TRANSPORT RESEARCH LABORATORY

Radiation safety standards for electronic fee collection and enforcement equipment

Prepared for Tolling and Private Finance Division, Department of the Environment, Transport and the Regions

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Executive Summary

The electronic fee collection and enforcement equipment tested at TRL produced non-ionising electromagnetic radiation in the microwave and infra-red regions. These wavelengths are known to be capable of causing human health problems in certain circumstances. This study reviews in general terms those health effects and considers the extent to which the equipment used in the tolling trials might be likely to cause problems by reference to agreed standards.

Incident non-ionising radiation affects human health through thermal and non-thermal mechanisms. The thermal effects are best understood and form the basis of current limits for human exposure.

Current UK and European standards require that the maximum Effective Isotropic Radiated Power output (EIRP) of a transmission array operating at 5.8 GHz should not exceed 3dBW. This translates to a maximum power output of 2W for an antenna without gain and reduces with increasing gain such that a typical 23dB gain antenna can generate 10mW. Manufacturers tend to operate equipment close to these limits in order to maximise the signal to noise ratio, and hence performance, of their equipment.

A proposed European pre-standard defines the limit of human exposure to microwaves at 5.8 GHz as a power density of 10 Wm^{-2}. Preliminary calculations suggest that, at maximum allowable power output, typical beacons would generate power densities more than 1000 times lower than this limit. These findings imply that microwaves from EFC beacons do not pose a health risk to road users in normal operating circumstances. However, the standards were set by considering continuous signals as insufficient research has been undertaken to provide the basis of a standard for pulsed signals.

The safe limits of exposure to infra-red (IR) radiation are even less certain. There are no appropriate UK standards against which the performance of the non-laser IR equipment can be compared. It is recommended that specialist measurements be carried out on the infra-red systems to verify these preliminary conclusions.

The sources examined during this study were relatively low powered compared with many other illuminators available for security applications. If it is important for the illumination to be essentially invisible to motorists, then more stringent filtering and more intense IR sources may be required.

With existing microwave and IR communication standards being revised, it is recommended that this subject be re-visited as new documents become available.

1 Introduction

Two specific tolling systems were the subject of technology trials at the TRL test track between November 1996 and June 1997. Both systems were required to demonstrate an automatic Electronic Fee Collection (EFC) transaction within a communication zone several metres in length. In addition, the systems were required to capture evidence automatically which could be used to support the enforcement of toll payment where the EFC transaction had been inadequate, for whatever reason.

For the tolling transaction both systems used 5.8 GHz microwave communications links between gantry-mounted beacons and vehicle-mounted 'on-board' units (OBUs). As evidence to support the enforcement of toll payment, both systems captured number-plate information using camera images illuminated with infra-red light. Using these frequencies from the electromagnetic spectrum (see Figure 1) provides reliable communication links, and adequate illumination of retro-reflective number plates under most ambient conditions.

Wavelength 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1
(metres)

X-rays Ultra-violet Visible IR (heat) Radiowaves

Violet 4 X 10^{-7} 7.5 X 10^{-7} Red

Figure 1 The electromagnetic spectrum

However, these wavelengths of electromagnetic radiation are known to be capable of causing human health problems in certain circumstances. The main known health effects of exposure to microwave and infra-red radiation are tissue damage caused by heating, including burns and cataracts. There is considerable ongoing debate about the potential for electromagnetic radiation to cause cancer, particularly under prolonged exposure.

The objective of this study was to review the potential effects on human health caused by the electromagnetic radiation.

2 Human health effects of non-ionising electromagnetic radiation

Electromagnetic radiation can affect human health by causing injury or impaired function.

The damage caused by incident non-ionising electromagnetic radiation arises because the tissue or tissue components absorb electromagnetic energy at specific wavelengths leading to heating. The rate of energy absorption is a function of the duration of exposure and the relative sensitivity of the tissue. As discussed further below, sensitivity is affected by a number of factors including the wavelengths of non-ionising electromagnetic radiation that the tissue absorbs.

In the context of this study, impaired functions (usually referred to as non-thermal health effects) are associated mainly with microwave radiation. The process by which microwaves disrupt the normal functioning of biological processes is not well understood, but is thought to be related to electric currents induced by the electromagnetic field.

The understanding of the thermal effects is sufficient to form the basis of current standards. As research continues into the non-thermal effects, these standards may change, but for the present the uncertainty in this area impinges little upon existing safety limits.

