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Determination of a laser eye dazzle safety framework

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A simple safety framework for laser eye dazzle, based on a complex model developed from human subject experiments, is proposed to address the urgent need for guidance within international laser safety standards. Maximum Dazzle Exposure (MDE) safety limits are derived that set the laser irradiance at the eye above which an object cannot be visually detected. A newly defined concept of dazzle level accounts for the extent of visual obscuration, and different ambient light levels are accommodated by determining safety limits for night, dusk/dawn, and day conditions. The resulting table of MDE values allows dazzle effects to be quantified in simple safety calculations across a wide range of scenarios. This safety framework is intended to empower the laser safety community to understand and quantify the impacts of laser eye dazzle, specify protection measures for those at risk, and assure the safety and effectiveness of laser dazzle devices. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.2351/1.5029384>

Key words: laser safety, laser eye dazzle, safety standards, laser eye protection, visible lasers, human vision

I. INTRODUCTION

Laser eye dazzle—the temporary impairment of human performance caused by visible wavelength laser light—is increasingly being encountered in civilian and military domains. Commercial aircraft are being maliciously targeted by high power handheld lasers that are capable of causing visual disruption to pilots at ranges of many kilometers, with almost 20 incidents per day reported during 2017 in the US alone.¹ Security forces are also increasingly deploying laser dazzle as a nonlethal option to warn and determine intent,² providing an intermediate step between “shouting” and “shooting.”

There is an urgent need for a safety framework that allows the impacts of laser eye dazzle to be understood and quantified. Cases of permanent eye damage caused by lasers are still relatively rare,^{3,4} with the risks of eye damage from laser systems being well understood and comprehensively documented in international laser safety standards.^{5,6} However, despite the significantly greater frequency of laser eye dazzle events, there is an absence of equivalent guidance for laser eye dazzle effects in these standards.

With the aim of enhancing international laser safety standards, the authors established their own methodology for assessing laser eye dazzle effects in 2015 (Ref. 7) and are now proposing a major revision. This earlier work recommended additional human subject experiments to improve accuracy, and a refined calculation approach to improve simplicity. Following the completion of the required human subject experiments,⁸ the

authors are now able to recommend an approach that is indeed improved in accuracy and simplicity.⁹

This paper presents the scientific background to the new laser eye dazzle safety framework, together with the full text of the proposed framework as an annex.¹⁰ This framework is designed to be a self-contained summary of what laser eye dazzle is, what effects it has on human performance, what the main contributors are to its severity, how to mitigate it, and how to predict its effects with simple calculations. The main body of this paper serves as a technical reference for the safety framework, detailing the derivation of the proposed Maximum Dazzle Exposure (MDE) safety limits with respect to the experimental data and underlying computer model.

II. MAXIMUM DAZZLE EXPOSURE CONCEPT

Integral to the simple calculation of laser eye dazzle effects is the concept of MDE. Laser eye dazzle causes part of the visual scene to be obscured by the appearance of a “dazzle field”—a bright, saturated region of vision as illustrated in Fig. 1. The MDE is the laser irradiance at the eye above which an object cannot be visually detected through this dazzle field. At laser irradiances higher than the MDE, the dazzle field prevents the observer from detecting the object, while at irradiances lower than the MDE the observer is able to detect the object. MDE is analogous to the established concept of Maximum Permissible Exposure (MPE) which sets the laser irradiance limit above which there is a risk of permanent eye damage.

It is not possible to specify a single MDE to account for all scenarios. Instead, a table of MDE values has been

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FIG. 1. Simulated image of the dazzle field caused by laser eye dazzle.

designed to cover the major contributors to the severity of laser eye dazzle, as will now be detailed.

A. Acceptable dazzle level

It is proposed that MDE values are specified for a set of dazzle levels (DLs). These dazzle levels quantify the extent of visual obscuration experienced, ranging from Very Low (2° full angle dazzle field, centered on the laser source) where a laser beam can be seen but it only obscures a minor extent of the visual field, to Low (10°), Medium (20°), and High (40°) which represent increasing extents of visual disruption (see Fig. 2). The MDE will be higher for higher DLs, and selection of the appropriate MDE will be dictated by the DL that is deemed acceptable according to the visual requirements of the observer for the task being completed.

B. Ambient light level

It is proposed that MDE values are specified for ambient luminance levels approximating night (0.1 cd m⁻²), dusk/dawn (10 cd m⁻²), and day (1000 cd m⁻²) conditions, with laser eye dazzle more readily achieved as the ambient light level decreases from day to night. The MDE will be greater for higher ambient light levels, and selection of the appropriate MDE is therefore dictated by the ambient luminance conditions under which laser exposure is anticipated.

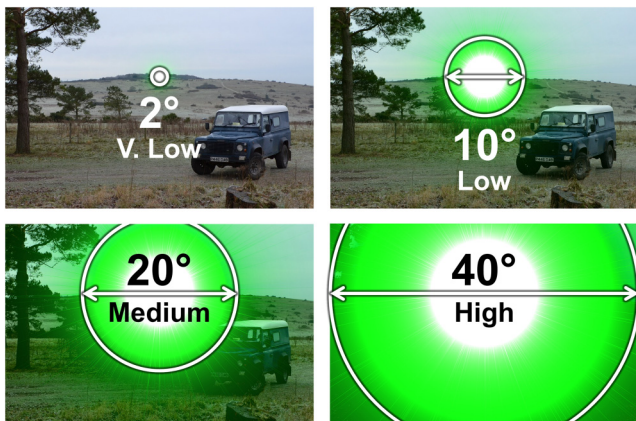


FIG. 2. Illustration of the visual extent of the four dazzle levels (image scene horizontal field of view is 40°).

