Computed SAR Distributions for the Occupants of a Car with a 400 MHz Transmitter on the Rear Seat

Alastair R. Ruddle

Vehicle Electrical Engineering Department, MIRA Limited
Watling Street, Nuneaton, Warwickshire, CV10 0TU, United Kingdom
alastair.ruddle@mira.co.uk

***Abstract*— Numerical simulations have been used to investigate the impact of occupant distribution on the field exposure threat due to a transmitter operating at 400 MHz inside a car. Eight different occupancy configurations involving the driver and up to three passengers were considered, and both 10 g and 1 g SAR measures were determined. The models suggest that mean SAR limits are likely to be reached at lower power levels than would be needed to reach maximum SAR limits. The presence of the vehicle structures is found to result in higher mean SAR values for all occupant locations, although maximum SAR levels are lower with the vehicle for the driver position. It is concluded that evaluating the in-vehicle field exposure threat by comparing average fields over the interior of the empty vehicle with the reference levels recommended for assessing the exposure of the general public provides a safety factor approaching two for the source configuration under investigation.**

I. Introduction

Electromagnetic field exposure guidelines (eg. [1]) are typically framed in terms of "reference levels" and "basic restrictions". The "reference levels" relate to quantities such as electric and magnetic field strengths, while the "basic restrictions" are specified in terms of quantities such as currents induced in the body, power density and SAR (specific absorption rate).

Compliance with the reference levels is assumed to guarantee compliance with the basic restrictions in non-localized uniform exposures, but the use of reference levels is not considered to be appropriate for the highly localized sources presented by personal transmitters. However, it is less clear how this approach translates to vehicles or buildings, where the local field may be significantly modified by reflections from the environment. In such resonant environments the exposure may be highly non-uniform, and could be so complex that reliable assessment by measurements may become difficult.

Statistical measures provide a more appropriate description of such field distributions, but require the availability of large numbers of samples. Simulation is therefore of increasing interest as a means of obtaining the large datasets needed to obtain reliable statistics without the limitations of physical tests. The latter include the chamber time needed for detailed mapping of field distributions, spurious field disturbances that may be introduced by field transducers and their positioning equipment, and the physical access restrictions that result from using probes of finite size in vehicles of complex geometry.

In both measurements and simulations it is much easier to assess compliance with the reference levels than with the basic restrictions. Homogenised physical "phantoms" are used to represent the human body in measurements (as in [2]), while "human simulants" need to be included in numerical models (either homogenized [3] or anatomically detailed [4]).

Numerical simulations have previously been used to investigate the impact of occupant distribution for SAR levels due to a roof-mounted antenna [5] and a body-worn system [6], and the use of reference levels to assess exposure risks for in-vehicle fields. This paper considers a further scenario in which a portable transmitter is located inside the passenger compartment, but is not in contact with any of the occupants.

II. Numerical Models

The vehicle model was derived from CAD geometry for the body-shell and doors of a passenger car, as well as the major metallic parts in the passenger compartment, such as the seat frames, rear window heater and interior steering components. Simulations of such systems at 390 MHz have been shown [7] to provide a good correlation with electric field measurements carried out on a complete vehicle. At higher frequencies, however, it is likely that additional components, such as the window glass, would also need to be included in the vehicle model.

The simulations were carried out using a commercial tool [8] based on the TLM technique [9]. The source was represented using a simple "zig-zag" monopole element (to obtain the required resonance at a realistic physical length) that is excited against a small conducting block representing the equipment housing. This system was located in the vicinity of the rear seat, with the antenna in a horizontal plane and aligned with the vehicle axis. The source was positioned between the two rear passenger locations, but slightly closer to the driver's side of the vehicle, as illustrated in Fig. 1 (with a separation of 12 cm from the nearest occupant location).