2.1 Short-term exposure

In very general terms the tissue damage caused by short term exposure to incident non-ionising electromagnetic radiation most likely to be of concern is effectively a consequence of localised heating. The sensitivity of the tissue in these circumstances is dependent on its water content and local thermoregulatory capabilities (e.g. blood supply, surface area to volume ratio). So, for example, the head, neck and cornea are particularly vulnerable to damage. The injuries sustained under short-term exposure are therefore most likely to be burns or cataracts, although obviously more severe medical conditions are likely to arise as the duration of exposure continues.

2.2 Long-term exposure

The question of the human health effects of long-term exposure to low levels of non-ionising electromagnetic radiation is highly controversial. In the past this has focused mainly on the risks of living in close proximity to high voltage electricity cables, although exposure at work (e.g. from visual display units) has also been an area of debate.

The key question is whether long-term exposure to low levels of non-ionising electromagnetic radiation can damage cellular DNA and thereby cause cancers. Following an exhaustive review (NRPB, 1992) the National Radiological Protection Board advisory group on non-ionising radiation concluded as follows:

> *'The experimental findings are... not very helpful. It cannot be concluded either that electromagnetic fields have no effect on the physiology of cells..., or that they produce effects that would, in other circumstances, be regarded as suggestive of potential carcinogenicity.'*

Although not specifically related to microwaves, they go on to conclude:

> *'In summary, the epidemiological findings... provide no firm evidence of the existence of a carcinogenic hazard from exposure... to the extremely low frequency electromagnetic fields that might be associated with residence near major sources of electricity supply, the use of electrical appliances, or work in the electrical, electronic and telecommunications industries.'*

2.3 Individual variations in sensitivity

Individual road users will vary in their susceptibility to the effects of incident non-ionising radiation. It is normal for standards to be set with an adequate margin of safety to take account of this variability. However, cardiac pacemakers and even some metallic neurostimulatory prosthetic implants may be affected by low intensity radiation, even though they are designed to cope with the typical EM fields that are encountered in every day life.

While the responsibility for ensuring the safety of people fitted with such devices rests with the standards bodies and the prosthetic implant manufacturers, it is not clear the extent to which any increased sensitivity has been addressed within the setting of existing standards. Advice may need to be sought from the manufacturer and the relevant health authority on this issue.

2.4 Pulsed v continuous waves

The 5.8 GHz microwave communications links used in the trials at TRL send digital signals, effectively pulsed electromagnetic waves. The international standards for human exposure to incident non-ionising electromagnetic radiation (reviewed later in this report) are based on *continuous* waves.

It is generally thought that pulsed waves have very different human health effects from those caused by continuous waves. However, there is currently little information available on pulsed wave effects for comparison with evidence on continuous wave effects. While there is a lack of research evidence to inform this debate it is not possible to be more certain of the significance of waveform factors. However, because pulsed waves may be more damaging than continuous waves and because the standards refer to continuous waves while the tolling equipment produces pulsed waves, it will be important to look for a significant margin of safety in comparing the exposure levels of these systems with the international standards.

3 Microwave radiation

3.1 Microwave communication standards

The European Committee for Posts and Telecommunications (CEPT) allocated the frequency range 5.795 GHz to 5.805 GHz for use for road tolling and other Road Transport Informatics applications (CEPT, 1992). Another band from 5.805 GHz to 5.815 GHz was later added to help fulfil the requirements of multi-lane systems and proposals have been made to extend further.

5.8 GHz is the agreed standard for microwave communications for electronic fee collection applications in Europe. While Japan and the USA may choose to operate at different frequencies and ISO is likely to seek to harmonise the standards worldwide, it will be many years before the agreed European standard might change. In this report only the potential human health effects of EFC systems based on microwave communications operating at 5.8 GHz have been considered.

3.2 Human exposure to microwaves

3.2.1 Measures and units

Two measures are used to set standards for human exposure to microwaves:

- maximum power output, and
- power density.

