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Ultraviolet radiation penetrating vehicle glass: a field based comparative study

M G Kimlin and A V Parisi

Centre for Astronomy and Atmospheric Research, Faculty of Sciences, University of Southern Queensland, Toowoomba 4350, Australia

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Abstract. The solar UV transmitted through automobile glass was measured in the field in two cars using a spectroradiometer. The two cars were identical except that one of the cars had all of the windows (except the windshield) tinted. The measured spectral erythemal UV on a horizontal plane with the windows fully closed was reduced in the tinted car by a factor of 42 when compared with the erythemal UV measured in the untinted car. The ambient UVA irradiances at various locations within four different makes of car and a tractor were also measured with a broad band UVA hand-held meter. The average normalized daily UVA exposure (measured with a broad band UVA meter) was 1.3 times higher in a large family sedan when compared with that in a small hatchback and the UVA exposure in a car with tinted windows was 3.8 times less than in a similar untinted car.

1. Introduction

One of the most common forms of human transport in developed countries is undoubtedly the automobile. In Australia, with large distances between population centres, many people may be drivers or passengers in a car for several hours at a time. Farmers who use tractors with glass cabins may also be in the cabin for extended periods of time when planting and harvesting crops. Automobile glass provides a barrier for the UVB (280–320 nm) component of the UV spectrum, but still allows considerable transmission of UVA (320–400 nm) (Parisi and Wong 1997). The UVB wavelengths are the most effective at inducing erythema in human skin with the UVA wavelengths less effective (CIE 1987). Nevertheless, repetitive exposure to UVA wavelengths causes premature aging and skin wrinkling (Kaminester 1996) and damage to human skin (Lavker *et al* 1995a, b).

High ambient UV levels in south-east Queensland, Australia (Sabburg *et al* 1998) combined with the fact that sun protective devices such as hats and sunscreens are not commonly used whilst travelling in cars, put Australians at risk of exposure to damaging UV in a car. This was quantified by Parisi and Wong (1998), who measured personal UV exposures in a small and large car. Other studies (Gies *et al* 1992), which were undertaken in the laboratory, also indicate that the UV transmitted through automobile glass is dependent on whether the glass is tinted or untinted.

This study expands on the work by Parisi and Wong (1998) and Gies *et al* (1992) by comparing the UV spectral transmittance with a spectroradiometer in the field through tinted and untinted automobile glass in two cars of similar make and model. No previous research has measured this. Additionally, the UVA irradiances in the field at various sites inside four different cars and a tractor cabin were measured.

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2. Materials and methods

2.1. Vehicles used

Two vehicles with no additional window tinting were selected from the small car class, 1998 model Holden Barina, three-door hatchback (window glass: Sekurit E9) and the large car class, namely 1998 model Holden VT Commodore, sedan (window glass: Pilkington DOT 298 M40 AS2) respectively. A further two cars, from the large family class, 1997 Ford Falcon GLi station wagons, one without additional window tinting (window glass: Pilkington DOT 298 M50 AS2, EZ-KOOL) and the other with an aftermarket window tint film (window tint: Solace T35 V.L.T) applied to all windows (except the windshield), were used in this study. A John Deere tractor with no additional window tinting applied to the windows was also used. In this paper the small and large car, station wagon, tinted station wagon and tractor will be referred to as S, L, W, WT and T respectively. All of the cars used in this study had the driver's seat on the right-hand side of the car, as cars in Australia travel on the left-hand side of the road. The tractor, T, had its single seat in the centre of the cabin.

2.2. Spectral UV transmission

The spectral UV transmission through the window glass in the W and WT cars with all of the windows closed was measured in a field at the campus of the University of Southern Queensland, Toowoomba, Australia (27.5°S) at 09:30 to 09:54 Australian Eastern Standard Time (EST) on 26 August 1998 using a calibrated spectroradiometer. A mercury vapour lamp was used for the wavelength calibration of the spectroradiometer prior to use and a 250 W quartz tungsten halogen (QTH) lamp, powered by a current stabilized d.c. power supply at 9.500 ± 0.005 A, with a calibration traceable to the Australian National Standard, CSIRO, Linfield, Australia was used for absolute calibration. Both cars were stationary and orientated with the front of the car facing west. The spectral measurements were performed in only the rear seat compartment of the W and WT cars due to the practical difficulty of undertaking the measurements at any other sites. All doors and windows were fully closed during the measurement period. This was to allow measurement of the UV transmittance through the glass only, and, due to the warm ambient air temperatures in Australia, cars are generally used with the air conditioner on and the windows fully closed.

