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Variation of Computed In-vehicle SAR with Number and Location of Occupants at Commonly Used Communications Frequencies

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Abstract—**Simulations of occupant SAR in a car equipped with on-board transmitters have been carried out using homogeneous human simulants. Results are presented for three SAR measures in eight occupancy configurations at four communications frequencies (400 MHz, 900 MHz, 1.8 GHz and 2.4 GHz) for a number of source locations. At radiated power levels of 1 W CW the computed SAR levels are well below recommended limits, but vary significantly with occupant number and distribution.**

Keywords-component; finite integration technique; FIT; SAR; specific absorption rate; TLM; transmission line matrix; vehicle

I. INTRODUCTION

Guidelines for limiting human exposure to electromagnetic fields have been proposed by a number of international and national organizations (eg. [1]–[3]). These are typically framed in terms of “reference levels” (sometimes called “action levels”) and “basic restrictions”. The reference levels relate to readily measureable quantities such as electric and magnetic field strengths, whereas the basic restrictions are specified in terms of current density and specific absorption rate (SAR) induced in body tissues by the local electromagnetic fields.

In-vehicle SAR levels have been investigated through measurement using physical phantoms with homogeneous electrical properties at 835 MHz [4], as well as at 146 MHz and 460 MHz [5]. Numerical simulations have been carried out using a homogeneous human simulant at 400 MHz [6], and at 900 MHz an anatomically detailed inhomogeneous human simulant has been simulated [7]. Simulations with up to four homogeneous human simulants have also been used to assess the impact of vehicle occupancy variations at 400 MHz [8]–[9] and 900 MHz [10]. This paper presents further investigations of the variability of in-vehicle SAR with vehicle occupancy, for additional frequencies and source configurations.

II. NUMERICAL MODELS

The simulations employed 3D vehicle models (see Fig. 1), which were derived from CAD geometry for the major metallic components of the vehicle structure (i.e. body-shell and doors), as well as significant metallic components located within the passenger compartment (i.e. cross-car beam, front and rear seat frames, and steering gear).

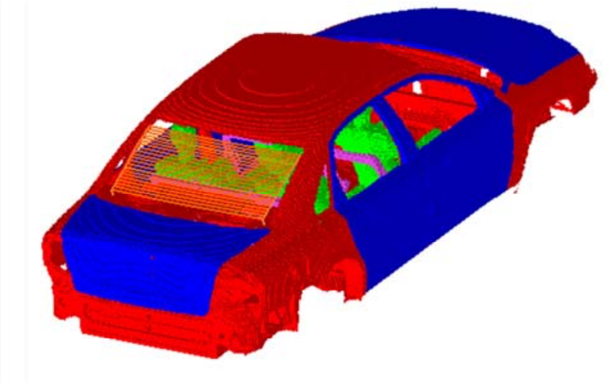

Figure 1. Model of car with driver and three passengers.

The geometry of the vehicle interior is not symmetric, and the presence of the steering wheel and associated components add further to the asymmetry. The models also included arrays of wires representing the de-misting heater in the rear window. However, dielectric components that are present in the interior (e.g., dashboard components, seat foam, door trims etc.) were not included in these models as their influence was expected to be small [11]. Furthermore, numerical [12] and experimental [13] results also suggest that window glazing has limited impact at frequencies for which the panel thickness is small relative to the wavelength. Consequently, the window glass was only included in the 2.4 GHz models.

Simulations with external quarter-wave monopoles and simple internal sources and were carried out at 400 MHz and 900 MHz using a commercial transmission line matrix solver (CST Microstripes [14]). In addition, the finite integration technique (CST Microwave Studio [15]) was used for simulations of internal quarter-wave monopoles at 900 MHz, 1.8 GHz and 2.4 GHz. The internal monopoles were located on the axis of the vehicle, in the middle of the rear parcel shelf and below the centre of the roof panel. The external monopoles were also located on the axis of the vehicle, 19.5 cm forward of the rear edge of the roof panel. The internal dipoles were located in the vicinity of the rear seats, displaced 4.5 cm from the vehicle axis towards the driver’s side, 80.5 cm below the highest point of the roof panel, and 40.5 cm forward of the centre of the rear edge of the roof panel.