Maximum power output

Maximum power output is a comparative measure of the radiated power output of an antenna. It is measured in terms of the maximum Effective Isotropic Radiated Power (EIRP). This is a comparison, at a given distance from the antenna, of the field strength from a directional antenna with the field strength from an isotropic (uniformly radiating) antenna. The power outputs of the two antennae are compared using a logarithmic scale, decibel watts (dBW), a decibel watt being ten times the logarithm of the ratio of the output power of the antenna over an input power of one watt. As an example, a 17 dB gain antenna with an input power of 1 W producing a radiated power of 0.2 W has an EIRP of 10 dBW:

EIRP (in dBW) = Antenna gain + Power

where,

$$\text{Power} = 10 \times [\log_{10}(0.2\text{W}/1\text{W})] = -7 \text{ dBW}$$
$$\text{Antenna gain} = 17 \text{ dB} \times 1\text{W} = 17 \text{ dBW}$$

An alternative measure is the decibel milliwatt (written as dBmW or dBm) which is identical to dBW, except that the beam power is placed over 1 milliwatt instead of 1 watt.

Power density

Power density reflects the fact that damage to human tissue caused by incident non-ionising radiation is dependent on the rate of energy absorption by the tissue. Amongst other things, this is affected by the duration of exposure and the relative sensitivity of the tissue. These issues are discussed above.

As the frequency of incident radiation increases, the depth in the body to which the radiation penetrates decreases (see Figure 2).

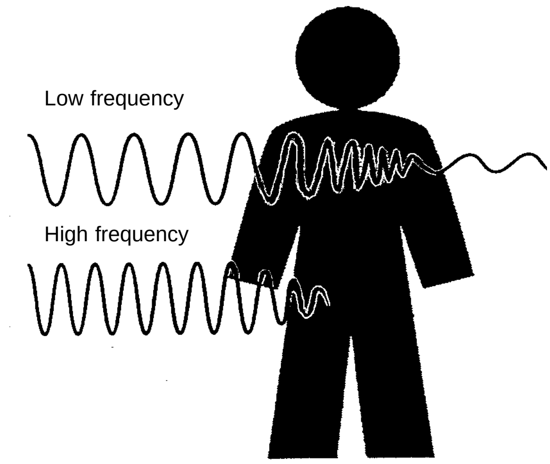

Figure 2 Absorption depth is proportional to the frequency of the radiation

Low frequencies

At low frequencies radiation penetrates deeper into tissues and causes deep-seated heating. Incident non-ionising radiation will, therefore, do significantly more damage to human tissue if it is concentrated in specific areas such as the head or the neck which have a relatively small surface area to volume ratio and high inherent sensitivity. Exposure limits in the standards are consequently much lower in these regions.

For low frequency radiation the rate of energy absorption by a tissue is a function of tissue volume and is known as the Specific Energy Absorption Rate (SAR), measured in Watts per kilogram.

High frequencies

As radiation frequency increases, SARs for specific areas of the body become less relevant as heating is concentrated in the skin and outer tissues. Since the exposure is then likely to lead to superficial burns, the rate of energy absorption by a tissue becomes a function of area. In such circumstances power density is then more accurately defined as power per unit area (normal to the direction of propagation), measured in Watts per square metre. For situations where SARs are not appropriate, the NRPB has produced a set of investigation levels, which if met, guarantee compliance with the basic restrictions.

3.2.2 Microwave standards

A number of standards and related documents address to some extent the power outputs of antennae transmitting in the microwave region. These are described in the following sections.

These standards are designed to address continuous wave signals. Digital or pulsed signals may have more severe health effects, but at present safe levels of exposure to such signals have not been established (see section 2.3). Like the latest generation of mobile phones the tolling systems assessed in recent trials at TRL operate on a pulsed (digital) signal basis.

CEPT Standards

CEPT recommends a maximum EIRP of 3dBW (CEPT T/R 22-04). Using the calculation method described above it can be deduced that this limit corresponds to a maximum power output of 2W for an antenna without gain. For antennae with gain, the allowable maximum power output is correspondingly reduced to stay within the CEPT limit. Using the calculation method above for some typical antenna gains used for EFC, output powers are shown in Table 1.

Table 1 Maximum power of antennae following the CEPT recommendations

Antenna gain	*Max. power output (mW)*
17	40
23	10
24	8

NRPB Standards

The National Radiological Protection Board (NRPB,1995) provide guidelines to protect against thermal effects of radiation above 10MHz. The current limits on exposure in terms of power density are summarised in Table 2. These are based on EN 60215 ‘Safety requirements for radio transmitting equipment’, 1987 (IEC 215).