C. Laser wavelength

It is proposed that MDE values should be scaled depending upon the laser wavelength being considered, according to the eye’s photopic sensitivity, ^{11,12} $V(\lambda)$. The eye is less sensitive to blue (e.g., $V(450\text{ nm}) = 0.0647$) and red (e.g., $V(650\text{ nm}) = 0.1193$) wavelengths compared to green (e.g., $V(550\text{ nm}) = 0.9890$), meaning that MDE values will be higher for wavelengths of lower sensitivity as more irradiance is required to achieve the same effect. All MDE values should therefore be divided by $V(\lambda)$ for the laser wavelength to give the appropriate MDE.

III. DERIVING MAXIMUM DAZZLE EXPOSURE VALUES

Table I illustrates the structure of the proposed MDE table to account for the primary contributors to the severity of laser eye dazzle. It provides a range of values which depend upon the acceptable dazzle level and the ambient light level, with all values being divided by $V(\lambda)$ to account for the laser wavelength dependence.

As the MDE represents the laser irradiance that prevents visual detection of an object, the object being viewed must be defined. A standard object size of 0.08° with 60% contrast has been chosen, based upon the authors’ human subject experiments⁸ which used a tumbling-E letter orientation task with 60% contrast characters of 0.4° size (0.08° bar size) viewed monocularly in negative contrast (i.e., dark letters on a light background). Detecting a 0.08° object is approximately equivalent to detecting a 5 m long car at a range of 3.5 km or a 0.5 m human torso at 350 m.

Table II populates the MDE table with values from the human subject experiments, as well as from the updated computer model. Experimental data from the authors’ earlier work^{8,13} were averaged across all laser wavelengths (up to eight) for each relevant combination of ambient luminance and object size, with the photopic luminous efficiency being factored out of the calculations. The experimental irradiance ranges given are the average value plus and minus one standard deviation, with footnote “a” denoting values that were extrapolated beyond the irradiance levels used in the actual experiment. Details of the averaging and extrapolation can be found in the analysis provided with the data set for this paper.¹⁴

Model data are based upon the previously reported calculation method^{7,8} with inputs as given in Table III. This method uses established models for human eye scatter and visual detection contrast thresholds and includes a laser

TABLE I. Structure of the proposed MDE table.

Dazzle level	MDE ($\mu\text{W cm}^{-2}$) at		
	Night	Dusk/dawn	Day
Very low	—	—	—
Low	—	—	—
Medium	—	—	—
High	—	—	—

÷ $V(\lambda)$

TABLE II. Human subject experiment and modeled MDE values for monocular viewing of the negative contrast 0.08° bar width, 0.4° E letter (60% contrast).

Dazzle level	Data source	MDE ($\mu\text{W cm}^{-2}$) at		
		Night	Dusk/dawn	Day
Very low	Expt.	—	0.1–0.4 ^a	14–18
	Model	0.0001	0.4	21
Low	Expt.	—	8–19	688–5619 ^a
	Model	0.003	17	1039
Medium	Expt.	—	43–106	3694–66 734 ^a
	Model	0.01	74	4495
High	Expt.	—	221–636	19 829–792 633 ^a
	Model	0.04	281	16 950

^aValues that were extrapolated beyond the irradiance levels used in the actual experiment.

exposure calibration factor derived from the human subject laser experiments. An age of 40 was chosen for these calculations, together with a dark eye pigmentation (=0.5), which was the approximate average profile of subjects used in the experiments. Again, these calculations can be found in detail in the supporting data set.¹⁴

It can be seen that the model provides values that are broadly within the range of the experimental data. As the experimental data become extrapolated, primarily at day ambient luminance levels, the model continues to be near the experimental data range although towards the lower end. As 2546 $\mu\text{W cm}^{-2}$ represents the MPE for a 0.25 s visible wavelength exposure, it is indeed preferable that the model errs on the side of caution for these high irradiance levels by setting a safety limit towards the lower end. The day MDE values in Table II that exceed the MPE were extrapolated beyond the irradiance values used in the actual experiment. The experiment never exceeded 1000 $\mu\text{W cm}^{-2}$, which is the MPE for a 10 s visible wavelength exposure.

The human subject experiments did not evaluate the 0.4° E at night ambient luminance levels because that target was too near threshold and could not be reliably discriminated by many of the subjects. Therefore, Table IV presents MDE values for the 0.16° bar size, 0.8° E character (70% contrast) that was evaluated at these ambient levels. As well

TABLE III. Input parameters to MDE model calculations for visual detection of a 0.08° object.

Parameter	Value		
Observer age (years)	40		
Eye pigmentation	0.5		
Object size for detection (deg)	0.08		
Object contrast	0.60		
Photopic luminous efficiency	1		
	Night	Dusk/dawn	Day
Ambient luminance (cd m^{-2})	0.1	10	1000
Contrast thresh., monocular negative	0.5794	0.0955	0.0730
Contrast thresh., binocular negative	0.3408	0.0562	0.0430
Contrast thresh., binocular positive	0.4908	0.0690	0.0433

TABLE IV. Human subject experiment and modeled MDE values for monocular viewing of the negative contrast 0.16° bar width, 0.8° E letter (70% contrast).