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The “human simulants” were of realistic size and shape to represent a large male, but assigned with homogeneous and isotropic electrical properties (see Table I). The electrical properties were approximated as two-thirds of the permittivity and conductivity values for average muscle at the frequencies of interest [16], which is widely used for homogenized whole body models (e.g. [17]–[18]). The tissue density required for the SAR calculations was assumed to be 1040 kg/m^3 [16]. The cell sizes used in the human simulants were 5 mm at 400 MHz, 4 mm at 900 MHz, 3 mm at 1.8 GHz and 2 mm at 2.4 GHz.

The use of homogeneous human simulants is at least representative of what could be practicable for measurements, and also minimizes the difficulties involved in adjusting the human geometry to accommodate different seating positions within the vehicle. The latter include adjustments to the angles at the hips, knees and ankles. Adjustments at the shoulders, elbows and wrists were also required to place the arms in representative positions for the driver and passengers. Since there was no internal structure in the human simulants, only the exterior surfaces had to be modified in order to generate the different occupant models.

In practice the number, size, shape and position of vehicle occupants may vary considerably, making a comprehensive investigation of all possibilities impracticable, even for a single vehicle. Consequently, the approach adopted in this work was to investigate occupant SAR distributions using 3D numerical simulations based on a representative subset of human simulants, with fixed sizes and seating positions. These are illustrated in Fig. 2, where DR denotes the driver, FP the front passenger, and RD and RP are the rear passenger positions behind the driver and front passenger, respectively. Even this considerable simplification results in eight different occupancy configurations to represent a driver with up to three passengers, which requires eight separate simulations. However, if the fourth passenger seating position (located in the middle of the back seat) had been taken into account this would have doubled the number of occupancy permutations, requiring sixteen simulations to be carried out for each source configuration.

TABLE I. ELECTRICAL PROPERTIES ASSIGNED TO HUMAN SIMULANTS

Frequency (MHz)	Permittivity	Conductivity (S/m)
400	38.65	0.545
900	37.3	0.647
1800	35.7	0.95
2400	35.2	1.13

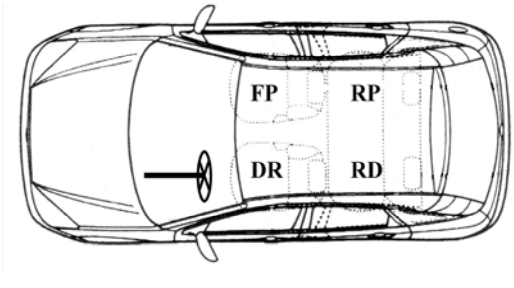

Figure 2. Occupant locations and designations.

The driver was assumed to be present in all of the SAR simulations, and further occupancy configurations were constructed by adding up to three passengers to create a total of eight occupancy cases. The number of occupants and their locations are summarized in Table II, for each of the eight occupancy cases. These include two single cases with either one person (Case 1) or four people (Case 4) in the vehicle. However, three possibilities arise when either a single passenger (denoted 2A, 2B and 2C), or two passengers (denoted 3A, 3B and 3C), are added to the driver.

III. COMPUTED OCCUPANT SAR LEVELS

The basic restrictions of [1]–[3] are defined in terms of maximum local SAR in the head and trunk, maximum local SAR in the limbs, and whole body average SAR (all based on averages over a period of six minutes, and over 10 g of contiguous tissue). Results for these three SAR measures were therefore obtained for each of the occupants present in all of the simulations.

The subset of the SAR data representing the head and trunk region for each occupant was taken to be behind the transverse vertical plane through the point where the legs join and between the longitudinal vertical planes through the points where the arms join the chest. The limb SAR data subset was obtained by subtracting the head and trunk subset from the whole body SAR data. The latter was used to determine the whole body average value.

All of the SAR results were normalized to a radiated power level of 1 W CW in order to both facilitate direct comparison between configurations and to allow simple scaling of the results to power levels of more practical interest (as SAR is proportional to radiated power). The results are summarized in Tables III–XIV, which show the range of the three SAR measures over all of the occupancy configurations for each of the occupants, as well as the corresponding occupancy case. Results at 400 MHz are given in Tables III–IV, Tables V–X contain 900 MHz data, Tables XI–XII contain 1.8 GHz data, and Tables XIII–XIV give 2.4 GHz results. The highest value over all occupants, as well as the corresponding occupant and occupancy configuration, is also highlighted in bold for each of the three SAR measures in every source configuration.