The spectroradiometer measured the UV irradiance in 1 nm intervals with the integrating sphere entrance aperture firstly on a horizontal plane and secondly orientated to the northern and southern side car windows respectively. This was designed to measure the areas of the highest and lowest spectral UV irradiances, i.e. for horizontal body sites whilst sitting in a car, such as the upper leg and shoulder, and vertical body sites, for example the arms. Immediately following the transmitted spectral UV irradiance scans in the W car, the spectroradiometer was placed in an open unshaded area outside the cars and the solar spectral UV irradiances scanned. This complete process of measuring the spectral UV transmittance was repeated for the WT car. All spectral UV measurements were conducted in clear-sky conditions. The solar ultraviolet spectral transmission of the Solace T35 V.L.T tint was measured to quantify the effect of the tint alone in UV transmission.

2.3. UVA irradiance

The UVA irradiances were measured with a broadband UVA detector (model 3D, V2.0, Solar Light Co., Philadelphia, PA, USA) in the four late model cars and the tractor cabin with the windows fully closed. Additionally, the ambient UVA irradiances outside the cars on a horizontal plane were measured on the selected measurement days using the same detector. The data were collected in Toowoomba, Australia between 30 July 1998 and 13 August 1998 in the morning, noon and afternoon (09:00 EST, 12:00 EST and 15:00 EST respectively). The morning, noon and afternoon measurements were repeated for each car on a separate day. The maximum cloud cover during the course of the experiments was 3 octa (with 8 octa representing total cloud coverage of the sky), with no measurements taking place whilst cloud was covering the solar disc. The UVA irradiances were measured on a horizontal plane on the front and rear seats of the S and L cars at the sites FD, FP, BD, BP as shown in figure 1(a) at a height of 20 cm above the seats and on the steering wheel (site SW). The UVA irradiances

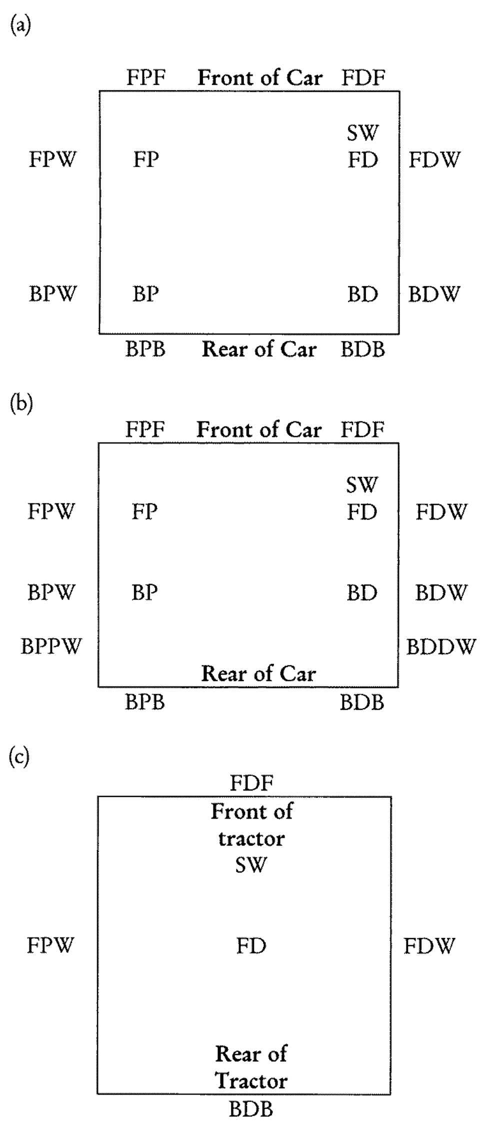

Figure 1. The UV irradiance measurement sites inside (a) the S and L cars, (b) the W and WT cars and (c) the tractor, T.

in the S and L cars were also measured normal to the glass at the sites FDW, FDF, FPF, FPW, BPW, BPB, BDB and BDW as shown in figure 1(a).