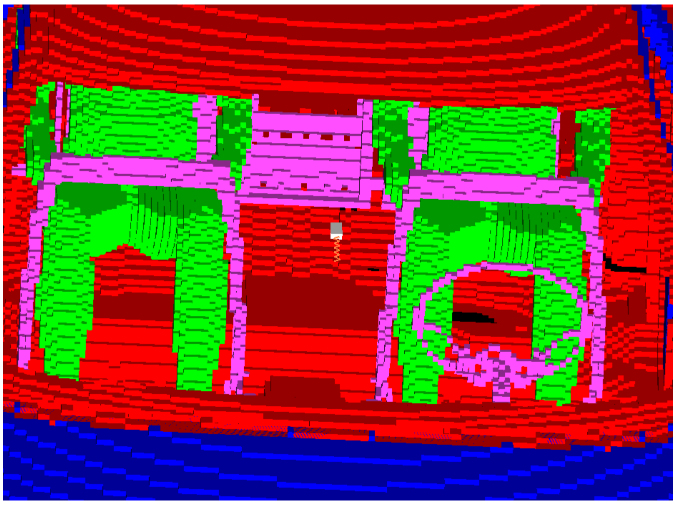

Fig. 1 Locations of source and rear passengers within model vehicle

Simulations of derived quantities such as SAR require models of the human occupants to be added to the basic vehicle model. However, seating positions vary between vehicle types, as well as between vehicles of similar type, and even between the front and rear seats of the same vehicle. This makes the definition of a "standard" human simulant for in-vehicle SAR calculations somewhat difficult. Localized distortions are likely and features such as the volume may be slightly modified between models representing occupants in different seating positions. For these reasons, the use of homogenous lossy dielectric bodies with electrical properties that are representative of the average for human tissues can help to reduce the effort involved in adjusting the basic human simulant geometry.

In this work, therefore, a homogenized human-like geometry was used to produce the four different occupant models required for the SAR simulations. It is reported that average permittivity and conductivity values for the body as a whole can be approximated using two-thirds of the values for human muscle tissue [10]. Measured data for the latter can be found in [11].

III. Empty Vehicle Results

Simple measures for the electric and magnetic field distributions over the interior volume that is accessible to the occupants are summarized in Table I, normalized to an arbitrary radiated power of 1 W. These results were obtained for the empty vehicle as a whole and specifically for the four regions corresponding to the locations of the human simulants in the occupied models. The occupant position described as "Front" in the tables below denotes a passenger seated beside the driver, while the position "Rear-D" denotes a passenger seated behind the driver and "Rear-P" refers to the rear seating position behind the front passenger.

The values in Table I are derived from field data at almost 2 million sampling points over the interior as a whole, and for more than 35,000 points over each of the occupant locations.

TABLE I
COMPUTED EMPTY VEHICLE FIELDS OVER WHOLE INTERIOR AND REGIONS OCCUPIED BY DRIVER AND PASSENGERS

Region of empty vehicle	RMS field levels at 400 MHz, 1W CW			
	Electric (V/m)		Magnetic (mA/m)	
	Max.	Mean.	Max.	Mean.
Interior	2279	17.39	3420	45
Driver	94.78	13.93	63	33
Front	24.66	13.03	67	29
Rear-D	61.15	25.26	206	73
Rear-P	38.72	18.02	160	45

The maximum levels for the whole interior are associated with the source located inside the passenger compartment. The relatively high maximum electric field for the driver region is probably associated with the steering wheel and related structures. Average field levels for the two front seating positions are of similar magnitude, and are both lower than for either of the rear passenger locations. The largest average fields are obtained for the passenger location that is closest to the source (ie. Rear-D).

IV. Occupied Vehicle Simulations

Although the SAR levels specified in [1] are given in terms of local averages over 10 g of contiguous tissue, other standards define limits in terms of a 1 g average. Some 1 g results are therefore included here. Limits are specified for both the average SAR for the whole body, and for the maximum SAR in specific regions of the body. Different maximum SAR limits are generally specified for the limbs, and for the head and trunk.

Assuming a driver and up to three passengers to be present in the vehicle results in eight possible occupancy configurations. Computed SAR levels for the various combinations of passengers are presented in Tables II-V, indicating both maximum and mean SAR for both 10 g averages (Tables II-III) and 1 g averages (Tables IV-V). The relative values shown in Tables II-V are normalized to the corresponding SAR levels for the case with the driver alone (all at the same radiated power level).