The normalized SAR values in these tables are expressed as a percentage of the corresponding basic restrictions. The SAR limits for general public exposure detailed in [2] are 2 W/kg for the head and trunk, 4 W/kg for the limbs, and 80 mW/kg for the whole body average.

TABLE II. OCCUPANCY CONFIGURATIONS USED IN SAR SIMULATIONS

Occupant numbers	Occupancy case	Occupants present			
		DR	FP	RP	RD
1 person	1	×	-	-	-
2 people	2A	×	×	-	-
	2B	×	-	×	-
	2C	×	-	-	×
3 people	3A	×	-	×	×
	3B	×	×	-	×
	3C	×	×	×	-
4 people	4	×	×	×	×

TABLE III. 400 MHz External Vertical Roof-Mounted Monopole Located Towards Rear of Roof Panel at 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	0.383	1	0.081	4
	FP	0.223	2a	0.059	4
	RP	0.593	2b	0.456	4
	RD	**0.596**	**2c**	0.474	4
Maximum for head and trunk	DR	0.280	1	0.040	4
	FP	0.139	2a	0.534	3a
	RP	0.563	3c	0.534	3a
	RD	**0.570**	**3a**	0.520	2c
Maximum for limbs	DR	**0.542**	**2a**	0.229	3a
	FP	0.049	2a	0.038	4
	RP	0.246	3c	0.105	4
	RD	0.391	2c	0.138	4

TABLE IV. 400 MHz Internal Horizontal Source in Vicinity of Rear Seats at 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	3.541	1	0.436	4
	FP	2.304	2a	0.508	4
	RP	5.318	3c	4.858	3a
	RD	**9.953**	**2c**	8.408	4
Maximum for head and trunk	DR	1.068	3c	0.137	4
	FP	1.624	3b	0.252	4
	RP	1.771	2b	1.509	3a
	RD	**7.005**	**2c**	5.955	4
Maximum for limbs	DR	2.745	1	0.083	4
	FP	0.451	2a	0.083	4
	RP	2.352	3a	1.574	2b
	RD	**4.963**	**3b**	4.208	4

TABLE V. 900 MHz External Vertical Roof-Mounted Monopole Located Towards Rear of Roof Panel at 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	0.166	1	0.064	4
	FP	0.111	2a	0.055	4
	RP	**0.241**	**2b**	0.199	4
	RD	0.209	2c	0.175	4
Maximum for head and trunk	DR	0.077	1	0.040	3c
	FP	0.053	2a	0.036	3c, 4
	RP	**0.187**	**3a**	0.160	2b
	RD	0.124	4	0.111	2c
Maximum for limbs	DR	0.050	1	0.021	4
	FP	0.034	3b	0.015	3c, 4
	RP	**0.101**	**2b**	0.077	3a, 4
	RD	0.058	3b	0.044	2c

Results for the external monopoles (Tables III and V) are markedly smaller (<0.6% of the limits, at 1 W CW) than for the sources inside the passenger compartment. This is expected as most of the energy is radiated away from the vehicle and only a relatively small proportion is coupled into the vehicle interior.

TABLE VI. 900 MHz Internal Vertical Dipole in Vicinity of Rear Seats at 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	3.796	1	1.574	3a
	FP	3.041	2a	1.336	4
	RP	**7.243**	**2b**	4.804	4
	RD	7.130	3a	6.838	4
Maximum for head and trunk	DR	2.256	2b	0.791	3b
	FP	1.439	3b	0.539	3c
	RP	4.247	2b	3.584	4
	RD	**8.605**	**3a**	7.090	2c
Maximum for limbs	DR	0.774	3c	0.328	3b
	FP	1.051	2b	0.522	3c
	RP	2.578	4	2.235	2b
	RD	**3.665**	**3b**	2.469	4

TABLE VII. 900 MHz Internal Horizontal Dipole Transverse to Vehicle Axis in Vicinity of Rear Seats at 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	5.884	1	1.623	4
	FP	4.283	2b	1.351	4
	RP	6.200	2c	4.474	4
	RD	**7.358**	**4**	6.579	3a
Maximum for head and trunk	DR	2.024	1	0.547	4
	FP	1.708	2a	0.632	4
	RP	1.302	3a	0.158	2b
	RD	**4.345**	**3b**	3.250	2c
Maximum for limbs	DR	1.345	1	0.240	4
	FP	1.064	2a	0.356	4
	RP	2.748	3a	1.717	3c
	RD	**4.305**	**4**	2.768	3b

