2020

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10.1016/j.firesaf.2020.103209
This is an author's accepted manuscript of:
Penney, G., Habibi, D., & Cattani, M. (2020). Improving firefighter tenability during entrapment and burnover: An analysis of vehicle protection systems. *Fire Safety Journal, 118*, article 103209. https://doi.org/10.1016/j.firesaf.2020.103209

Original research manuscript

Improving firefighter tenability during entrapment and burnover: an analysis of vehicle protection systems.

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Received: date; Accepted: date; Published: date

Abstract: When attempting to suppress severe wildfire the possibility for firefighting crews to be overrun by wildfire, known as entrapment and burnover, remains a catastrophic and all too common occurrence. While improvements have been made to vehicle protection systems to increase the safety of firefighters caught in burnover, the potential effectiveness of these systems remains limited. This study involved systematic analysis of 62 historical entrapment and burnover reports from the USA, Australian and New Zealand from 1978 to 2020 (Phase 1), and 135 simulated wildfires encompassing the 99th percentile of Australian fire weather conditions, fuel structures and terrain (Phase 2). Analysis of historical entrapments identified existing vehicle protection systems have failure points well below the reported Fire Danger Index associated with the majority of house loss during wildfire events in Australia. Increasing the performance threshold of vehicle protection systems to the historical mean fire line intensity identified at the point of entrapment increased efficacy, and, prevented vehicle protection systems being overwhelmed in simulations regardless of Fire Danger Index and up to windspeeds of 55 kmh^{-1}. In order to further improve firefighter protection during entrapment and burnover it is recommended the radiant heat flux performance threshold of vehicle protection systems are increased.

Keywords: wildfire, firefighting, burnover, entrapment, fatality, vehicle protection systems

1. Introduction

Firefighters are regularly required to protect life, property and areas of natural significance from destructive wildfires. A combination of offensive and defensive strategies are usually necessary, selected depending on the fire behaviour, availability of resources, access to the fire, and fuel structure itself [1-13]. Offensive strategies include direct head fire or flank fire attack (Figure 1) and typically require firefighters to apply suppressants from hand held attack lines or machine monitors. An alternate offensive strategy, the parallel attack, is where firefighters fall back some safe distance, construct containment lines parallel to the fire line and then burn out the intervening vegetation. Defensive strategies are employed when the fire behaviour is too intense to be safely attacked with active fire suppression. Defensive strategies include building containment lines, backburning, defending properties and focusing on evacuation of people and livestock [6,12,13].

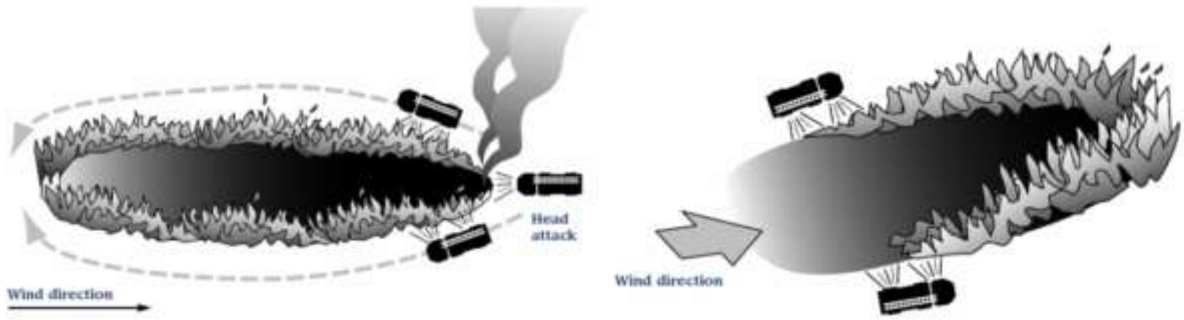


Figure 1. Direct attack on the head fire (left) vs direct attack on the flank (right) (Source: [6, p10-11].

During wildfire operations the use of inappropriate suppression tactics [10] or sudden changes in wind direction [14,15] can result in firefighters being directly caught by wildfire smoke and fire, a situation known as entrapment. The occurrence of wildfire flame directly impacting firefighters is known as burnover. The threat posed from entrapment and burnover is significant and has resulted in 411 firefighter deaths in the USA from 1910 to 2006 [16], 92 Australian firefighter deaths from 1901 to 2011 [17] and 165 Canadian firefighter deaths between 1941 and 2010 [18]. In many cases multiple fatalities resulted from a single entrapment and burnover. The causes entrapment and burnover are well known [19], although more recent studies have increased this understanding by defining human factors and fire behaviour leading up to these events [14,15,20-24].

