Computed SAR Levels in Vehicle Occupants Due to On-Board Transmissions at 900 MHz

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Abstract**—Numerical simulations have been carried out to assess the specific absorption rate (SAR) in vehicle occupants due to on-board 900 MHz transmissions. The sources considered include a simple external roof-mounted antenna and internal transmitters that are not in contact with the body. The simulations employed homogeneous human simulants to obtain induced SAR values, and investigated a variety of occupancy configurations, ranging from only the driver to a driver and three passengers. Both local and whole-body average SAR levels are found to vary widely with the number and placement of occupants, as well as with antenna configuration. Nonetheless, the computed SAR levels are found to be well below recommended limits for general public exposure at typical radiated power levels.**

I. Introduction

The passenger compartments of vehicles are resonant environments containing geometrically complex internal structures. Consequently, electromagnetic energy that is coupled into these regions results in spatial field distributions that are highly inhomogeneous, with localized hot-spots that may be associated with much higher field magnitudes than would result in open environments at the same power level. For example, simulations of in-vehicle field distributions due to 400 MHz transmissions [1] indicate that the maximum fields inside the empty passenger compartment of a car may be more than two orders of magnitude higher than the average.

The specific absorption rate (SAR) resulting in vehicle occupants have been investigated experimentally at 146 MHz and 460 MHz [2] for external antenna installations. It is reported that although the empty vehicle field levels exceeded FCC recommendation at power levels around 100 W, the SAR values (measured in a physical phantom located in a car with the front half cut away) did not exceed recommended limits.

While the additional losses introduced by adding occupants will act to reduce overall field levels, the number and location of occupants within a vehicle can also be expected to modify the resonances that are present within the passenger compartment. Thus the impact of passengers may not be straightforward to predict. In fact, localized increases in field strength [1] and cable coupling [3] due to the addition of human simulants have been found in vehicle simulations. In addition, numerical investigations at 400 MHz for a roof-mounted antenna [4] and an internal source [5] indicate that the worst-case SAR is not obtained for the driver alone or with three passengers, but arises when one or two passengers are present. Thus, SAR values in the occupants of a car may vary depending on the number and relative position of the occupants, as well as on the location of the source.

This paper summarizes computed in-vehicle SAR results for a representative range of vehicle occupancy configurations at 900 MHz, for both a roof-mounted antenna and three internal sources that are not in contact with the human body.

II. Numerical Models

The numerical SAR simulations were carried out using a commercial tool [6] based on the transmission-line matrix (TLM) technique, a full-wave 3D field modelling method [7].

A. Vehicle Model

The vehicle model used in these investigations was derived from CAD geometry for the body-shell and doors of a medium-sized passenger car, as well as major metallic parts in the passenger compartment such as the seat frames, interior steering components and rear window heater. Simulations based on similar metal-only vehicle models have been shown to provide a good correlation with spatial electric field measurements carried out on a complete vehicle at 390 MHz [7], and with measured broadband coupling to points inside a complete vehicle at frequencies up to 1 GHz [9]. At higher frequencies, however, it is likely that window glass would also need to be included in the vehicle model since this is found [10] to increase average internal field strengths in simulations, although other dielectric materials, such as seat foam and interior trim, are expected to have little impact on the internal field statistics [11].

B. Human Simulants

Seating positions vary between vehicle types, as well as between vehicles of similar type, and even between different seats of the same vehicle. For a phantom representing the driver of a car the arms and feet should be positioned to represent use of the steering wheel and pedals. The front passenger is likely to be in a very similar posture, although with the arms down and feet flat. For the rear passengers, the arms and feet should also be down, but the positions of the legs are likely to have to be different from the front seating positions, due to the position of the front seat frames. Thus, for a given vehicle model at least three variants of a basic human model are required in order to represent the driver and passengers in a representative range of occupancy scenarios.

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. The use of single anatomically detailed human simulant in a car model has been reported [12]. However, the effort involved in re-working the geometry for a heterogeneous model could be considerable compared with a simpler homogeneous model. The latter only requires a single set of exterior surfaces to be modified to obtain variants for different seating positions.

Homogeneous phantoms are already used in applications such as assessing compliance with regulations for mobile telephones [13]. In this work, therefore, a homogeneous human simulant of realistic size and shape (based on a large male) was used, with electrical properties corresponding to two-thirds of the average values for muscle tissue at this frequency (obtained from [14]). The "two-thirds muscle" approximation is widely used for homogeneous whole-body models (eg. [15], [16]).

C. Sources

The sources used in this investigation included:

- vertical ¼-wave monopole mounted at rear of roof;
- internal ½-wave vertical dipole;
- internal ½-wave transverse horizontal dipole;
- internal ½-wave longitudinal horizontal dipole.

The roof-mounted monopole is intended to represent a typical external antenna installation that is widely used in vehicles. The internal dipoles are used as a highly simplified representation of a transmitter that is operating inside the passenger compartment, but not in direct or very close contact with any of the occupants. The feed point for all three of the dipole cases was fixed at the same location in the rear of the passenger compartment, between the rear seating positions and slightly displaced from the vehicle axis towards the driver's side of the vehicle.