TABLE II
MAXIMUM 10 G SAR FOR VARIOUS OCCUPANCY CONFIGURATIONS, NORMALIZED TO DRIVER ONLY CASE

Number of occupants	Highest 10 g SAR, relative to driver only (%)			
	Driver	Front	Rear-D	Rear-P
4	3.03	4.60	153.23	67.35
3	4.51		154.46	85.70
	19.45	11.35		58.99
	7.89	29.59	180.74	
2	6.60		184.47	
	17.88			57.32
	36.80	26.85		

TABLE III
MEAN 10 G SAR FOR VARIOUS OCCUPANCY CONFIGURATIONS, NORMALIZED TO DRIVER ONLY CASE

Number of occupants	Mean 10 g SAR, relative to driver only (%)			
	Driver	Front	Rear-D	Rear-P
4	12.33	14.34	237.4	139.1
3	15.48		240.3	137.1
	58.02	28.94		150.1
	28.58	40.24	260.5	
2	31.15		281.0	
	61.36			146.5
	85.16	65.05		

TABLE IV
MAXIMUM 1 G SAR FOR VARIOUS OCCUPANCY CONFIGURATIONS, NORMALIZED TO DRIVER ONLY CASE

Number of occupants	Highest 1 g SAR, relative to driver only (%)			
	Driver	Front	Rear-D	Rear-P
4	1.06	1.61	49.15	41.25
3	1.60		49.49	52.66
	9.96	2.86		23.65
	5.73	8.52	58.01	
2	6.48		59.12	
	9.88			39.53
	36.43	9.05		

TABLE V
MEAN 1 G SAR FOR VARIOUS OCCUPANCY CONFIGURATIONS, NORMALIZED TO DRIVER ONLY CASE

Number of occupants	Mean 1 g SAR, relative to driver only (%)			
	Driver	Front	Rear-D	Rear-P
4	12.36	14.39	238.5	139.9
3	15.51		241.4	137.9
	58.17	28.96		150.8
	28.55	40.39	261.8	
2	31.10		282.5	
	61.47			147.2
	85.09	65.14		

The mean 10 g and 1 g SAR results are very similar, with the highest values occurring for the two rear passenger positions. The maximum 10 g SAR shows a similar pattern, but the highest 1 g SAR levels in the passengers are all lower than for the driver alone. This probably reflects the fact that the 10 g SAR is averaged over a larger volume of tissue.

The results in Tables VI-VII show the projected maximum and mean empty vehicle fields at power levels that would result in SAR values at the maximum and mean SAR limits of [1] for general public exposure, relative to the corresponding field reference levels. These results indicate that mean SAR is a more immediate threat than maximum SAR, and that the mean SAR limits can be reached for power levels at which the mean fields over the interior of the empty vehicle are approaching twice the field reference levels of [1] for general public exposure at 400 MHz (ie. 28 V/m and 73 mA/m).

TABLE VI
EMPTY VEHICLE FIELDS AT POWER FOR MAXIMUM 10 G SAR LIMITS, NORMALIZED TO REFERENCE LEVELS OF [1]

Region of empty vehicle	Empty vehicle fields at maximum 10 g SAR limits – relative to reference levels			
	Electric field		Magnetic field	
	Max.	Mean	Max.	Mean
Interior	361.8	2.76	208.2	2.74
Driver	15.04	2.21	3.84	2.01
Front	3.91	2.07	4.08	1.77
Rear-D	9.71	4.01	12.54	4.44
Rear-P	6.15	2.86	9.74	2.74

TABLE VII
EMPTY VEHICLE FIELDS AT POWER FOR MEAN 10 G SAR LIMITS, NORMALIZED TO REFERENCE LEVELS OF [1]

Region of empty vehicle	Empty vehicle fields at mean 10 g SAR limits – relative to reference levels			
	Electric field		Magnetic field	
	Max.	Mean	Max.	Mean
Interior	258.0	1.97	148.5	1.95
Driver	10.73	1.58	2.74	1.43
Front	2.79	1.48	2.91	1.26
Rear-D	6.92	2.86	8.95	3.17
Rear-P	4.38	2.04	6.95	1.95

V. IMPACT OF VEHICLE STRUCTURE

Simulations with the vehicle structures removed from the models, such that the relative positions of the human simulants were unchanged, were used to assess the influence of the vehicle on the field exposure. Computed 10 g and 1 g SAR levels for the vehicle with four occupants are given in Table VIII, normalized to the values obtained for the same group of human simulants without the car.