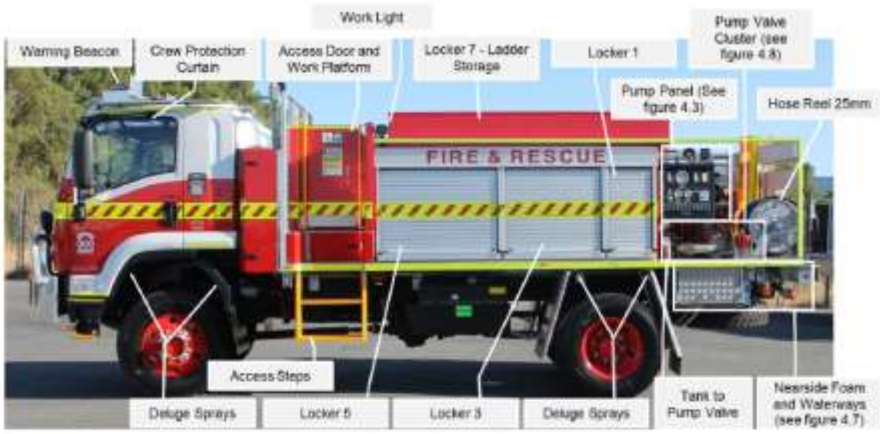
In an effort to improve firefighter safety and aiming to protect the integrity of firefighting vehicles, enabling escape and improving the tenability for entrapped occupants, Australian fire services have invested in vehicle protection systems (VPS).

Vehicle protection systems include [25,26] (figure 2):

1. Installation of deluge sprinklers, drop down thermal shielding blankets and personal fire blankets;
2. Protect components essential to vehicle mobility against thermal damage, through shielding, relocation and lagging;
3. Protect components critical to firefighting against thermal damage, through shielding, relocation and lagging;
4. Ensuring the cabin is a suitable refuge and provides a continuous enclosure of non-combustible materials through:
   i. removal of wheel arches, mudguards, step shrouds, cabin body aesthetic panels, side mirror mounts, door handles, backing plates and underbody panels; or
   ii. Where this is not possible, making these products fire resistant;
5. Protection of windows that are not essential for vision including the replacement of rear and side rear windows with solid panels;
6. Adding infill panels between the cabin and the vehicle tray; and
7. Modifying the air-conditioning system to prevent smoke and heated gases entering the cabin.

(a)

(b)



(c)

Figure 2. Burnover protection systems (**a**) Drop down shielding blanket deployed [6,25]; (**b**) Firefighter (person) under a personal fire blanket [6,25]; (**c**) Typical wildfire fighting appliance showing position of side deluge sprays [6].

The vehicle protection system deluge sprays are designed to [25]:

1. Prevent glass failure, i.e. to ensure integrity of the cabin;
2. Cool the cabin to reduce occupant heat exposure; and
3. Cool the tyres to reduce risk of ignition.

The deluge system is required to be activated from the cabin, operate for a minimum of 5 minutes from the time the 'crew protection water alert' sounds which occurs once water tank reserves reach 600 L, and to have a nominal flow rate of 120 $Lmin^{-1}$ with a flow pressure of 3 bar [25]. An audible and visual warning device alerts crews once they have reached the deluge system reserve capacity, however the crew can continue to utilise this reserve without restriction. Not all appliances can be fitted with deluge systems. For instance Light Tankers, a small four wheel drive appliance with a 500 L water tank, cannot be fitted with deluge systems due to insufficient water capacity to generate the required protection duration and existing vehicle weight restrictions [26,27].