III. Computed SAR at 900 MHz

Human electromagnetic field exposure recommendations commonly identify different local SAR limits for some regions of the body. For example, [17] and [18] identify specific local SAR limits for the limbs and for the head and trunk. Consequently, the spatial SAR data obtained from the simulations (at around 430,000 points for each occupant) was partitioned for each occupant under each of the source and occupancy combinations in order to assess the maximum values in these specific regions. The 10 g SAR values obtained for maximum local SAR in the head and trunk, maximum local SAR in the limbs, and whole body average SAR, are summarized in Tables I–IV, for each of the four sources.

Considering a driver and up to three passengers results in eight different occupancy configurations. In these tables the occupant locations DR, FP, RD and RP denote the driver, front passenger, passenger behind the driver, and rear passenger behind the front passenger, respectively. The empty grey cells indicate unoccupied seating positions. The worst-case (ie. largest value) for each of the three SAR measures, taking account of all occupants and occupancy configurations, is indicated in bold. The results are also normalized to a common radiated power level of 1 W CW.

A. External source

The 1 W SAR values obtained for the external monopole antenna, mounted on the axis of the vehicle, are considerably lower than those obtained for the internal sources. This reflects the fact that only a small proportion of the radiated power is coupled into the vehicle interior, with the majority radiating away from the vehicle.

The external source is on the axis of the vehicle, and the passengers are located at the same distance from the axis. Nonetheless, the SAR measures for the two rear passengers are different even when both are present. This probably results from the inherent asymmetry of the vehicle interior, which is dominated by the steering gear.

The highest SAR values for external source are found in the rear seating positions, which is not unexpected as the source is located at the rear of the roof panel. The highest head and trunk SAR levels correspond to one of two-person occupancy configurations. However, the highest limb and average SAR levels are found for one of the three-person occupancy configurations. The SAR measures are found to vary by factors of up to around 5, depending on the occupancy configuration.

B. Internal sources

For the internal sources, all of the power is radiated directly into the passenger compartment. The SAR values obtained for these cases are significantly higher (one or two orders of magnitude) than for the external source.

The highest SAR levels for the internal sources again occur in the rear passengers, most commonly for the passenger located behind the driver. This pattern is also expected, as the source is located between the rear passengers, but slightly displaced to the driver's side of the vehicle. However, the highest SAR levels for the internal sources occur for two, three or four person occupancy configurations, depending on the specific measure and the orientation of the source. Thus, it is not possible to identify an obvious worst-case occupancy configuration.

The highest local SAR values are generally found for the limbs, although there are some cases where head and trunk SAR is apparently higher. However, detailed visual inspection of the spatial SAR distributions revealed that the maxima for the head and trunk actually occur in the hip region. Since the boundaries between trunk and limbs are not specifically defined, it is perhaps debatable which of the two maximum SAR limits is applicable to this region.

TABLE I
COMPUTED SAR MEASURES FOR VERTICAL ROOF-MOUNTED MONOPOLE MOUNTED TOWARDS REAR OF ROOF PANEL

SAR measure	**Occupant numbers**	**10 g SAR (mW/kg) at 1 W CW**			
		DR	**FP**	**RP**	**RD**
Whole-body average SAR (limit for general public in [17], [18] is 80 mW/kg)	1 person	0.133			
	2 people	0.099	0.089		
		0.095		**0.193**	
		0.087			0.167
	3 people	0.060		0.163	0.149
		0.066	0.065		0.166
		0.077	0.060	0.178	
	4 people	0.051	0.044	0.159	0.140
Maximum local SAR for head and trunk (general public limit is 2 W/kg)	1 person	1.541			
	2 people	1.081	1.061		
		1.353		3.194	
		0.906			2.218
	3 people	1.006		**3.733**	2.409
		0.931	0.814		2.401
		0.801	0.722	3.335	
	4 people	0.802	0.722	3.683	2.489
Maximum local SAR for limbs (general public limit is 4 W/kg)	1 person	2.004			
	2 people	1.783	0.977		
		1.520		**4.054**	
		1.784			1.746
	3 people	0.902		3.061	1.900
		1.658	1.374		2.334
		0.851	0.593	3.727	
	4 people	0.852	0.593	3.061	2.280

TABLE II
COMPUTED SAR MEASURES FOR INTERNAL VERTICAL DIPOLE IN VICINITY OF REAR SEATS

SAR measure	**Occupant numbers**	**10 g SAR (mW/kg) at 1 W CW**			
		DR	**FP**	**RP**	**RD**
Whole-body average SAR (limit for general public in [17], [18] is 80 mW/kg)	1 person	3.037			
	2 people	2.640	2.433		
		2.651		**5.794**	
		1.673			5.591
	3 people	1.259		3.908	5.704
		1.409	2.257		5.509
		2.530	1.362	5.304	
	4 people	1.274	1.069	3.843	5.470
Maximum local SAR for head and trunk (general public limit is 2 W/kg)	1 person	35.57			
	2 people	38.07	18.67		
		45.11		84.94	
		20.52			141.8
	3 people	24.86		64.86	172.1
		15.81	28.77		101.4
		41.56	10.78	79.30	
	4 people	23.21	11.77	71.67	**153.3**
Maximum local SAR for limbs (general public limit is 4 W/kg)	1 person	29.49			
	2 people	24.87	42.04		
		24.28		89.38	
		22.33			100.3
	3 people	15.53		100.6	106.8
		13.12	26.99		**146.6**
		30.94	20.89	93.90	
	4 people	17.53	21.32	103.1	98.75