Dazzle level	Data source	MDE ($\mu\text{W cm}^{-2}$) at		
		Night	Dusk/dawn	Day
Very low	Expt.	0.002–0.004 ^a	0.4–1.5 ^a	38–78
	Model	0.005	1.1	55
Low	Expt.	0.12–0.16 ^a	20–46	1562–25 588 ^a
	Model	0.24	56	2698
Medium	Expt.	0.69–0.75	103–217	7723–309 383 ^a
	Model	1.0	241	11 668
High	Expt.	3.6–4.1	525–1054 ^a	38 200–3 740 664 ^a
	Model	3.9	907	43 998

^aValues that were extrapolated beyond the irradiance levels used in the actual experiment.

as supporting the accuracy of the model’s predictions at dusk/dawn and day levels, these data show that the model is also capable of predicting exposure levels at night ambient luminance levels with a good degree of accuracy.

Having demonstrated the ability of the model to predict MDE values accurately, the model was next applied to the more representative scenario of an object being viewed binocularly. This involved changing the contrast threshold values for visual detection as shown in Table III, and reverting back to the 0.08° object with 60% contrast. After calculating MDE values for binocular negative contrast and binocular positive contrast object detection, the two values for each entry were averaged to give the MDE table shown in Table V.

Following the derivation of these values, some rounding was conducted to simplify presentation, giving the values in Table VI which are offered as the proposed table of MDE values to be used in laser safety standards.

Recognizing that these MDE values will be higher for all laser wavelengths outside the eye’s peak response at 555 nm (where $V(\lambda)=1$), they indicate that at night, only around 1 nW cm^{-2} is required for a Very Low DL, while a High DL can be achieved with around 0.6 $\mu\text{W cm}^{-2}$. That same irradiance would only induce a Very Low DL at dusk/dawn, where around 450 $\mu\text{W cm}^{-2}$ would be required for a High DL. During the day, a Very Low DL can be achieved with around 40 $\mu\text{W cm}^{-2}$, but greater levels of dazzle require

TABLE V. Modeled MDE values for binocular detection of a 0.08° object with 60% contrast.

Dazzle level	MDE ($\mu\text{W cm}^{-2}$) at		
	Night	Dusk/dawn	Day
Very low	0.00074	0.58	38
Low	0.036	28	1859
Medium	0.16	122	8042
High	0.59	462	30 326

TABLE VI. Proposed standard table of MDE values.

Dazzle level	MDE ($\mu\text{W cm}^{-2}$) at		
	Night	Dusk/dawn	Day
Very low	0.001	0.6	40
Low	0.04	30	2000 ^a
Medium	0.16	120	8000 ^a
High	0.6	450	30 000 ^a

^aValues that exceed the visible wavelength MPE of $1000\mu\text{W cm}^{-2}$ for a 10 s exposure. The MPE could also be exceeded in other cases when dividing by small $V(\lambda)$ values.

irradiances that exceed the visible wavelength MPE—i.e., the observer would be at risk of eye damage if exposed to these levels of dazzle.

IV. DISCUSSION

The final MDE table should be taken only as an approximate guide to the laser irradiances required to cause the stated dazzle levels at the given ambient light levels. MDE values would be expected to be higher for detection of larger or higher contrast objects, and lower for the detection of smaller or lower contrast objects than the 0.08° 60% contrast object assumed here. MDE values would also be expected to be higher for younger observers and lower for older observers, compared with the 40 year old observer assumed here. It should also be noted that a 40 year old with dark eyes who is detecting a 0.08° 60% contrast object (i.e., the precise case presented here) would also likely experience dazzle different from that predicted by this table as there is variance among the population in terms of eye scatter and how laser dazzle impacts visual performance. However, the MDE table does give a useful approximation of these visual effects and allows a rapid understanding of the likely impact of given laser irradiances.

MDE values can also be used to predict a safe distance for operating in the presence of laser dazzle, known as the Nominal Ocular Dazzle Distance (NODD).⁷ The NODD is defined as the distance beyond which the irradiance delivered by a laser is below the MDE. The NODD is therefore the dazzle equivalent to the Nominal Ocular Hazard Distance (NOHD) that is used to quantify the safe distance to operate from a laser system to avoid any risk of eye damage. NODD can be derived from MDE values in exactly the same way as NOHD is calculated from MPE values, with details of the calculation and some worked examples provided in the safety framework annex.¹⁰

The annex¹⁰ includes some visualizations of the dazzle field caused by laser eye dazzle, as also shown in Fig. 1. These visualizations are based upon an extended version of a previously reported technique.¹⁵ They use the new scatter function generated by the human subject experiments⁸ and incorporate additional visual effects for added realism, such as a representation of the ciliary corona.¹⁶ Just like the MDE table, they cannot give a precise replication of the experience of laser eye dazzle, but they are intended to give a rapid appreciation of

what laser eye dazzle looks like and how its severity is affected by laser irradiance, ambient light level, and laser wavelength.

As with the main experiment that validates this work,^{8,13} the authors have made available the complete data and analysis from this paper to encourage independent verification of the methodology.¹⁴ A spreadsheet calculator has also been published¹⁷ to facilitate calculation of MDE and NODD values for specific scenarios, together with optical density requirements for laser eye protection.

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¹LaserPointerSafety.com, see http://laserpointersafety.com/news/news/other-news_files/d5fca5f3330bef52f1c5465b03502776-569.php for “US: 6,753 laser/aircraft incidents reported to FAA in 2017; 9% lower than 2016” (2018).