Limited field experimentation has been completed [28,29] and the inherent danger of wildfire suppression during elevated fire weather conditions has prevented the potential effectiveness of vehicle protection systems being suitably quantified in full scale field experimentation. Addressing this gap is vital and forms a critical component of thorough fire engineering safety analysis [30-33]. Current external vehicle protection systems utilised in Australian fire service vehicles incorporate drop down thermal shielding blankets and sprinkler deluge systems have been tested against fire line intensities of between 2,500-10,000 kWm^{-1} and designed to withstand 7,500 kWm^{-1} [33]. In similar tests, Nichols et al. [34] reported that cabin tenability was maintained when simulated fire line intensities of up to 12,000 kWm^{-1} were maintained for up to 14 seconds when water spray protection systems were used in conjunction with window radiation shields, whilst Sargeant et al. [35, p7] reported that

"In general vehicle orientated front on remained tenable at radiation levels up to 30 kWm^{-2}. while side on and rear facing vehicles lost integrity at around 10 to 15 kWm^{-2}"

By comparison forensic wildfire analysis [36] and field experimentation [37,38,39] identified fire line intensities of up to 88,000 kWm^{-1} and radiant heat fluxes in excess of 100 kWm^{-2} can be experienced for longer durations during landscape scale wildfires, far exceeding the limits of crew protection systems [34].

Blanchi et al. [40] report, virtually all house loss from wildfire in Australia occurs on days when the Fire Danger Index exceeds the 99.5th percentile in the distribution of daily Fire Danger Index for each of the regions considered, with the majority of house loss occurring on days of Fire Danger Index greater than 100. Further, they report there is little house loss on days where the Fire Danger Index did not exceed 50. Firefighting crews are also more likely to expose themselves to greater levels of personal risk when civilians and houses are under direct threat from fire [41], suggesting that firefighters are more likely going to expose themselves to the threat of entrapment and burnover when houses are being lost (i.e. when the Fire Danger Index exceeds 50).

In recent research we explored two of the critical factors influencing the potential success of wildfire suppression at the rural urban interface, these being firefighter tenabilty [10] and critical water flow rates for the extinguishment of the head fire [11]. The potential effectiveness of vehicle protection systems in providing an adequate level of firefighter protection in the event of burnover during suppression efforts remains unquantified. Without validation of these systems, both Incident Management Teams and firefighters may overestimate crew safety during wildfire suppression based on the belief they will be adequately protected. The objectives of this study are therefore defined as:

1. Quantify the effectiveness of existing vehilce protection systems in increasing the tenability of firefighters during entrapment and burnover; and
2. Provide guidance to improve potential effectiveness of vehicle protection systems in improving firefighter tenability during entrapment and burnover.

Given the magnitude of wildfire behaviour reported [36-39] it is hypothesised that existing vehicle protection systems are unable to adequately improve firefighter tenability in the event of burnover during suppression at the rural urban interface. Systematic analysis of historical entrapments and burnover (Phase 1) and simulated wildfires encompassing the 99th percentile of weather conditions and forest fuel loads (Phase 2) is used to test the hypotheses:

H_1 = Existing vehicle protection systems would have been effective in less than 50% of historical burnovers resulting in firefighter injury or fatality; and

H_2 = Existing vehicle protection systems would not be effective in simulated wildfires during conditions representative of days when house loss is expected (i.e. Fire Danger Index exceeding 50).

In order to test the effectiveness of vehicle protection systems clear objectives and performance threshold must be defined [30,31,42]. Effectiveness is defined as the product of fire safety system efficacy and reliability [43]. Efficacy is the degree to which a system achieves its objective, a factor of 1.00 signifies the system achieves all objectives. Reliability is the probability that the system operates as required, a factor of 1.00 signifies 100% reliability. The objective of vehicle protection systems (VPS) is to increase the tenability of firefighters during vehicle entrapment and burnover. For the purposes of the study the performance threshold (PT) required to meet this objective were aligned to the thresholds reported by [33-35] and defined as:

PT1. VPS is determined to have worked effectively where fire line intensity (I) is less than 7,500 kWm^{-1} (the current rating of VPS);

PT2. VPS is determined to have worked effectively where fire line intensity (I) is less than 10,000 kWm^{-1} (the maximum intensity VPS have been tested to);

PT3. VPS is determined to have worked effectively where fire line intensity (I) is less than 12,000 kWm^{-1} (maximum short duration intensity VPS can withstand);

PT4. VPS is determined to have worked effectively where fire line intensity (*I*) is less than the mean historical upper reported / calculated intensity for all entrapments resulting in fatality or injury;

PT5. VPS is determined to have worked effectively where radiant heat flux (RHF) is less than 15 kWm^{-2}, assuming vehicles are orientated side on or with the rear to the advancing headfire; and

PT6. VPS is determined to have worked effectively where radiant heat flux (RHF) is less than 30 kWm^{-2}, assuming vehicles orientated front on to the advancing headfire.