Other European power density standards

The European standard BS EN 60215 (British Standard, 1996) stipulates peak levels of the electric and magnetic fields produced by transmitting equipment as 200 V/m or 0.5 A/m, respectively in the frequency range 30 MHz to 30 GHz. These provisional limits correspond to an approximate radiation power density of 100 Wm^{-2}. These apply to distances in excess of 5 cm from the surface of any equipment. The levels, and the standard methods by which they are to be measured, are under consideration.

The European Committee for Electrotechnical Standardization, (CENELEC) have published a European pre-standard, DD ENV 50166-2, which stipulates that the maximum permissible incident radiation, is to be 10 Wm^{-2}. Being a pre-standard, it is still open to discussion and amendment.

US Power density standards

The American IEEE standard for safety levels with respect to human exposure to radio frequency EM fields, (3 kHz to 300 GHz), state that the maximum permissible power density, S is directly proportional to the frequency, (f), of the EM radiation such that $S = f/1500\ mWcm^{-2}$. This particular relationship applies only in the frequency range 3 to 15 GHz and gives a value of S (at 5.8 GHz) of 38.7 Wm^{-2}.

Table 2 Basic restrictions on exposure to electromagnetic radiation (from ‘Restrictions on exposure to static and time varying electromagnetic fields’, NRPB 1995)

Frequency range	*Quality*	*Limit*
100 kHz to 10 GHz	SAR averaged over the body and over any 15 min period	0.4 W kg^{-1}
	SAR averaged over any 10 g in the head or fetus and over any 6 min period	10 W kg^{-1}
	SAR averaged over any 100 g in the neck and trunk and over any 6 min period	10 W kg^{-1}
	SAR averaged over any 100 g in the limbs and over any 6 min period	20 W kg^{-1}
1.6 GHz to 300 GHz	Power density incident on any part of the body	100 W m^{-2}

3.2.3 Summary of microwave limits

Table 3 Summary of microwave emission limits at 5.8GHz

Applicability	*Source*	*Quantity being addressed*	*Value*
European	CEPT	max. power output	3 dBW
National	NRPB	Power density	100 Wm^{-2}
European	BS EN 60215	Power density	100 Wm^{-2}
European	CENELEC DD ENV 50166	Power density	10 Wm^{-2}
American	IEEE	Power density	39 Wm^{-2}

3.3 Compliance of equipment with microwave standards

3.3.1 Maximum power output

A microwave Electronic Fee Collection (EFC) system typically consists of multiple antennae with different gains operating at slightly different frequencies. This makes the calculation of maximum power output a complex process.

For such a situation, the CEPT requirements stipulate that the EIRP of the whole array should be less than or equal to 3 dBW.

Figure 3 EFC Microwave transaction under gantry on the TRL test track

Verification of this level is complex and requires knowledge of antenna gains and beam footprints as well as calibrated measurement apparatus. Manufacturers are cautious about discussing power output levels and antenna gains. In part, this is because of commercial considerations but it is worth noting that it is possible to improve signal to noise ratio, and potentially system performance, by increasing power output. Power densities resulting from typical antennae radiating the maximum power permitted by CEPT are well inside safety requirements (as is illustrated below) so it may be possible to safely enhance performance during trials by transmitting at power levels above the CEPT requirement.

3.3.2 Power density

In order to consider the power density incident on a human passing through a microwave footprint created by tolling equipment it is necessary to consider the radiated power of the source and the distance from the microwave source to the subject.

To determine power levels at a distance from a radiating source, both the inverse square law and the antenna beam pattern have to be considered. Some gross simplifying assumptions are made below to provide 'ball-park' quantification of an extremely complex situation. The validity of the application of the inverse square law is further considered in Appendix A.

Take as an example a transaction antenna of 23dB gain which is radiating the maximum power permitted by CEPT of 10mW. At 6m from the source, the majority of the radiation falls within an area of $0.6m^2$. Assuming that this can be considered uniform, the power density is less than 10mW over $1m^2$, or $0.01Wm^{-2}$. This is a factor of 1000 below the most stringent power density requirement of Table 3.

Power densities at other distances can be estimated (making assumptions as noted above). Simple calculations suggest that the 10mW would have to be concentrated within a circle of diameter 40mm before the $10Wm^{-2}$ limit was breached, and this is smaller than the aperture of the transmitting beacon.

On the basis described above, it can be concluded that in all normal circumstances the performance of microwave EFC transaction equipment is likely to fall within the safe limits for human exposure as long as the CEPT power radiating requirement is satisfied.