TABLE VIII. 900 MHz Internal Horizontal Dipole Parallel to Vehicle Axis in Vicinity of Rear Seats at 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	4.013	1	0.849	4
	FP	3.604	2a	0.931	4
	RP	7.563	3a	6.214	3c
	RD	**7.846**	**2c**	6.748	4
Maximum for head and trunk	DR	1.553	3c	0.350	4
	FP	2.370	3b	0.316	4
	RP	3.682	2b	2.142	4
	RD	**4.748**	**4**	3.454	2c
Maximum for limbs	DR	0.774	1	0.210	4
	FP	0.961	2a	0.207	4
	RP	4.910	2b	4.678	3c
	RD	**8.000**	**4**	4.958	3b

Of the internal sources, the monopole placed on the rear parcel shelf (Tables X, XII and XIV) is associated with the smallest SAR measures (<2% of the limits, at 1 W CW). This is presumably because a large proportion of the energy is radiated out through the nearby rear window.

TABLE IX. 900 MHZ INTERNAL VERTICAL MONOPOLE LOCATED BELOW CENTRE OF ROOF PANEL AT 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	**3.478**	**1**	1.725	4
	FP	2.491	2a	1.960	4
	RP	3.063	2b	2.409	4
	RD	2.548	2c	2.100	4
Maximum for head and trunk	DR	**3.281**	**1**	1.345	4
	FP	1.347	2a	0.879	4
	RP	1.466	4	0.856	3c
	RD	1.681	4	1.311	2c
Maximum for limbs	DR	0.968	1	0.441	3b
	FP	0.830	3b	0.730	4
	RP	1.317	2b	0.519	3c
	RD	**1.991**	**2c**	0.444	4

TABLE X. 900 MHZ INTERNAL VERTICAL MONOPOLE LOCATED AT CENTRE OF REAR PARCEL SHELF AT 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	1.151	1	0.463	4
	FP	1.023	2a	0.576	4
	RP	**1.941**	**2b**	1.445	3a
	RD	1.748	3a	1.426	4
Maximum for head and trunk	DR	0.904	1	0.253	4
	FP	0.970	3b	0.489	4
	RP	**0.993**	**2b**	0.705	3a
	RD	0.894	2c	0.755	3b
Maximum for limbs	DR	0.277	1	0.134	3b
	FP	0.210	3c	0.169	4
	RP	**0.417**	**2b**	0.366	3a
	RD	0.391	4	0.244	2c

TABLE XI. 1.8 GHZ INTERNAL VERTICAL MONOPOLE LOCATED BELOW CENTRE OF ROOF PANEL AT 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	**3.600**	**1**	2.083	4
	FP	2.884	2a	2.246	4
	RP	3.209	2b	2.216	4
	RD	2.915	2c	2.325	4
Maximum for head and trunk	DR	**4.633**	**1**	2.658	2b
	FP	1.681	2a	1.627	4
	RP	1.084	2b	0.852	3a
	RD	1.424	3b	1.382	2c
Maximum for limbs	DR	1.351	4	0.934	2b
	FP	**1.948**	**2a**	1.425	4
	RP	1.094	2b	0.532	4
	RD	1.059	3a	0.628	4

Sources that were placed further into the interior of the passenger compartment resulted in the highest SAR values. These range up to almost 10% of the limits, for sources at 1 W CW radiated power. The highest values were found for sources at 400 MHz (see Table IV) and 900 MHz (Tables VI –VIII).