2. Phase 1 – Historical burnover analysis

2.1 Study Design

International safety reports and coronial inquiries were reviewed to identify occurrences of firefighter injury or fatality during wildfire suppression and extract wildfire behaviour at the time of impact. Wildfire behaviour at the time of impact was subsequently deterministically evaluated against defined VPS fire line intensity and radiant heat flux performance thresholds.

To increase the number of burnover events for analysis, inclusion criteria for initial investigation were broad, with the search terms of entrapment; fire; firefighter; burnover; wildfire; or bushfire (being the Australian term for wildfire) applied. Databases were searched as far back as electronic records permitted. The full text of the studies identified by the searchers were retrieved, references were screened for additional papers and a further selection process undertaken (Table 1). During the second review of the selected reports, the search terms fatality; injury; intensity; spread; rate; flame; and length were applied to refine results. As the research specifically related to entrapment and burnover during wildfire suppression incidents arising from prescribed burns were excluded.

Table 1. Data collection and analysis summary

Source	**Available reports**	**Reports identified during first review**	**Reports included after second review**
Coroner Court of New South Wales 1979-2020 [44]	560	14	0
Coroner Court of Queensland 2004-2020 [45]	802	17	0
Coroners Court of Victoria 2008-2020 [46]	1760	50	0
Coroners Court of Tasmania 2015-2018 [47]	307	7	0
Coroners Court of South Australia 2016-2020 [48]	678	1	0
Coroners Court of Western Australia 2014-2019 [49]	323	5	1 (F)
Fire Sciences Lab Merged Entrapment Database [50]	415	415	25 (F) 186 (Inj)
Fire services literature, ResearchGate and referenced papers	11	11	2 (F)

Note: (F) indicates incident with fatality; (INJ) indicates incident with injury only

Data pertaining to fire line intensity (*I*), headfire rate of spread (*RoS*) and flame length (*Lf*) was extrapolated from each report. Where intensity was not directly reported at the point of entrapment and burnover, but either rate of spread or flame length was reported, intensity was calculated using equations (1) to (8) as appropriate and fuel load values detailed in Australian Standard AS3959 *Construction of buildings in bushfire prone areas* [51], subsequently referred to as AS3959. Heat of combustion of 18,600 $kJkg^{-1}$ was selected for the analysis, being within the values detailed in table 2. Reports were excluded if insufficient detail regarding fire line intensity, head fire rate of spread or

flame length to extract or calculate wildfire intensity was available. All reports included in the study are detailed in Appendix 1. Performance Threshold 1 to 4 were deterministically assessed against fire line intensity at the point of entrapment and burnover.

The assumptions associated with the modelling are:

1. The term wildfire fuel is broadly applied to the vegetation potentially consumed by a fire burning in vegetation, regardless of the active fire area itself [52-59]. Wildfire fuel is defined by its physical structure and properties which are represented by numerical inputs relevant to the appropriate model being applied and classified into set vegtation categories [52,53]. For the purposes of this research, wildfire fuel is considered to be the fine fuels, typically less than 6mm in diameter, that will be consumed by the approaching headfire. Vegetation categories are defined in accordance with AS3959 [51] as Forest, Woodland, Scrub, Shrub and Grass;
2. Pyrolysis of vegetation and combustion of turbulent diffusion flames of a bushfire front is extremely complex. Existing empirical models rely heavily on the assumption that radiation is overwhelmingly responsible for heat transfer between the flame and the receiving body [38,39,52,59,60]. It is assumed the fire front is geometrically represented by a uniform parallelepiped the width of the head fire (figure 3), with sufficient flame depth for the flame emissivity to reach at least 0.8 (identified as being greater than 5 m and potentially deeper than 10 m) [13,61,62], and flame length dependent on associated fire modelling that assumes the fire has attained a quasi-steady rate of spread (RoS) [1,59,63]. The assumed flame geometry is commonly known as the "radiant heat panel", with the horizontal position of the panel considered to be located below the midpoint between the base and tip of the flame front (fig 3) [13,59,63]. Both the flame temperature and emissivity are assumed to be consistent across the panel, whilst the receiving body is assumed to be aligned perpendicular to the approaching fire front [51,52]. Radiant heat flux is the radiation in kWm^{-2} received by a body at a specified distance from the radiant heat panel, considering any shielding and the spectral properties of both the fire and the firefighter, vehicle, house etc. [13,52,64]
3. Dold, Zinoviev and Leslie [65] describe wildfires as eruptive and unstable combustion involving a process of dynamic interaction between rate of spread, flame length and fire line intensity. The mathematical relationship between wildfire behaviour, flame geometry and radiant heat flux described in AS3959 [51] is explained and expanded in equations (1) to (9); and
4. A critical component of the fireline intensity is the heat of combustion (H), defined as the amount of heat released when a unit quantity of fuel is oxidized completely to yield stable end products [32]. Values for H for common types of vegetation are identified in Table 2. Australian Standard 3959 [51] details that intensity (I), in kWm^{-1} and corrected for slope, is calculated using Byram's fireline intensity equation.