4 Infra-red radiation

4.1 Infra-red radiation in enforcement

With camera based enforcement systems, the enforcement camera's field of view can be illuminated with infra-red light, to allow imaging at night, and to enhance contrast during daylight. The infra-red illuminator is sited next to the camera to maximise retro-reflected light from the numberplate.

If a vehicle passing through an EFC system is identified as a violator, an image of the vehicle's rear number plate is typically captured by a security camera. For night operations, and to reduce the effects of inclement weather conditions, the scene is typically illuminated by infra-red (IR) light.

Infra-red illumination of this kind is already in routine, widespread use in the UK to facilitate security surveillance, for example using closed-circuit television.

4.2 Specific risks to human health

While the comments made in section 2 are relevant in considering human health effects, for the type and range of exposure most likely to occur from IR illumination in these circumstances, the prime potential damage site is the eye. Staring at a conventional visible light source causes the iris to contract, restricting the amount of light entering the eye to prevent the most sensitive, light-detecting part of the eye, the retina, from being damaged. However, an IR source does not, typically, produce significant visible light and so the iris will not contract, potentially allowing the retina to be exposed to damaging levels of incident radiation. Damage to the cornea (discussed in section 2) is also a general risk to the eye from IR radiation.

4.3 Standards and recommended safety levels

The area of the electromagnetic spectrum identified as the 'near IR' region is from about 770 nanometres to 1.4 micrometres. The safety limits set for IR bulbs in this region are best described as vague.

UK and European standards

There are currently no relevant UK standards to which such equipment must conform. A process of limit setting is, however, currently under assessment. Dutch authorities have begun research into the setting of limits on emissions of non-laser IR lamps, but their report is not expected for at least another year.

US Standards

The American Conference of Governmental Industrial Hygienists, (ACGIH), publish a set of threshold limit values, (TLV), on biological exposure indices, which are reviewed and updated each year. For an IR lamp in the near IR region, according to the US (ACGIH) regulations, radiance viewed by the eye, should be limited to:

$$\sum_{770}^{1440} L_\lambda . d\lambda \leq 0.6 / \alpha$$

Where L_λ is the spectral radiance of the source (i.e. the power density as a function of direction and wavelength, in units of $Wm^{-2}sr^{-1}m^{-1}$) and α is the ratio of the diameter of the source over the viewing distance and λ is the wavelength. To obtain an accurate plot of the spectral radiance would require making detailed measurements since individual sources have different properties and different emission curves.

Laser product standards in UK and Europe

The infra-red sources typically used in the enforcement section of EFC systems are not laser products and hence do not have to conform to BS EN 60825-1, the laser products standards. However, applying the laser standards may provide a useful comparison and it might be hypothesised that the limits set in the laser product standards are likely to be no less stringent than would apply to other IR sources.

The Maximum Permissible Exposure (MPE) values given in the standard depend upon:

- the spectrum of wavelengths
- the angular extent of the source
- the exposure time or pulse duration
- the nature of the tissue exposed

These points are considered separately below.

The IR sources being considered here clearly contain multiple wavelengths. The standard advises that 'exposure from several wavelengths should be assumed to have an additive effect on a proportional basis of spectral effectiveness'.

The IR sources would be regarded as 'extended' in terms of their radiating surface. Calculating MPE for such laser sources is complex but are generally more permissive than single sources.

An additional factor which needs to be considered when dealing with IR sources is the pulsed or continuous nature of their radiation. Pulsed light has considerable advantages in terms of covert illumination. IR sources can be synchronised with electronic shutters of video cameras at frame rates, thus reducing the average power levels and visibility of the illuminating source. The laser standards are not particularly helpful here and say that 'since there are only limited data on multiple pulse exposure criteria, caution must be used in the evaluation of exposure to repetitively pulsed radiation'.

In terms of exposure, the cornea is one of the tissues most sensitive to damage by infra-red light and so can be used to ascertain safe human exposure levels.

The standard implies (in its figure 10b), that the maximum irradiance should be limited to between approximately 5 and 10 Wm^{-2} (depending on wavelength) for unlimited time exposure.

5 Discussion

5.1 Microwave power output

Manufacturers have expressed a concern that there could be a risk that the CEPT standard, limiting the EIRP of an antenna to 3 dBW (33 dBmW), will only be suitable for simple initial systems and that the development of a full multi-lane free flow tolling system may be hard to implement with the existing restrictive standards.