TABLE III
COMPUTED SAR MEASURES FOR INTERNAL HORIZONTAL DIPOLE TRANSVERSE TO VEHICLE AXIS

SAR measure	**Occupant numbers**	**10 g SAR (mW/kg) at 1 W CW**			
		DR	**FP**	**RP**	**RD**
Whole-body average SAR (limit for general public in [17], [18] is 80 mW/kg)	1 person	4.707			
	2 people	3.633	3.426		
		2.617		4.960	
		2.861			5.612
	3 people	1.446		3.676	5.866
		2.419	2.165		5.263
		2.049	1.886	4.611	
	4 people	1.298	1.081	3.579	**5.886**
Maximum local SAR for head and trunk (general public limit is 2 W/kg)	1 person	40.47			
	2 people	33.35	34.15		
		27.63		3.15	
		30.50			64.99
	3 people	14.88		26.03	80.19
		29.34	26.03		**86.89**
		20.13	24.89	24.89	
	4 people	10.93	12.64	12.64	86.75
Maximum local SAR for limbs (general public limit is 4 W/kg)	1 person	53.79			
	2 people	30.40	42.57		
		31.01		109.4	
		28.34			128.9
	3 people	19.16		109.9	166.8
		21.42	33.56		110.7
		13.99	15.10	68.67	
	4 people	9.583	14.22	76.48	**172.2**

TABLE IV
COMPUTED SAR MEASURES FOR INTERNAL HORIZONTAL DIPOLE ALIGNED WITH VEHICLE AXIS

SAR measure	**Occupant numbers**	**10 g SAR (mW/kg) at 1 W CW**			
		DR	**FP**	**RP**	**RD**
Whole-body average SAR (limit for general public in [17], [18] is 80 mW/kg)	1 person	3.210			
	2 people	2.514	2.883		
		2.607		5.291	
		1.808			**6.277**
	3 people	0.781		6.050	5.441
		2.742	1.280		5.916
		2.496	1.145	4.971	
	4 people	0.679	0.745	5.923	5.398
Maximum local SAR for head and trunk (general public limit is 2 W/kg)	1 person	30.79			
	2 people	25.54	43.32		
		33.51		73.64	
		13.53			69.08
	3 people	8.824		43.96	92.55
		13.06	47.40		72.45
		31.05	11.54	72.24	
	4 people	7.005	6.311	42.84	**94.95**
Maximum local SAR for limbs (general public limit is 4 W/kg)	1 person	30.94			
	2 people	22.32	38.43		
		27.93		196.4	
		30.45			208.6
	3 people	14.46		194.7	311.7
		15.52	17.83		198.3
		28.60	23.95	187.1	
	4 people	8.403	8.291	195.4	**320.0**

For the internal sources, the SAR measures are found to vary even more widely, by factors ranging up to more than twenty, depending on the occupancy configuration and antenna orientation.

C. Comparison with SAR limits

For general public exposure, the SAR limits recommended in [17] and [18] are:

- whole-body average – 80 mW/kg;
- maximum head and trunk SAR– 2 W/kg;
- maximum limb SAR– 4 W/kg.

The limits for occupational exposure are somewhat higher than for the general public.

In all cases the 1 W CW results are considerably lower than the recommended limits for general public exposure. For all three measures, the worst-case SAR measures at 1 W CW radiated power are no more than 8% of the general public exposure limits of [17] and [18], and commonly much smaller.

Since SAR is proportional to radiated power the results of Tables I–IV can be linearly scaled to other power levels of possible interest. The model results suggest that SAR limits might be reached at radiated power of around 415 W CW for the external source, and 12 W CW for the internal sources. The latter corresponds well with analytical estimates [10] for the power level that could result in average internal field strengths at the field reference levels, which indicate 4 W CW for a car at 1 GHz [19]. The field reference levels are intended to provide a conservative assessment of the potential SAR risk.

IV. Conclusions

The results obtained indicate that occupant SAR levels in vehicles equipped with on-board 900 MHz transmitters may vary considerably depending on the number and relative position of the occupants, as well as with the location of the source. However, there is no readily identifiable “worst-case” occupancy configuration.

The SAR levels estimated at 1 W CW radiated power are considerably lower than recommended limits for general public exposure. These results also suggest that SAR limits are unlikely to be breached at this frequency for typical operational power levels for real communications equipment (eg. 2 W maximum for mobile telephone handsets). In practice, however, the effective radiated power of real-world systems is likely to be lower than the nominal value, because of finite duty cycles.

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