TABLE XII. 1.8 GHZ INTERNAL VERTICAL MONOPOLE LOCATED AT CENTRE OF REAR PARCEL SHELF AT 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	0.908	1	0.428	4
	FP	0.910	2a	0.505	3c
	RP	**1.313**	**2b**	1.009	3a
	RD	1.210	2c	0.909	4
Maximum for head and trunk	DR	0.506	2c	0.203	3a
	FP	0.676	4	0.339	3b
	RP	**1.156**	**4**	0.528	3a
	RD	0.878	2c	0.547	3b
Maximum for limbs	DR	0.354	2b	0.117	4
	FP	0.420	3b	0.154	4
	RP	**0.646**	**2b**	0.224	4
	RD	0.577	3b	0.231	4

TABLE XIII. 2.4 GHZ INTERNAL VERTICAL MONOPOLE LOCATED BELOW CENTRE OF ROOF PANEL AT 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	2.959	1	2.293	4
	FP	2.873	2a	2.151	4
	RP	**3.268**	**2b**	2.365	4
	RD	3.041	2c	2.283	4
Maximum for head and trunk	DR	3.312	3b	2.669	4
	FP	**3.611**	**3c**	3.302	4
	RP	1.954	3a	1.273	4
	RD	1.793	3a	1.521	3a
Maximum for limbs	DR	**2.221**	**2b**	0.977	1
	FP	1.860	3b	0.921	2a
	RP	1.339	2b	0.856	4
	RD	1.946	3a	1.328	4

TABLE XIV. 2.4 GHZ INTERNAL VERTICAL MONOPOLE LOCATED AT CENTRE OF REAR PARCEL SHELF AT 1 W CW

10 g SAR measure	**Vehicle occupant**	**SAR measures relative to limits of [2]**			
		Highest		**Lowest**	
		% of limit	**Case**	**% of limit**	**Case**
Whole body average	DR	0.874	1	0.436	4
	FP	0.783	2a	0.494	4
	RP	**1.214**	**2b**	1.030	4
	RD	1.173	3b	0.944	4
Maximum for head and trunk	DR	0.811	3b	0.518	2a
	FP	1.001	2a	0.761	4
	RP	1.428	4	0.828	2b
	RD	**1.432**	**3a**	0.888	4
Maximum for limbs	DR	0.184	3b	0.114	4
	FP	0.262	2a	0.136	3b
	RP	0.428	3c	0.365	4
	RD	**0.461**	**4**	0.395	3b

The highest SAR levels are generally found in the rear passengers, reflecting the fact that most of the sources were placed towards the rear of the car. With the monopole located below the centre of the roof (Tables IX, XI and XIII) the highest levels are found in the driver and front passenger (FP).

IV. DISCUSSION

All of the SAR results are significantly below (<10%) the limits of [2] for radiated power levels of 1 W CW. Moreover, the SAR measures would be expected to be even lower for real-world transmissions with finite duty cycles. Thus, these results suggest that transmissions from an internal source are unlikely reach the SAR limits for total radiated power levels up to 10 W. For the roof-mounted antennas much higher power levels could be tolerated as the proportion of the power coupled into the passenger compartment is relatively small.

The SAR values obtained from the simulations vary with source location, with occupancy configuration, and between occupants. Furthermore, the particular SAR measures that are associated with the highest values also vary between configurations. In general the SAR values are smaller when more occupants are present, but in some instances the largest values occur with four occupants present. The occupant and occupancy configurations associated with the highest SAR levels, relative to the limits, are summarized in Table XV, for each of the 12 source configurations. The only occupancy cases not represented in Table XV are 2A and 3B. Thus, there is no readily identifiable "universal worst-case" occupancy case.

TABLE XV. OCCURRENCE OF HIGHEST SAR MEASURES RESULTING FOR EACH OF TWELVE SOURCE CONFIGURATIONS INVESTIGATED

Frequency (MHz)	**Antenna position**	**SAR measure**	**Vehicle occupant**	**Occupancy case**
400	External roof-mounted monopole	Whole body average	RD	2C
	Internal longitudinal source	Whole body average	RD	2C
900	External roof-mounted monopole	Whole body average	RP	2B
	Internal vertical dipole	Head and trunk max.	RD	3A
	Internal transverse dipole	Whole body average	RD	4
	Internal longitudinal dipole	Limbs max.	RD	4
	Internal monopole under roof	Whole body average	DR	1
	Internal monopole on parcel shelf	Whole body average	RP	2B
1800	Internal monopole under roof	Head and trunk max.	DR	1
	Internal monopole on parcel shelf	Whole body average	RP	2B
2400	Internal monopole under roof	Head and trunk max.	FP	3C
	Internal monopole on parcel shelf	Head and trunk max.	RD	3A