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¹⁰See supplementary material at <https://doi.org/10.2351/1.5029384> for complete text of the proposed laser eye dazzle safety framework.

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¹²CVRL Database, see <http://www.cvrl.org/> for CIE “physiologically-relevant” luminous efficiency functions consistent with the Stockman & Sharpe cone fundamentals, 2-deg functions.

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ANNEX – TEXT OF THE PROPOSED LASER EYE DAZZLE SAFETY FRAMEWORK

A. Introduction

Laser eye dazzle is the temporary impairment of human performance caused by light from visible wavelength (400 – 700 nm) lasers. It includes both visual and non-visual effects, and can occur at irradiances far lower than those required to cause permanent retinal damage. Dazzle as defined here is sometimes referred to as disability glare, visual interference or visual disruption.

Laser eye dazzle is an issue of safety, as temporarily impairing human abilities can have serious consequences in many critical applications such as vehicle piloting or weapon aiming.

This laser eye dazzle safety framework begins with an overview of the main effects of laser eye dazzle together with factors that affect the severity of dazzle experienced, supported by simulated images of the human perception of dazzle. It then provides practical advice for the mitigation of laser eye dazzle effects, before providing a simple methodology to calculate dazzle effects and required protection levels (also implemented in a downloadable spreadsheet [1]). Further technical background to this framework can be found in the main section of this paper.

B. Effects

Laser eye dazzle can have both visual and non-visual effects that impact upon human performance.

B.1. Visual effects

During laser exposure – Part of the visual scene may be obscured by the appearance of a 'dazzle field' – a bright, saturated region of vision as illustrated in Fig. 1 – the size of which represents the severity of the laser eye dazzle (larger dazzle field = 'worse' dazzle). This spreading out of the laser in the visual field is caused by scattering of light within the eye itself, and it can block vision across angles from the laser axis ranging from a few degrees out to tens of degrees. When this obstructs the view of important features in a scene it can reduce the ability to successfully perform tasks. For example, limiting the view of a road would reduce the ability to continue driving down that road.



Fig. 1. Simulated image of the dazzle field caused by laser eye dazzle

After laser exposure – There may be continued visual effects in the form of afterimages (sometimes referred to as flashblindness or persistence), similar to those experienced after looking at a bright room light. These may initially obscure parts of the visual field, but will fade over time, with the severity of the laser eye dazzle event dictating the recovery time which could be seconds or even minutes in severe cases. Again, any disruption to vision could obscure important details in the scene which could impede task performance.

B.2. Non-visual effects

Upon first exposure – The onset of a laser eye dazzle event is likely to startle the individual and possibly trigger an aversion response such as closing the eyes or looking away. This could negatively affect tasks where maintaining consistent attention is important such as during the landing of an aircraft.

During laser exposure – The presence of a bright light source, regardless of its severity, is likely to cause distraction from the task being undertaken. This could have particularly severe consequences in high mental work load situations such as those experienced by pilots, where the additional incident could cause mistakes to be made in the primary task.

C. Contributors

The total impact of laser eye dazzle on human abilities is a combination of the severity of the laser event itself, coupled with the difficulty of the task being undertaken by the individual being exposed.

C.1. Dazzle severity

Laser irradiance – One of the primary contributors to the severity of laser eye dazzle is the laser irradiance incident upon the eye (higher irradiance = worse dazzle) which will depend upon the power of the laser itself (higher power = worse dazzle), the divergence of the laser (lower divergence = worse dazzle), and the range from the laser source (shorter range = worse dazzle). Fig. 2 illustrates the perceived laser eye dazzle differences between irradiances of 0.5, 5, 50 and 500 $\mu\text{W}\cdot\text{cm}^{-2}$ for a green (532 nm) laser. 0.5 $\mu\text{W}\cdot\text{cm}^{-2}$ is roughly equivalent to a 0.5 W laser pointer at a range of 5.6 km, while 500 $\mu\text{W}\cdot\text{cm}^{-2}$ is equivalent to the same laser at a range of around 180 m. For comparison, the Maximum Permissible Exposure (MPE) (defining the 'safe' exposure level in terms of the risk of permanent eye damage) for visible wavelengths is 1,000 $\mu\text{W}\cdot\text{cm}^{-2}$ for a 10 second exposure and 2,546 $\mu\text{W}\cdot\text{cm}^{-2}$ for a 0.25 second exposure [2,3].

Ambient light level – Laser eye dazzle is more readily achieved when the laser irradiance at the eye is large compared with the ambient stimulus to the eye, meaning that for equivalent laser irradiances the severity of dazzle is worse in dark conditions (lower ambient light level = worse dazzle). Fig. 2 illustrates the perceived laser eye dazzle differences between ambient light levels of 1,000 $\text{cd}\cdot\text{m}^{-2}$ (day), 10 $\text{cd}\cdot\text{m}^{-2}$ (dusk/dawn) and 0.1 $\text{cd}\cdot\text{m}^{-2}$ (night). It can be seen that significant scene obscuration is possible in dark conditions for relatively low irradiance levels, while for day conditions, irradiances approaching the MPE still have a relatively minor dazzle effect.