$$I = HW(RoS)/36 \tag{1}$$

Where H is the heat of combustion ($kJkg^{-1}$), shown in table 2, W is total fuel load (tha^{-1}) and RoS is the head fire rate of spread in kmh^{-1}, corrected for slope.

Table 2. Heat of Combustion

Fuel	Heat of Combustion (kJ/kg)	Source
Wood (European Beech)	19500	[32, Table 1-5.3]
Wood (Ponderosa Pine)	19400	[32, Table 1-5.3]
Australian vegetation	18600	[51]

In forest and woodland vegetation Lf is calculated by:

$$L_f = \frac{13RoS + 0.24W}{2} \tag{2}$$

We rearrange equation 1 and substituting it for *RoS* provides:

$$L_f = \frac{13\left({}^{36I}/_{HW}\right) + 0.24W}{2} \tag{3}$$

Therefore:

$$I = \frac{HW\left(2L_f - 0.24W\right)}{468} \tag{4}$$

For scrub and shrub vegetation structures, *Lf* is calculated by:

$$L_f = 0.0775 I^{0.46} \tag{5}$$

We rearrange this equation, enabling *I* to be calculated by:

$$I = \left(\frac{L_f}{0.0775}\right)^{2.2} \tag{6}$$

In grassland vegetation, *Lf* is calculated by:

$$L_f = 1.192\left(\frac{I}{1000}\right)^{0.5} \tag{7}$$

We rearrange this equation, enabling *I* to be calculated by:

$$I = 1000\left(\frac{L_f}{1.192}\right)^{2} \tag{8}$$

Radiant heat flux is calculated for all vegetation structures using the equation:

$$q = \tau\phi E \tag{9}$$

where q is the radiant heat flux impinging the target in kW/m^2, τ is the atmospheric transmissivity, E is the flame emissive power in kW/m^2 and ϕ is the view factor.

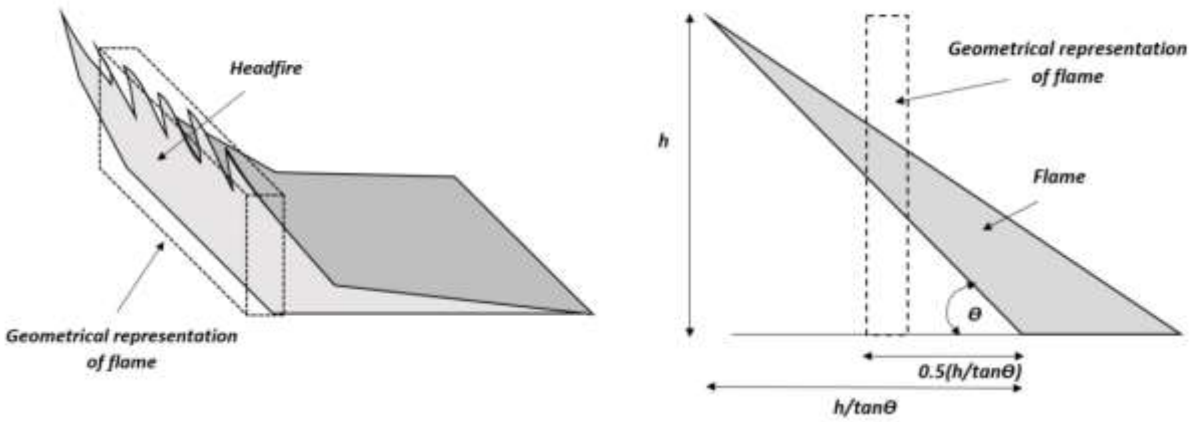


Figure 3. Geometrical representation of the wildfire headfire. The radiant heat panel (left) and flame geometry (right)