TABLE VIII.
COMPUTED SAR LEVELS FOR GROUP OF 4 HUMAN SIMULANTS IN CAR, RELATIVE TO LEVELS OBTAINED WITH CAR REMOVED FROM MODEL.

Human simulant	Relative SAR levels			
	10 g average		1 g average	
	Max.	Mean	Max.	Mean
Driver	0.85	1.63	0.88	1.64
Front	1.00	1.52	0.89	1.53
Rear-D	1.74	2.04	1.70	2.04
Rear-P	1.28	1.37	2.10	1.38

The presence of the vehicle structures results in higher mean SAR values for all occupant locations, for both 10 g and 1 g SAR measures. The mean SAR in the occupant closest to the source is approximately doubled in the vehicle. However, the enhancement of the mean SAR levels is greater for the occupants in the front of the car than for the position behind the front passenger. The maximum SAR levels for the driver are lower with the car than without it. For the front passenger, the highest 10 g SAR is unaffected by the car, although the highest 1 g SAR is 11% lower in the car.

The highest 10 g SAR levels for the driver position occur in the inner leg with the vehicle structure removed from the model (see Fig. 2). When the vehicle is included, SAR levels in this region are reduced (see Fig. 3, which uses the same colour scale and output plane as Fig. 2). With the vehicle, the highest SAR levels in front occupants shift from the limbs to the head and truck, where lower maximum SAR limits apply.

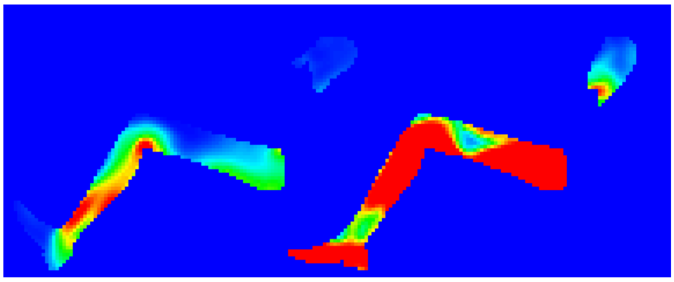

Fig. 2 SAR (10 g) in vertical plane through leg of driver without car

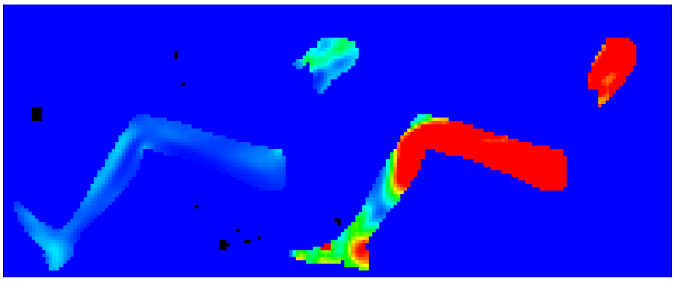

Fig. 3 SAR (10 g) in vertical plane through leg of driver with car

VI. CONCLUSIONS

For a vehicle with a 400 MHz source inside the passenger compartment, but not in contact with the occupants, models suggest that mean SAR limits are likely to be reached at lower power levels than would be needed to reach the maximum SAR limits. Models of the source and human simulants without the vehicle structure demonstrate that higher mean SAR values occur for all occupant locations in the vehicle, and that the spatial distribution of SAR within the simulants is also modified by the car.

Projected average empty vehicle fields over the locations of the occupants range from 1.26 to 3.17 times the field reference levels of [1] for general public exposure at the corresponding mean 10 g SAR limits (based on the worst-case over the eight vehicle occupancy scenarios). However, the highest average SAR corresponds to the position behind the driver, where an average electric field of 2.86 times the reference level would be expected over this region of the empty vehicle at the power level associated with the 10 g SAR limit. Although the resulting average fields over the adjacent rear passenger position are much closer to the reference levels, the associated mean SAR is much smaller (150% of driver only mean 10 g SAR at most) than those for the position behind the driver (up to 281% of driver only mean 10 g SAR).