For the W and WT cars, the UVA irradiances were measured at the same sites as the S and L cars, with the additional measurement sites of BPPW and BDDW normal to the glass as shown in figure 1(b). The additional measurement sites, BPPW and BDDW, for the W and WT cars are due to a station wagon having an additional glass insert in the rear of the wagon.

For all the cars, the doors were closed and the windows fully closed and the UVA irradiance measurements were undertaken with the front of the car in four different orientations; north, south, east and west respectively. The measurements were taken with these four orientations to take into account the movement of a vehicle while driving.

Due to the tractor, T, having only one seat for the operator, the UVA irradiances were measured on the seat at the site FD at a height of 20 cm above the seat and on the steering wheel (site SW) on a horizontal plane. The UVA irradiances in the tractor, T, were measured normal to the glass at the sites FDW, FDF, FPW and BDB as shown in figure 1(c). Due to the impracticality of moving the tractor, the UVA irradiance measurements were undertaken with the front of the tractor facing west only. Additionally, the tractor measurements were undertaken at noon only.

3. Results

3.1. Spectral UV transmission

The solar spectral UV transmission of the Solace T35 V.L.T window tint alone was measured in the field using the spectroradiometer and is shown in figure 2. The window tint removed all of the UVB spectrum and only allowed through a small proportion of the UVA spectrum. The spectral UV transmission through automobile glass in the field measured with a

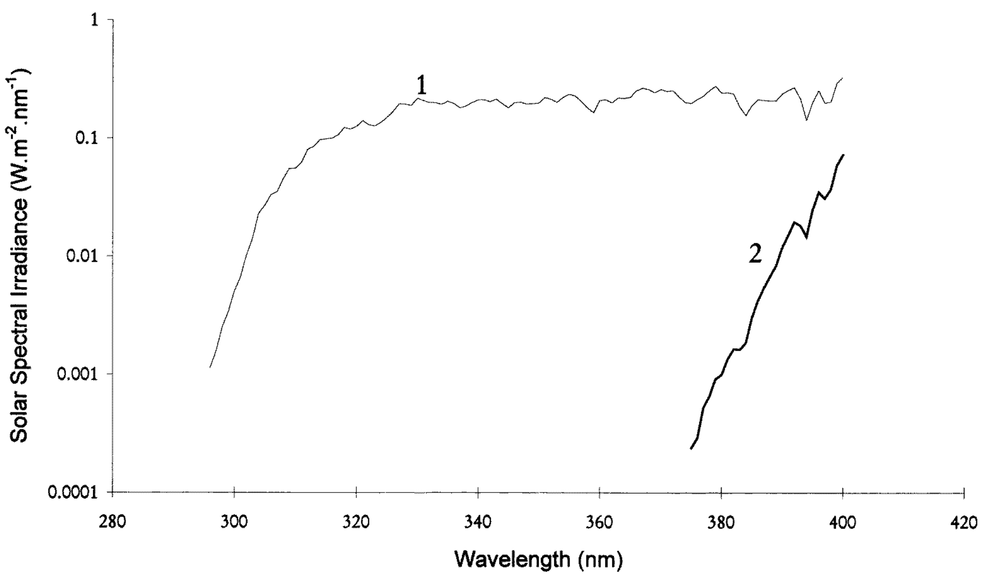

Figure 2. (1) The Solar UV spectrum and (2) the solar UV spectrum filtered through Solace T35 V.L.T window tint.