2.2. Results

Of the 4,856 reports initially reviewed, 4,336 were excluded as they did not meet the initial inclusion criteria. Of the remaining 520 reports, 56 reports were excluded because they did not involve a fatality or injury; two reports were excluded because they detailed accidents unrelated to entrapment (one structure fire propane tank explosion and one ATV rollover); eight reports were excluded as they related to controlled burns; and 392 reports were excluded because they contained insufficient information to extract or calculate fire line intensity. A total of 62 reports were included in the final study, 42% (n=26) containing firefighter fatalities and 58% (n=36) reports containing firefighter injuries only.

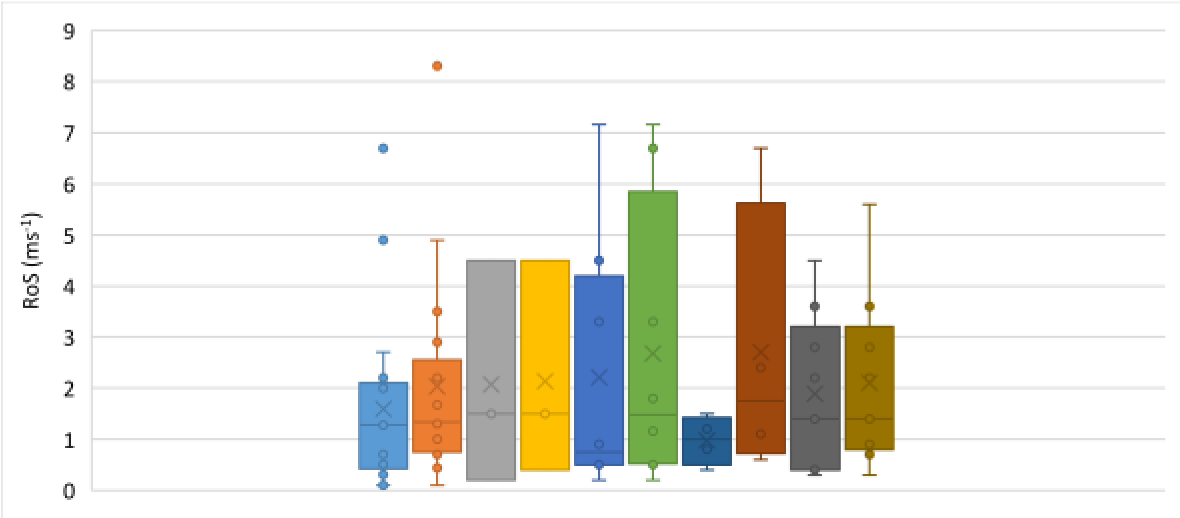
By vegetation, forest fuel structures accounted for approximately 62% (n=16) of fatal entrapments, scrub 23% (n=6), shrub 7.5% (n=2) and grassland 7.5% (n=2). For entrapments involving injury only, forest accounted for approximately 25% (n=9) of incidents, woodlands 14% (n=5), scrub 11% (n=4), shrub 17% (n=6) and grassland 33% (n=12).

For all entrapments resulting in either fatality or injury, forest accounted for approximately 40% (n=25) of incidents, woodlands 9% (n=5), scrub 16% (n=10), shrub 13% (n=8) and grassland 22% (n=14). Wildfire behaviour (lower and upper reported / calculated values) during entrapments and burnover at the time of fatality, injury and all incidents is detailed in Table 3, with distribution across all incidents illustrated in Figure 4. The highest RoS by vegetation type was Forest 8.3ms^{-1}, Woodland 4.53 ms^{-1}, Scrub 7.23 ms^{-1}, Shrub 6.73 ms^{-1}, and Grass 5.63 ms^{-1}. The highest intensity and flame length occurred in planation Forest fires during fatal entrapments, with the highest reported intensity being 249,226 kWm^{-1}, the highest calculated intensity being 318,990 kWm^{-1} and the largest flame length being reported as between 45.7 to 61 m. The mean (μ) upper reported / calculated intensity across all entrapments was 64,453 kWm^{-1} and was subsequently adopted as the intensity threshold for Performance Threshold 4. Acknowledging the limitations and assumptions of the wildfire models used in the study, these figures are consistent with explosive wildfire behaviour over short runs [1,66].