Considering the interior as a whole, the radiated power corresponding to the mean 10 g SAR limit would result in average field levels exceeding the reference levels by 97% for electric field and 95% for magnetic field. Thus, taking account of the eight vehicle occupancy scenarios, an evaluation based on comparing average fields over the interior of the empty vehicle with the reference levels of [1] provides a safety factor approaching two for the source configuration considered here.

Simulations of whole body average SAR due to uniform plane wave exposure indicate that the power density reference levels of [1] provide safety factors ranging from 2 to 10 for the band 20–2000MHz [12]. For frequencies around 400 MHz the power density safety factor is around 5, suggesting a corresponding value of 2.25 for field, which is similar to that found for the non-uniform, in-vehicle exposure studied here.

ACKNOWLEDGEMENT

The work outlined above was carried out as part of the SEFERE project, a collaborative research project supported by the UK Department of Trade and Industry (Technology Programme reference TP/3/DSM/6/I/15266). The project consortium includes MIRA Ltd (coordinator), ARUP Communications, BAE Systems Ltd, Harada Industries Europe Ltd, Jaguar Cars, UK Police Information Technology Organisation, Sheffield University and Volvo Car Corporation (Sweden). Further information regarding SEFERE can be found on the project website (*http://www.sefere.org*).

REFERENCES

[1] ICNIRP, "Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300 GHz)", *Health Physics*, Vol. 74, No. 4, 1998, pp. 494-522.

[2] D.O. McCoy, D.M. Zakharia and Q. Balzano, Field strengths and specific absorption rates in automotive environments, *IEEE Trans. Vehicular Tech.*, Vol. 48, No. 4, July 1999, pp. 1287-1303.

[3] A.R. Ruddle, Modelling electromagnetic field exposure and SAR in vehicles due to on-board transmitters, in *Proc. 16th Zurich EMC Symposium*, February 2005, pp. 145-150.

[4] G. Anzaldi, E.C. Delgado, P.J. Riu and F. Silva, FDTD analysis of SAR from a cell phone inside a vehicle, in *Proc. 16th Zurich EMC Symposium*, February 2005, pp. 155-160.

[5] A.R. Ruddle, Impact of passenger distribution on computed electromagnetic field exposure for vehicles with on-board transmitters, in *Proc. EMC Europe Workshop on EMC of Wireless Systems*, Rome, Italy, September 2005, pp. 411-414.

[6] A.R. Ruddle, "Influence of passengers on computed field exposure due to a personal TETRA radio used inside a vehicle", in *Proc. 7th European EMC Symposium*, Barcelona, Spain, September, 2006 pp. 592-597.

[7] A.R. Ruddle, "Validation of predicted 3D electromagnetic field distributions due to vehicle-mounted antennas against measured 2D external electric field mapping", *IET Science, Measurement and Technology,* Vol. 1, No. 1, January 2007, pp. 71-75.

[8] D.P. Johns, R. Scaramuzza and A.J. Wlodarczyk, "Micro-Stripes – microwave design tool based on 3D-TLM", in *Proc. 1st International Workshop on Transmission Line Matrix (TLM) Modeling – Theory and Applications*, Victoria, BC, Canada, August 1995, pp.169-177

[9] C. Christopoulos, *The transmission-line modelling method: TLM*, IEEE Press, 1995.

[10] C.H. Durney, H. Massoudi, and M.F. Iskander, "Radiofrequency radiation dosimetry handbook", 4th Edition, Brooks Air Force Base Technical Report USAFSAM-TR-85-73, October 1986.

[11] C. Gabriel and S. Gabriel, "Compilation of the dielectric properties of body tissues at RF and microwave frequencies", Brooks Air Force Base Technical Report AL/OE-TR-1996-0037, June 1996.

[12] A.F. McKinlay et al, "Review of the Scientific Evidence for Limiting Exposure to Electromagnetic Fields (0–300 GHz)", *Documents of the NRPB*, Volume 15, No. 3, 2004, pp. 142-145.