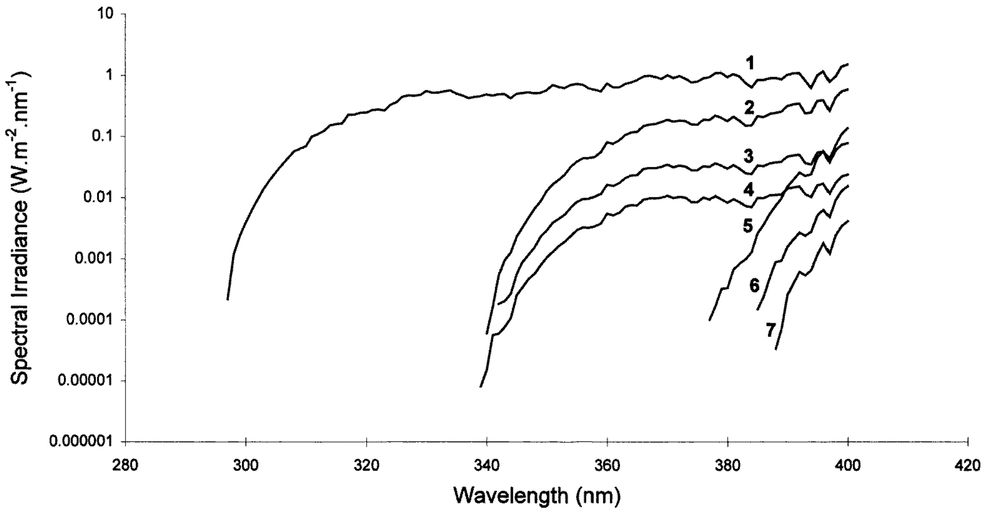

Figure 3. Spectral UV irradiances in W (windows untinted) and WT (windows tinted) cars: (1) solar UV spectrum outside the car; (2) entrance optics facing north inside the car, untinted windows; (3) entrance optics horizontal in car, untinted windows; (4) entrance optics facing south inside the car, untinted windows; (5) entrance optics facing north inside the car, tinted windows; (6) entrance optics horizontal in car, tinted windows; (7) entrance optics facing south inside the car, tinted windows.

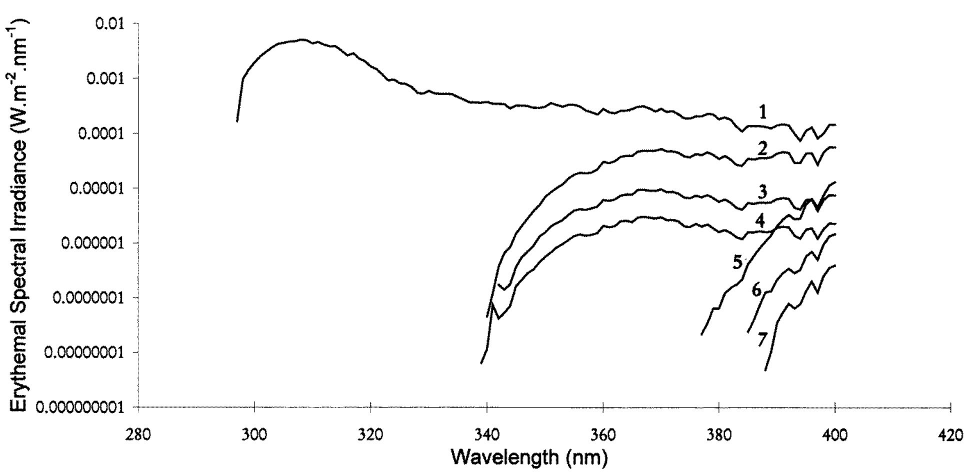

Figure 4. Erythemally weighted spectral UV irradiances in W (windows untinted) and WT (windows tinted) cars: (1) solar UV spectrum outside the car; (2) entrance optics facing north inside the car, untinted windows; (3) entrance optics horizontal in car, untinted windows; (4) entrance optics facing south inside the car, untinted windows; (5) entrance optics facing north inside the car, tinted windows; (6) entrance optics horizontal in car, tinted windows; (7) entrance optics facing south inside the car, tinted windows.

spectroradiometer is shown in figure 3 and the same spectral data weighted with the erythemal action spectrum (CIE 1987) are shown in figure 4. Both car W (untinted windows) and car WT (tinted windows) had the UVB (280–320 nm) component of the solar UV spectrum removed by the window glass alone as shown in table 1. However, car W still allowed transmission of the

Table 1. UV and erythemal irradiances for solar UV transmission through automobile glass for the integrating sphere aperture orientated to the south (S), horizontal (H) and to the north (N).