Despite some uncertainty in microwave safety requirements, that antennae complying with existing CEPT requirements are considered well within recommended exposure limits.

5.2 Microwave exposure

The microwave exposure limits developed by the NRPB, were designed to prevent adverse health effects caused by non-ionising EM waves. As it is difficult to obtain a value of the energy absorbed by specific areas of the human body, investigation levels of power density were derived such that compliance with the investigation level implied compliance with the exposure limit.

The NRPB level of 100 Wm^{-2} is the same as that set in the current British standard. The US and IEEE limit is 39 Wm^{-2}. However the CENELEC pre-standard, DD ENV 50166-2, published in 1995, proposes revised levels of 10 Wm^{-2}.

Approximate calculations in Section 3 imply that the beacons employed during the track trials were compliant with existing safety standards and would conform to the new CENELEC pre-standard with no difficulty.

5.3 Infra-red exposure

The sources examined during this study were relatively low powered compared with many other illuminators used in security applications. If it is important for illumination to be essentially invisible to motorists, then more stringent filtering and more intense IR sources may be required.

6 Conclusions and recommendations

This study has identified the most relevant requirements and standards concerning human health issues associated with infra-red and microwave radiation arising from fee collection and enforcement equipment.

In both the infra-red and microwave regions of the spectrum there is debate concerning safety levels, particularly as regards pulsed radiation. Irrespective of standards, power levels should be kept as low as possible consistent with required system operation.

Measurement of system performance in terms of microwave and infra-red emissions is complex and involves specialist equipment.

With existing microwave and IR communication standards being revised, it is recommended that this subject be re-visited as the new documents become available.

7 Acknowledgements

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Appendix A: Validity of inverse square law assumption

As the microwaves are emitted from the antenna they have a curved wavefront as the waveguide is diffracted through free space. After the waveguide has travelled a certain distance, (known as the Raleigh distance), this bending of the wavefront can be neglected and can be treated as a plane wave. The mathematical treatment of a plane wave is substantially simpler than for a diffracting one. The two types of wavefronts have different names. Curved wavefronts are called Fresnel diffraction and plane wavefronts are called Fraunhoffer. The Raleigh distance, (R, measured in metres), is defined as:

$$R = \frac{2d^2}{\lambda}$$

where,

d is the maximum dimension across the aperture and λ is the wavelength of the radiation in meters.

Assuming a value of d to be approximately 700 mm and obtaining a value for λ approximately 0.0517 metres from the equation:

$$c = \lambda f$$

c being the speed of light in a vacuum and f, the microwave frequency of 5.8 GHz.

Putting these values into the Raleigh equation, yields a value of R as 19 metres. The distances concerned are less than this and so the wavefront is not plane wave and therefore hard to deal with. However, below:

$$R = \frac{d^2}{4\lambda}$$

The wave can be considered to be sufficiently plane for the inverse square law to be a reasonable approximation. This means at distances of over 2.3 metres, the equations are considered to hold.

Appendix B: Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
AFC	Automatic Fee Collection
ANSI	American National Standards Institute
CEN	European Committee for Normalisation
CENELEC	European Committee for Electrotechnical Standardization
CEPT	European Committee of Posts and Telecommunications
DETR	Department of the Environment, Transport and the Regions
DNA	Deoxyribonucleic Acid
DSRC	Dedicated Short Range Communication
EIRP	Effective Isotropic Radiated Power
EM	Electromagnetic
EFC	Electronic Fee Collection
ERC	European Radiocommunication Committee
ERP	Effective Radiated Power
IEEE	Institute of Electrical and Electronics Engineers
IR	Infra-Red
ISO	International Organisation for Standardization
mW	Milliwatts (1mW = 0.001W)
MPE	Maximum Permissible Exposure
NRPB	National Radiological Protection Board
OBU	On Board Unit
RF	Radio Frequency
SAR	Specific Energy Absorption Rate
TLV	Threshold Limit Values
TRL	Transport Research Laboratory
W	Watts

Abstract

This report examines the electromagnetic radiation arising from microwave beacons and infra-red illuminators which were components of the systems tested during the technology trials on the TRL track. A general summary of the main human health effects of exposure to relevant non-ionising radiation is provided. The report also discusses UK, European and US radiation standards.