The maximum SAR values obtained for a given source configuration vary between occupants and between occupancy cases, but the range is generally greater for the driver than for the passengers. This probably reflects the fact that the passengers are present in only four of the simulations for each source configuration, whereas the driver is present in every simulation. However, the available results suggest that the range of variation between occupancy configurations declines with increasing frequency. The largest ratios of the highest to the lowest maximum SAR measures, which are predominantly associated with the driver, were found to be 33 at 400 MHz, 8.3 at 900 MHz (in this case, for passenger RP), 3 at 1.8 GHz and 2.3 at 2.4 GHz. For the external roof-mounted monopole examples this ratio reaches values (again for the driver) of 7 at 400 MHz, but only 2.6 at 900 MHz (only internal sources were investigated at 1.8 GHz and 2.4 GHz). Variations between the different occupancy configurations, as well as increases in SAR values when additional occupants are present, probably result from changes in the resonances within the passenger compartment. At higher frequencies the impact of changes in the occupant distribution is perhaps less significant as greater numbers of modes will be present and the internal field distribution is likely to be more homogeneous. Nevertheless, the highest SAR measures obtained at 2.4 GHz correspond to cases with the driver and two passengers present.

The effort involved in undertaking a comprehensive investigation of SAR values under different occupancy configuration, which could be carried out either by numerical modelling or by physical measurements, could be substantial. The numerical investigation outlined here involved eight simulation runs for each occupancy configuration. For the time-domain techniques used in these simulations the models converge more rapidly with more occupants. The model run-time was of the order of 1.5–2 days per simulation (running on four 2.85 GHz processors) at 2.4 GHz, therefore requiring around two weeks of continuous computing per source position, and the memory requirement was around 31 Gbytes. The lower frequency models required substantially less memory (e.g. 16 Gbytes for 1.8 GHz, and 5 Gbytes for 900 MHz) and ran much faster (e.g. 12 hours for 1.8 GHz, 4 hours for 900 MHz). However, the volume of data to be subsequently processed is substantial, so it would be desirable to minimize this effort by investigating fewer configurations, and/or only evaluating SAR in one or two individuals even if others are present.

Similar issues could also be envisaged in an experimental investigation. A set of four phantoms would be required in order to emulate the investigation described here, with the capability to map the internal spatial field distribution throughout the interior of the phantoms. Having such a mapping capability in four phantoms would be expensive, so a more cost effective approach could be to use one instrumented phantom and three "dummy" phantoms that simply provide sources of absorption and scattering. However, this would mean that the instrumented phantom would need to be systematically exchanged with each of the dummy phantoms in turn in order to acquire the full range of data represented in the simulations. Furthermore, there would be significant practical difficulties in attempting to measure fields in the arms and legs.

The highest SAR measures obtained from the simulations were whole body average SAR for half of the source configurations. Although the highest SAR measures for most of the other source configurations were maximum SAR in the head and trunk, in one case the highest SAR measure was maximum SAR in the limbs.

The implications of these observations for assessments of human field exposure risk are that SAR data may be required for a number of occupants and for a number of occupancy configurations in order to ensure that the highest values are obtained for the three SAR measures. If the SAR measures obtained from limited investigations (e.g. for the driver only) are of the order of a several percent of the limits then the results obtained in this study suggest that some occupancy configurations may result in SAR levels that could reach the limits. However, if the results obtained from limited investigations are extremely small relative to the limits then it is unlikely that values for other configurations will be sufficiently high to approach the limits.

V. CONCLUSIONS

A total of 96 simulations have been carried out to investigate the impact of occupant numbers and distribution on in-vehicle SAR using homogeneous human simulants. These simulations represent exposure of a driver and up to three passengers to transmissions from a number of source locations (both inside and outside the passenger compartment) for frequencies of 400 MHz, 900 MHz, 1.8 GHz and 2.4 GHz. The SAR measures extracted included the local maximum in the head and trunk, the maximum in the limbs, and the whole body average. For an assumed radiated power level of 1 W CW, the highest SAR values obtained were less than 10% of the general public limits of [2]. These SAR values would be even lower for real-world transmissions with finite duty cycles, but greater at higher power levels.