		Irradiances (W m^{-2})					
		Car W (untinted)			Car WT (tinted)		
Band	Solar	S	H	N	S	H	N
UVB	2.1	0	0	0	0	0	0
UVA	54.5	0.47	1.48	9.54	0.021	0.072	0.61
UV$_{ery}$	0.116	9.66×10^{-5}	3.11×10^{-4}	1.80×10^{-3}	1.78×10^{-6}	7.38×10^{-6}	6.65×10^{-5}

UVA waveband of the solar UV spectrum, whilst the addition of window tint on the windows of car WT removed a greater proportion of the solar UVA component when compared with the UVA transmission of car W for all three orientations of the integrating sphere aperture. The transmitted UV irradiances measured in a car are strongly linked to the orientation of the detector. When the entrance aperture of the spectroradiometer was orientated to the south side of the cars (in a direction away from the solar disc), the UVA irradiance decreased by a factor of 3.1 when compared with the UVA irradiance on a horizontal plane in the W car and decreased by factor of 3.4 compared with the horizontal plane in the WT car. Also, when the entrance aperture of the spectroradiometer was orientated to the north side in the W car (facing the solar disc), the UVA irradiance increased by a factor of 6.4 from the UVA measured in the W car on a horizontal plane. For the WT car the UVA irradiance on a vertical plane at the north side increased by a factor of 8.5 for the WT car compared with the horizontal plane.

The erythemally weighted UV (UV$_{ery}$), on a horizontal plane in car WT (tinted windows) was 42 times lower than the UV$_{ery}$ measured in car W (no tinting) for the integrating sphere aperture on a horizontal plane. In car W, the erythemal irradiance measured with the integrating sphere facing south and north compared with horizontal was decreased by a factor of 3.2 and increased by a factor of 5.8 respectively. In comparison, for car WT the erythemal irradiance measured with the integrating sphere facing south and north compared with horizontal was decreased by a factor of 4.1 and increased by a factor of 9 respectively.

3.2. UVA irradiances

The UVA irradiances measured with the broad band meter for the cars S, L, W and WT, along with the tractor, T, are provided in table 2. For the cars, the results are the averages of the measurements taken with the front of the cars facing in the north, south, east and west directions at each measurement time. Statistically significant (Student's t-test $p < 0.05$) variation existed between vehicle type, measurement location, time of day and whether the windows had been tinted. For example, the W car had a UVA range of 1.3 W m^{-2} to 4.5 W m^{-2} during the morning, whilst car WT had a UVA range of 0 W m^{-2} to 1.9 W m^{-2} in the morning. At noon the ranges were 1.9 W m^{-2} to 5.1 W m^{-2} and 0.1 W m^{-2} to 2.9 W m^{-2} respectively and at 3 p.m. the ranges were 1.0 W m^{-2} to 3.1 W m^{-2} and 0 W m^{-2} to 1.8 W m^{-2} for W and WT cars respectively.

Table 3 shows the average UVA values in table 2 normalized to ambient UVA on a horizontal plane outside the cars for all cars for the three measurement periods of morning, noon and afternoon for all-sites along with the all-sites, horizontal sites and side window sites average. The irradiances were normalized to account for differences in irradiance on different

Table 2. UVA irradiances through S, L, W, WT and T vehicle glass. For the cars, the values are the averages of the irradiances with the cars in the north, south, east and west directions. (See figure 1 for measurement sites.)