Laser wavelength – The severity of laser eye dazzle is greater at wavelengths at which the eye has a higher response, according to the photopic luminous efficiency function, $V(\lambda)$, as shown in Fig. 3 [4,5]. Therefore deep blue (~ 400 nm) and deep red (~ 700 nm) cause less dazzle effect for a given laser irradiance than wavelengths around the

ANNEX – TEXT OF THE PROPOSED LASER EYE DAZZLE SAFETY FRAMEWORK

from C. A. Williamson and L. N. McLin, "Determination of a laser eye dazzle safety framework," Journal of Laser Applications 30, 032010 (2018).
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central green peak (~ 555 nm) of this efficiency curve. Fig. 4 illustrates the perceived laser eye dazzle differences between wavelengths of 532 nm (green), 650 nm (red) and 445 nm (blue) with equal laser irradiance.

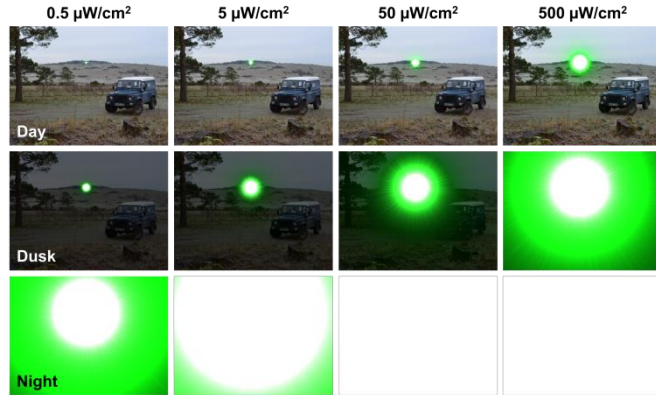


Fig. 2. Simulated images giving an approximate representation of human visual dazzle from a green (532 nm) laser from low (0.5 μW·cm⁻²) to high (500 μW·cm⁻²) laser irradiances at day (1,000 cd·m⁻²), dusk/dawn (10 cd·m⁻²) and night (0.1 cd·m⁻²) ambient light levels. Each image has a scene horizontal field of view of 40°.

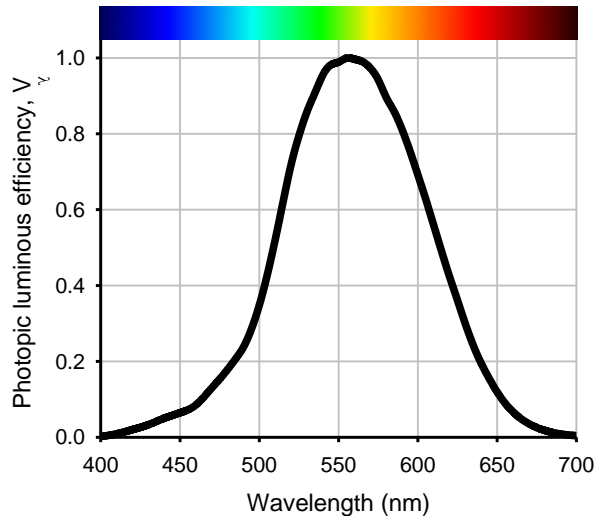


Fig. 3. Photopic luminous efficiency for the human eye. Numerical values are listed in Table 4 [4,5].

Dusk, 50 μW/cm²



Fig. 4. Simulated images showing human dazzle differences between blue (445 nm), green (532 nm) and red (650 nm) lasers of equal irradiance (50 μW·cm⁻²) at dusk/dawn (10 cd·m⁻²) conditions. Each image has a scene horizontal field of view of 40°.

Other factors – The severity of dazzle is also affected by: age (older = worse dazzle) and eye color (lighter = worse dazzle). Additional factors with a more complex relationship with the dazzle severity include: windscreens; eyewear; atmospheric turbulence; atmospheric visibility; and exposure duration.

C.2. Difficulty of the task

Proximity of desired visual point to the laser axis – The severity of the laser eye dazzle field reduces with increasing angular offset from the laser source itself, and so it will be more difficult to visually detect/identify objects the closer they are to the laser axis (visual task closer to the laser axis = higher impact on performance).

Object size – In the presence of laser eye dazzle it is easier to detect/identify larger objects than smaller objects, just as is the case without laser eye dazzle present (smaller object = higher impact on performance).

Object contrast – Again, as under normal circumstances, with laser eye dazzle present it is more difficult to detect/identify objects that are low contrast in nature e.g. a green vehicle against a forest background (lower object contrast = higher impact on performance).

Complexity of task – Both visual and non-visual effects of laser eye dazzle will have an impact on performance that is commensurate with the complexity of the task being performed. For example, exposing a pilot to laser eye dazzle during normal level flight may have little impact upon performance, but subjecting the same pilot to laser eye dazzle during the final stages of a landing approach in difficult weather conditions could have a more severe impact (more complex task = higher impact on performance).

D. Mitigation

The human performance impacts of laser eye dazzle can be minimized by a combination of actions which should take place before, during and after the exposure.

D.1. Before laser exposure

Training – It is important for individuals to understand the effects of laser eye dazzle and how they might impact upon performance, so that they are better prepared to confidently deal with a real-life laser eye dazzle event. Ideally, individuals should be exposed to laser eye dazzle in a controlled environment to prepare them for the effects. Training should also include details of current threat levels, incident statistics, and recommended mitigation techniques (as outlined here).

Laser Eye Protection (LEP) – Individuals at risk of laser eye dazzle should be issued appropriate laser eye protection that is designed to filter out anticipated laser wavelengths whilst allowing visual detection/identification abilities to be retained. LEP of the correct specification can strongly suppress the dazzle field, although it will reduce overall light transmission and introduce some coloration to the visual scene (Fig. 5 gives a simulated example). Compatibility of LEP with essential visual information (e.g. warning lights, navigational aids) should be evaluated before use.