The SAR values obtained from the simulations were found to vary with source location and occupancy configuration, as well as between occupants. In general the SAR values are smaller when more occupants are present, but in some instances the largest values occur with four occupants present. However, the available results suggest that the spread of results for a given individual declines with increasing frequency. Thus, although there is no readily identifiable “universal worst-case” occupancy configuration, it may be feasible to employ fewer SAR simulations or measurements to assess the exposure risk at frequencies in the GHz range. Below 1 GHz the number and distribution of vehicle occupants have a more significant impact on the SAR results, suggesting that a more comprehensive investigation of occupant SAR distributions under different occupancy conditions may be required at these frequencies unless the results of preliminary simulation or measurements are not extremely small relative to the limits.

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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, pp. 494–522, April 1998.

[2] 1999/519/EC, “Council Recommendation of 12th July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)”, Official J. EC, No. L 199, pp. 59–702004/40, 30th July 1999.

[3] 2004/40/EC, “Directive of the European Parliament and of the Council of 29th April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)”, Official J. EU, No. L 184, pp. 1-9, 24th May 2004.

[4] A.W. Guy and C.–K. Chou, “Specific absorption rate s of energy in man models exposed to cellular UHF mobile-antenna fields”, IEEE Trans. MTT, Vol. 34, N. 6, June 1986, pp. 671–680.

[5] D.O. McCoy, D.M. Zakharia and Q. Balzano, “Field strengths and specific absorption rates in automotive environments”, IEEE Trans. Veh. Tech., Vol. 48, No. 4, July 1999, pp. 1287–1303.

[6] A.R. Ruddle, “Modelling electromagnetic field exposure and SAR in vehicles due to on-board transmitters”, Proc. 16th Zurich Int. EMC Symp., Zurich, Switzerland, February 2005, pp. 145–150.

[7] G. Anzaldi, F. Silva, M. Fernandez, M. Quilez and P.J. Riu, “Initial analysis of SAR from a cell phone inside a vehicle by numerical computation”, IEEE Trans. Biomed. Eng., Vol. 54, No. 5, May 2007, pp. 921–930.

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

[9] A.R. Ruddle, “Computed SAR distributions for the occupants of a car with a 400 MHz transmitter on the rear seat”, Proc. 18th Zurich Int. EMC Symp., Munich, Germany, September 2007, pp. 37–40.

[10] A.R. Ruddle, “Simulation of in-vehicle SAR Levels at 900 MHz for a car with various transmitter positions and human occupancy configurations”, Proc. BioEM 2009, Davos, Switzerland, June 2009, paper P276.

[11] A.R. Ruddle, H. Zhang, L. Low, J. Rigelsford and R.J. Langley “Numerical investigation of the impact of dielectric components on electromagnetic field distributions in the passenger compartment of a vehicle”, Proc. 20th Zurich Int. EMC Symp., Zurich, Switzerland, January 2009, pp. 213–216.

[12] A.R. Ruddle, “Validation of simple estimates for average field strengths in complex cavities against detailed results obtained from a 3D numerical model of a car”, IET Science, Measurement and Technology, Vol. 2, No. 6, November 2008, pp. 455–466.

[13] A.R. Ruddle, "Measured impact of vehicle seats and glazing on the coupling of electromagnetic fields into vehicles and their wiring harnesses", Proc. 15th Int. Zurich EMC Symp., Zurich, Switzerland, February 2003, pp. 487-492.

[14] (2010) Microstripes page of CST website. [Online]. Available: http://www.cst.com/Content/Products/MST/Overview.aspx

[15] (2010) Microwave Studio page of CST website. [Online]. Available: http://www.cst.com/Content/Products/MWS/Overview.aspx

[16] (2010) Body Tissue Dielectric Parameters Tool on FCC website. [Online]. Available: http://www.fcc.gov/oet/rfsafety/dielectric.html

[17] S. Watanabe, T. Nagaoka, K. Sakurai, S. Watanabe, E. Kunieda, M. Taki and Y. Yamanaka, "Development of voxel male and female whole-body models and dosimetry", Proc. 27th URSI General Assembly, 2002, paper 1164.

[18] I. Chatterjee, G. Yong-Gong and O.P. Gandhi, "Quantification of electromagnetic absorption in humans from body-mounted communication transceivers", IEEE Trans. Veh. Tech., Vol. 34, No. 2, pp. 55-62, May 1985.