		UVA irradiances (W m^{-2})												
		Morning				Noon					Afternoon			
Site	Orientation	Car S	Car L	Car W	Car WT	Car S	Car L	Car W	Car WT	T	Car S	Car L	Car W	Car WT
FD	Horizontal	1.8	1.3	1.8	1.9	2.9	0.21	3.3	2.9	3.0	2.6	2.1	2.0	1.8
FP	Horizontal	1.5	1.4	1.9	1.9	2.8	0.19	3.1	2.9		2.5	2.3	2.0	1.8
BD	Horizontal	1.5	1.4	1.8	1.5	2.8	0.18	2.9	2.5		2.3	2.0	1.9	1.6
BP	Horizontal	5.0	6.8	4.5	0.5	7.4	0.78	5.0	0.3		6.4	7.4	2.4	0.1
SW	Horizontal	2.0	2.5	1.8	0.8	3.9	0.40	3.4	1.5		1.5	1.3	1.3	0.6
FDW	Normal to glass	1.6	1.8	1.5	0.5	2.0	0.39	2.5	0.9	2.0	1.9	1.4	1.3	0.4
FDF	Normal to glass	5.9	7.3	4.1	0.5	7.8	1.49	5.3	0.4	7.1	7.4	6.0	3.1	0.0
FPF	Normal to glass	4.8	5.6	4.1	0.4	7.1	1.64	5.1	0.5		6.6	5.8	3.0	0.1
FPW	Normal to glass	1.3	1.4	1.3	0.0	2.5	0.59	1.9	0.1	4.0	1.9	1.8	1.1	0.1
BPW	Normal to glass	1.6	1.1	1.3	0.1	3.3	0.56	2.9	0.4		1.1	1.3	1.0	0.0
BPB	Normal to glass	4.3	6.8	3.4	0.0	7.0	0.86	4.4	0.3		5.5	5.1	2.0	0.1
BDB	Normal to glass	5.4	7.1	2.9	0.1	9.6	1.20	4.6	0.3	7.2	6.8	6.8	2.3	0.1
BDW	Normal to glass	5.4	7.1	3.0	0.4	9.5	1.20	4.5	0.3		6.8	6.5	2.0	0.1
BDDW	Normal to glass			2.9	0.6			5.1	0.5				1.6	0.1
BPPW	Normal to glass			3.9	0.6			3.6	0.3				2.0	0.1

Table 3. The irradiances at each site normalized to the ambient irradiances. The last three rows are the all-sites, horizontal and side window sites averages for morning, noon and afternoon. (See figure 1 for measurement sites.)

		Normalized Irradiances												
		Morning				Noon					Afternoon			
Site	Orientation	Car S	Car L	Car W	Car WT	Car S	Car L	Car W	Car WT	T	Car S	Car L	Car W	Car WT
FD	Horizontal	0.09	0.05	0.08	0.08	0.09	0.07	0.08	0.07	0.07	0.10	0.09	0.07	0.08
FP	Horizontal	0.08	0.05	0.09	0.08	0.09	0.06	0.07	0.07		0.09	0.09	0.07	0.08
BD	Horizontal	0.08	0.06	0.08	0.06	0.09	0.06	0.07	0.06		0.08	0.08	0.07	0.07
BP	Horizontal	0.24	0.29	0.21	0.02	0.23	0.23	0.12	0.01		0.24	0.31	0.08	0.01
SW	Horizontal	0.10	0.10	0.08	0.03	0.12	0.12	0.08	0.04		0.06	0.05	0.04	0.03
FDW	Normal to glass	0.08	0.07	0.07	0.02	0.06	0.14	0.06	0.02	0.09	0.07	0.06	0.04	0.02
FDF	Normal to glass	0.28	0.31	0.20	0.02	0.24	0.51	0.13	0.01	0.28	0.27	0.25	0.11	0.00
FPF	Normal to glass	0.23	0.23	0.20	0.02	0.22	0.57	0.12	0.01		0.25	0.24	0.11	0.01
FPW	Normal to glass	0.06	0.06	0.06	0.00	0.07	0.22	0.04	0.00	0.01	0.07	0.08	0.04	0.01
BPW	Normal to glass	0.08	0.05	0.06	0.01	0.09	0.19	0.07	0.01		0.04	0.05	0.04	0.00
BPB	Normal to glass	0.21	0.29	0.16	0.00	0.22	0.26	0.10	0.01		0.21	0.22	0.07	0.01
BDB	Normal to glass	0.26	0.30	0.14	0.01	0.31	0.36	0.11	0.01	0.29	0.25	0.29	0.08	0.01
BDW	Normal to glass	0.26	0.30	0.14	0.02	0.30	0.36	0.11	0.01		0.25	0.28	0.07	0.01
BDDW	Normal to glass			0.14	0.03			0.12	0.01				0.06	0.01
BPPW	Normal to glass			0.18	0.03			0.09	0.01				0.07	0.01
	All-sites average	0.16	0.17	0.13	0.03	0.16	0.24	0.09	0.02	0.15	0.15	0.18	0.07	0.02
	Horizontal sites average	0.12	0.11	0.11	0.05	0.12	0.11	0.08	0.05	0.07	0.11	0.12	0.07	0.05
	Side window sites average	0.18	0.20	0.14	0.02	0.19	0.33	0.10	0.01	0.17	0.18	0.18	0.07	0.01

Table 4. All-day UVA exposures for each type of car. (See figure 1 for measurement sites.)