It may be difficult to anticipate the laser wavelengths likely to be encountered due to the large variety of visible wavelength lasers on the market, meaning that a single pair of LEP may not mitigate all laser eye dazzle occurrences. LEP should always meet applicable protective equipment and laser safety standards.

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Fig. 5. Simulated representation of the visual impact of wearing LEP, with and without laser exposure. Each image has a scene horizontal field of view of 40°.

D.2. During laser exposure

Wear LEP if available – If appropriate LEP is available it can reduce the laser eye dazzle effect whilst permitting visual abilities to be maintained as illustrated in Fig. 5 (albeit with the caveats mentioned above). Should a laser exposure actually be of a level that could cause permanent retinal damage, appropriately specified LEP may also protect from this hazard.

Do not look into the beam – If possible the individual should look away from the beam which will reduce the severity of the dazzle field in their field of view, and reduce the likelihood of afterimages.

Manoeuvre away – If possible, manoeuvring away from the laser source will also serve to reduce/remove the dazzle effect.

Shield eyes – Just as when trying to look near the sun, blocking the bright light source with a hand or visor can greatly reduce its dazzling effect and may allow sufficient visibility to permit the continuation of activities.

Do not rub eyes – Rubbing of eyes may cause damage to the cornea and will not improve vision during a laser exposure.

Warn others – If possible, others near the path of the laser beam should be warned as to its presence to enable them to mentally and physically prepare for exposure e.g. by wearing LEP.

D.3. After laser exposure

Visual checks – If there is any concern that a laser exposure has caused eye damage, the individual should seek an eye examination.

Report the incident – All occurrences of laser eye dazzle should be reported to the appropriate authority as soon as possible. Particularly useful information to record includes the location, time/date and duration of the incident, an estimated location of and range to the laser source, the extent of visual obscuration experienced, and the color of the laser. This information will strengthen the overall intelligence picture of these occurrences, thus allowing improved training and more effective specification of LEP in the future.

E. Calculations

The concepts of Dazzle Level (DL), Maximum Dazzle Exposure (MDE) and Nominal Ocular Dazzle Distance (NODD) permit the hazards of laser eye dazzle to be quantified and mitigated by appropriate protection measures. A downloadable spreadsheet [1] is available to facilitate calculations according to the methodology outlined in this section.

E.1. Dazzle Level (DL)

A Dazzle Level (DL) describes the size of the dazzle field caused by a laser eye dazzle event. Four DLs are used to categorize the visual extent of the dazzle field as Very Low, Low, Medium or High, corresponding to dazzle field full angles of 2, 10, 20 and 40° respectively (Table 1). These are centered on the laser source and correspond to the angular size of the visual field that is obscured within an observer’s field of vision, as illustrated by Fig. 6.

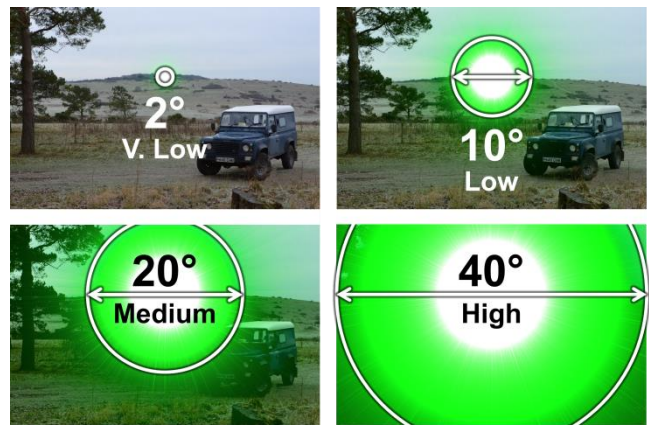


Fig. 6. Illustration of the visual extent of the four dazzle levels (image scene horizontal field of view is 40°)

Table 1. Dazzle levels and their corresponding visual extents.

Dazzle Level	Full angle of dazzle extent (°)
Very Low	2
Low	10
Medium	20
High	40

For estimation purposes, a Very Low DL is approximately the width of a raised thumb from an outstretched arm (i.e. the width of the thumb obscures around 2° total angle). A clenched fist at arm’s length is approximately a Low DL (10° total angle), a spread hand is approximately a Medium DL from thumb tip across to little finger tip (20° total angle), while a High DL is approximately the span of two spread hands next to each other (40° total angle).

E.2. Maximum Dazzle Exposure (MDE)

The Maximum Dazzle Exposure (MDE) is the laser irradiance at the eye above which an object cannot be visually detected. At higher laser irradiances than the MDE, the dazzle field prevents the observer from detecting the object, while at lower irradiances than the MDE the observer is able to detect the object.

MDE values given in Table 2 [6] are approximate exposure limits to restrict the dazzle field to the stated DL for the ambient light levels

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summarized in Table 3. All MDE values should be divided by the photopic luminous efficiency, $V(\lambda)$, for the laser wavelength being considered ($V(\lambda)$ values are listed in Table 4). All values of $V(\lambda)$ are less than 1, meaning that the MDE values for a given laser wavelength will always be greater than the baseline values shown in Table 2. According to values for $V(\lambda)$, the MDE for green will be lower than for blue, for example, indicating that a higher irradiance is needed for a blue laser to achieve the same visual effect as a green laser.

