Magnetic Loop Antenna. Type ALP-70. 10 kHz - 30 MHz.

Double Ridged Guide Antenna Type 3115. 1 - 18 GHz.

Log Periodic Antenna 300 MHz – 1 GHz.

Bi Conical Antenna 30 – 300 Mhz.

A.2. Test Equipment (Train).

Hewlett-Packard HP8591EM EMC Spectrum Analyser. 9 kHz – 1.8 GHz.

Magnetic Loop Antenna. Type ALP-70. 10 kHz - 30 MHz.

Bi Conical Antenna 30 MHz – 1 GHz.

ANNEX B. MEASUREMENT RESULTS

B.1. ELECTRIC VEHICLE

B.2. HYBRID VEHICLE

B.3. HGV WITH HIGH-SPEED DIGITAL DATA BUS

B.4. MULTIPLE ELECTRICAL UNIT TRAIN