		UVA exposure			
Site	Orientation	Car S	Car L	Car W	Car WT
FD	Horizontal	1998	1512	1674	1620
FP	Horizontal	1890	1404	1620	1620
BD	Horizontal	1836	1404	1566	1350
BP	Horizontal	5076	5724	2862	270
SW	Horizontal	2160	2106	1512	756
FDW	Normal to glass	1458	2214	1242	432
FDF	Normal to glass	5562	8532	3078	216
FPF	Normal to glass	4968	8694	2970	270
FPW	Normal to glass	1458	3132	972	54
BPW	Normal to glass	1620	2592	1296	162
BPB	Normal to glass	4644	5562	2322	162
BDB	Normal to glass	6102	7074	2376	216
BDW	Normal to glass	5994	7020	2322	270
BDDW	Normal to glass			2376	324
BPPW	Normal to glass			2322	324
	All-sites average	3444	4382	2034	536
	Horizontal average	2592	2430	1847	1123
	Normal to glass average	3975	5603	2128	243

days. For the S car, the noon all-sites average was the same as the morning all-sites average. This may be due to the car windows, being mounted in a predominately vertical position, transmitting higher levels of UV at large solar zenith angles, such as recorded in the morning and afternoon measurements, whereas the small solar zenith angle during the noon period means that there is more shading of the interior by the top of the car. Car L all-sites average noon measurement was increased by a factor of 1.4 compared with the morning all sites average measurement. The Car W and WT all-sites average noon measurement was decreased by a factor of 1.4 and 1.5 respectively compared with the morning all-sites average measurement. The recorded differences may be due to the varying window types, thickness and window tinting.

For the morning, noon and afternoon measurement times, the side window sites average irradiances were higher than or in one case equal to the horizontal sites average for vehicles, S, L, W and T. For car WT, the side windows sites average was reduced by a factor of 10 at noon compared with car W as a result of the aftermarket film tint. Car WT showed lower side window site averages than the corresponding side window site averages of the other cars. The UVA exposure in the tractor, T, was highest on the east and west sides of the tractor, due to the tractor being orientated in only one direction, and the measurement being undertaken at noon. As the operator of the tractor sits in the middle of the cabin, rather than sitting to the right side as when driving a car, the effect of orientation on the exposure on the operator may be higher than that in a car.

The UVA irradiances, normalized to ambient, recorded in the morning, noon and afternoon measurements were linearly interpolated to provide an all-day UVA exposure at a particular site as shown in table 4. The all-day UVA exposure averaged over all the sites in car S was 1.3 times lower than the all-day, all-measurement-site average UVA exposure for car L. The all-day, all-measurement-site average UVA exposure in car W was 3.8 times higher than the all-day UVA exposure in car WT.

4. Discussion

The solar spectral UV irradiances have been measured in the field in two types of car with a spectroradiometer. These are the first measurements of this type. In this case, when an aftermarket window tint is applied to car windows, the transmitted erythemal UV on a horizontal plane was reduced by a factor of 42 when comparing two identical cars, one with window tinting and another without. The tinting provides significant protection from UV radiation. Specifically, even though the glass alone removed all of the UVB radiation, the UVA radiation was significantly reduced by the window tint. The all-day, all-measurement-site average broadband UVA irradiances were in the high to low rank order of cars L, S, W and WT respectively. The UVA exposure in WT was 8.2 times less than that in car L and 1.3 times less in car S compared with car L. The normalized UVA values recorded at noon were 1.7 times higher in the tractor, T, compared with car W and 7.5 times higher than in car WT. These high UVA exposures through glass, place people who drive for long periods of time, such as sales representatives and farmers, at risk of serious skin damage unless protective devices such as sunscreens or clothing are used while in a car.

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