The appropriate MPE should always be calculated and taken as the limiting exposure value to prevent the risk of eye damage.

Table 2. MDE values for the four dazzle levels at night (0.1 cd·m⁻²), dusk/dawn (10 cd·m⁻²) and day (1,000 cd·m⁻²) ambient light levels [6]. The appropriate MPE should always be calculated and taken as the limiting exposure value to prevent the risk of eye damage.

Dazzle Level	MDE (μW·cm ⁻²) at			
	Night	Dusk/Dawn	Day	
Very Low	0.001	0.6	40	÷ $V(\lambda)$
Low	0.04	30	*2,000	
Medium	0.16	120	*8,000	
High	0.6	450	*30,000	

*denotes values that exceed the visible wavelength MPE of 1,000 μW·cm⁻² for a 10 second exposure. The MPE could also be exceeded in other cases when dividing by small $V(\lambda)$ values.

Table 3. Ambient luminance levels.

Level	Ambient luminance (cd·m ⁻²)
Night	0.1
Dusk/Dawn	10
Day	1,000

Table 4. Lookup table of photopic luminous efficiency, $V(\lambda)$, for visible wavelengths, λ , between 400 and 700 nm [4,5]

λ (nm)	$V(\lambda)$	λ (nm)	$V(\lambda)$	λ (nm)	$V(\lambda)$
400	0.0025	500	0.3484	600	0.6919
405	0.0050	505	0.4278	605	0.6270
410	0.0091	510	0.5205	610	0.5584
415	0.0143	515	0.6206	615	0.4896
420	0.0203	520	0.7181	620	0.4230
425	0.0261	525	0.7946	625	0.3609
430	0.0332	530	0.8576	630	0.2981
435	0.0416	535	0.9071	635	0.2417
440	0.0503	540	0.9545	640	0.1943
445	0.0574	545	0.9814	645	0.1547
450	0.0647	550	0.9890	650	0.1193
455	0.0724	555	0.9995	655	0.0898
460	0.0851	560	0.9968	660	0.0667
465	0.1060	565	0.9903	665	0.0490
470	0.1299	570	0.9733	670	0.0356
475	0.1535	575	0.9425	675	0.0255
480	0.1788	580	0.8964	680	0.0181
485	0.2065	585	0.8587	685	0.0126
490	0.2379	590	0.8116	690	0.0087
495	0.2851	595	0.7545	695	0.0060
				700	0.0042

The given numbers are based upon the visual detection of an object of 0.08° size (approximately equivalent to detecting a 5 m long car at a range of 3.5 km or a 0.5 m human torso at 350 m) with 60% contrast by a 40 year old dark-eyed observer. MDE values would be greater for detection of larger or higher contrast objects, and for younger observers. Correspondingly, MDE values would be less for detection of smaller or lower contrast objects, and for older observers.

The MDE values should be taken as an approximate guide to allow rapid understanding of the likely impact of given laser irradiances. While they are derived from an extensive collection of human laser exposure experiments, together with a validated mathematical model, the human experience of laser eye dazzle varies for different people, different applications and different visual tasks. They should therefore be used for guidance only.

E.3. Nominal Ocular Dazzle Distance (NODD)

The Nominal Ocular Dazzle Distance (NODD) is the distance beyond which the irradiance delivered by a laser is below the MDE. At distances closer than the NODD, the MDE is exceeded and an object cannot be visually detected, while at distances further away than the NODD, the irradiance is below the MDE and an object can be successfully detected.

The NODD can be calculated from the following equation,

$$NODD = \frac{1}{\phi} \sqrt{\frac{4\Phi}{\pi MDE}}, \tag{1}$$

where Φ is the laser power (W), ϕ is the laser divergence (rad), the MDE is in units of W·cm⁻² (= 10⁻⁶ · MDE in μW·cm⁻²) and the resulting NODD is in cm.

Using the MDE values from Table 2 as exposure limits, the NODD determines the minimum observer-to-laser range to restrict the dazzle field to the stated DL for the given ambient light levels.

E.4. Optical Density (OD)

The Optical Density (OD) is the laser protection required to reduce the laser irradiance at the eye down to the MDE, should the observer-to-laser range be less than the NODD. The optical density at wavelength λ , D_λ , is defined by the following equations,

$$D_\lambda = \log\left(\frac{E}{MDE}\right), \tag{2}$$

$$E = \frac{\Phi}{\pi\left(r\frac{\phi}{2}\right)^2} \tag{3}$$

where E (W·cm⁻²) is the laser irradiance at an observer who is a distance of r (cm) from the laser source.

Using the MDE values from Table 2 as exposure limits, the OD determines the laser protection required (when observing at a distance closer than the NODD) to restrict the dazzle field to the stated DL for the given ambient light levels.

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F. Example calculations

Exposure limits for 532 nm (green) lasers can be determined from Table 2 by dividing each value by $V(\lambda) = 0.8774$ (derived by linear interpolation of the laser luminous efficiency data in Table 4). The resulting MDE values are shown in Table 5.

Table 5. MDE values for 532 nm laser, $V(\lambda) = 0.8774$.

Dazzle Level	MDE ($\mu\text{W}\cdot\text{cm}^{-2}$) at		
	Night	Dusk/Dawn	Day
Very Low	0.0011	0.68	46
Low	0.05	34	*2,279
Medium	0.18	137	*9,118
High	0.68	513	*34,192

* denotes values that exceed the $1,000 \mu\text{W}\cdot\text{cm}^{-2}$ MPE for a 10 second exposure at 532 nm.

It can be seen that limiting 532 nm exposures to $0.0011 \mu\text{W}\cdot\text{cm}^{-2}$ at night will restrict the dazzle field to a Very Low DL. For the same Very Low DL at dusk/dawn the limit is $0.68 \mu\text{W}\cdot\text{cm}^{-2}$, and during day it is $46 \mu\text{W}\cdot\text{cm}^{-2}$. $0.68 \mu\text{W}\cdot\text{cm}^{-2}$ at night and $513 \mu\text{W}\cdot\text{cm}^{-2}$ at dusk/dawn will restrict the dazzle field to a High DL. The day exposure limits for Low, Medium and High DLs exceed the $1,000 \mu\text{W}\cdot\text{cm}^{-2}$ MPE which should therefore be taken as the limit for a 10 second exposure.

NODDs for a 532 nm laser with a power of 0.5 W and a divergence of 0.002 rad can be calculated from Table 5 and equation (1). The resulting NODD values in km are shown in Table 6, representing the minimum observer-to-laser ranges to restrict the dazzle field to the stated DL for the given ambient light levels.

Table 6. Calculated NODD values for 532 nm, 0.5 W, 0.002 rad laser.

Dazzle Level	NODD (km) at		
	Night	Dusk/Dawn	Day
Very Low	118.2	4.8	0.59
Low	18.7	0.68	^0.08
Medium	9.3	0.34	^0.04
High	4.8	0.18	^0.02

^ denotes distances that are closer than the 0.13 km NOHD for this laser.

These values indicate that, at night, a minimum observer-to-laser range of 118.2 km is needed to restrict the dazzle field to a Very Low DL, while this falls to 4.8 km at dusk/dawn and 0.59 km at night. A 4.8 km minimum distance at night and 0.18 km at dusk/dawn will restrict the dazzle field to a High DL. The NODDs for Low, Medium and High DLs at day are less than the NOHD value of 0.13 km for a 10 second exposure, which should therefore be used as the limiting value to prevent the risk of eye damage.

Fig. 7 visually summarizes these NODD values and allows the DL to be rapidly assessed for a given engagement scenario. For example, if the example laser was viewed at a range of 0.3 km, following the vertical line at 0.3 km shows that an observer would experience a High DL at night, a Medium DL at dusk/dawn, and a Very Low DL during the day.

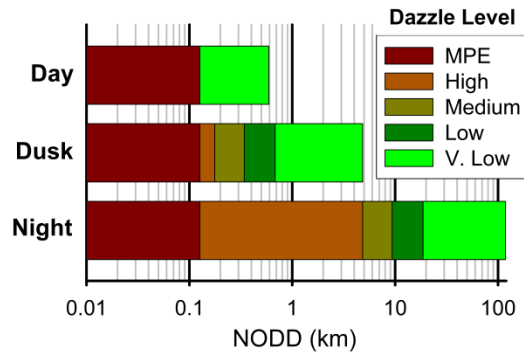


Fig. 7. Visualization of NODD values for the 532 nm, 0.5 W, 0.002 rad laser, indicating dazzle levels versus range for day, dusk/dawn and night ambient luminances.

The required OD for viewing this laser at a range of 0.3 km ($r = 30,000 \text{ cm}$) can be calculated from Table 5 and equations (2) and (3). The resulting OD values are shown in Table 7, representing the laser protection required to restrict the dazzle field to the stated DL for the given ambient light levels when viewing the laser from 0.3 km.

Table 7. Calculated OD values for viewing a 532 nm, 0.5 W, 0.002 rad laser at 0.3 km range.

Dazzle Level	OD required at		
	Night	Dusk/Dawn	Day
Very Low	5.2	2.4	0.6
Low	3.6	0.7	NONE
Medium	3.0	0.1	NONE
High	2.4	NONE	NONE

These values show that OD 5.2 is required to restrict the dazzle field to a Very Low DL at night, while OD 2.4 is needed at dusk/dawn and 0.6 at night for the same Very Low DL. To restrict to a High DL requires OD 2.4 at night, while no OD is needed at dusk/dawn or day as the observation range of 0.3 km is greater than the NODD values in Table 6.

The OD levels presented here are given as guidance for the preservation of visual abilities, but for any practical applications there will naturally be a compromise between the specified OD and the visual penalties introduced by the laser eye protection during normal operations, as previously discussed.

G. Summary

This laser eye dazzle safety framework provides education on the contributing effects and dependencies of laser eye dazzle, together with practical advice to mitigate the effects. It also introduces new language and calculations to allow laser eye dazzle effects to be quantified. These include the concepts of Dazzle Levels (DLs) to describe the size of the dazzle field, Maximum Dazzle Exposure (MDE) to define the laser irradiance at the eye above which an object cannot be visually detected, and Nominal Ocular Dazzle Distance (NODD) to establish the distance beyond which a laser’s irradiance is below the MDE.

Key to this framework is the provision of a standard table of MDE values across a range of DLs and ambient light levels. This table provides a useful approximation for rapidly estimating laser eye dazzle

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effects, and allows the calculation of NODD values and required laser eye protection levels. An example has been provided to illustrate use of the MDE table together with the associated calculations for NODD and OD, and a downloadable spreadsheet [1] is available for the reader to perform their own calculations. It should be stressed that the provided MDE values are an approximation and will vary for different people, different applications and different visual tasks. They should therefore be used for guidance only.

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