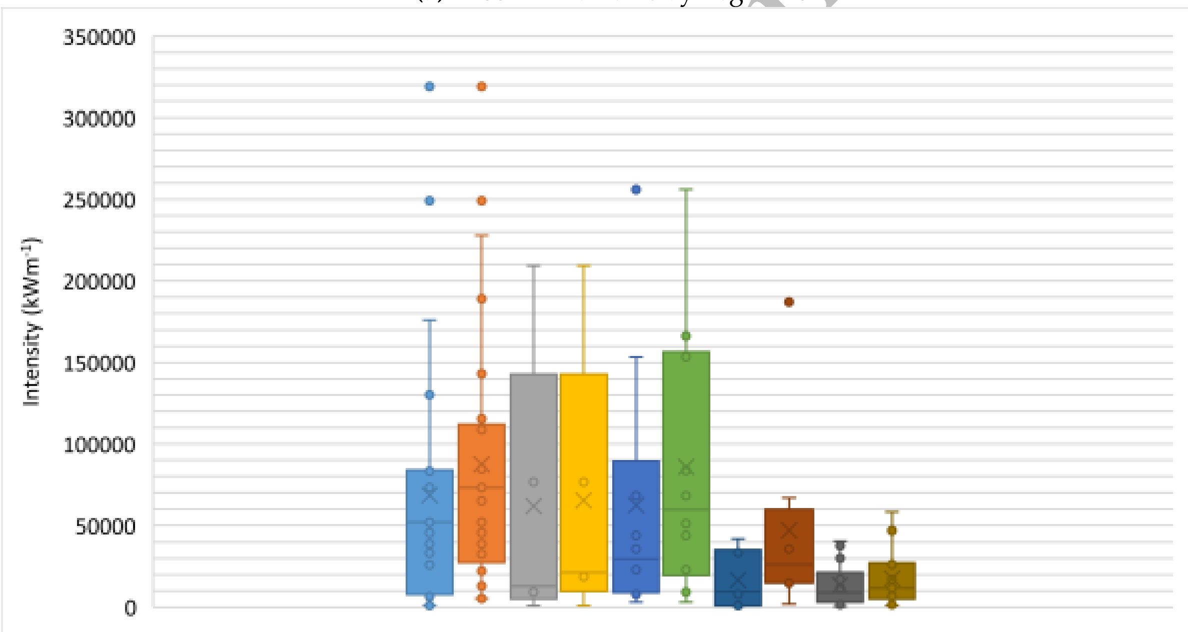
Table 3. Wildfire behaviour at point of impact during entrapments resulting in injury or fatality, showing minimum and maximum reported or calculated values, mean (μ) and standard deviation (σ)

Fatality only incidents (n=26)				
Wildfire behaviour	**min**	**max**	**μ**	**σ**
RoS lower reported value (ms^{-1})	0.1	7.2	2.0	2.1
RoS upper reported value (ms^{-1})	0.1	8.3	2.3	2.4
I lower reported / calculated value (kWm^{-1})	1012	318990	68523	87142
I upper reported / calculated value (kWm^{-1})	3113	318990	83545	85912
L_F lower reported value (m)	1.8	45.7	13.7	13.0
L_F upper reported value (m)	3.0	61	19.8	18.5
Injury only incidents (n=36)				
Wildfire behaviour	**min**	**max**	**μ**	**σ**
RoS lower reported value (ms^{-1})	0.2	4.5	1.5	1.4
RoS upper reported value (ms^{-1})	0.2	6.7	2.2	1.8
I lower reported / calculated value (kWm^{-1})	253	209250	32937	7481
I upper reported / calculated value (kWm^{-1})	850	227850	50664	60349
L_F lower reported value (m)	0.6	45.7	8.5	10.9
L_F upper reported value (m)	1.2	76.2	11.8	15.5
All incidents considered (n=62)				
Wildfire behaviour	**min**	**max**	**μ**	**σ**
RoS lower reported value (ms^{-1})	0.1	7.2	1.8	1.8
RoS upper reported value (ms^{-1})	0.1	8.3	2.2	2.1

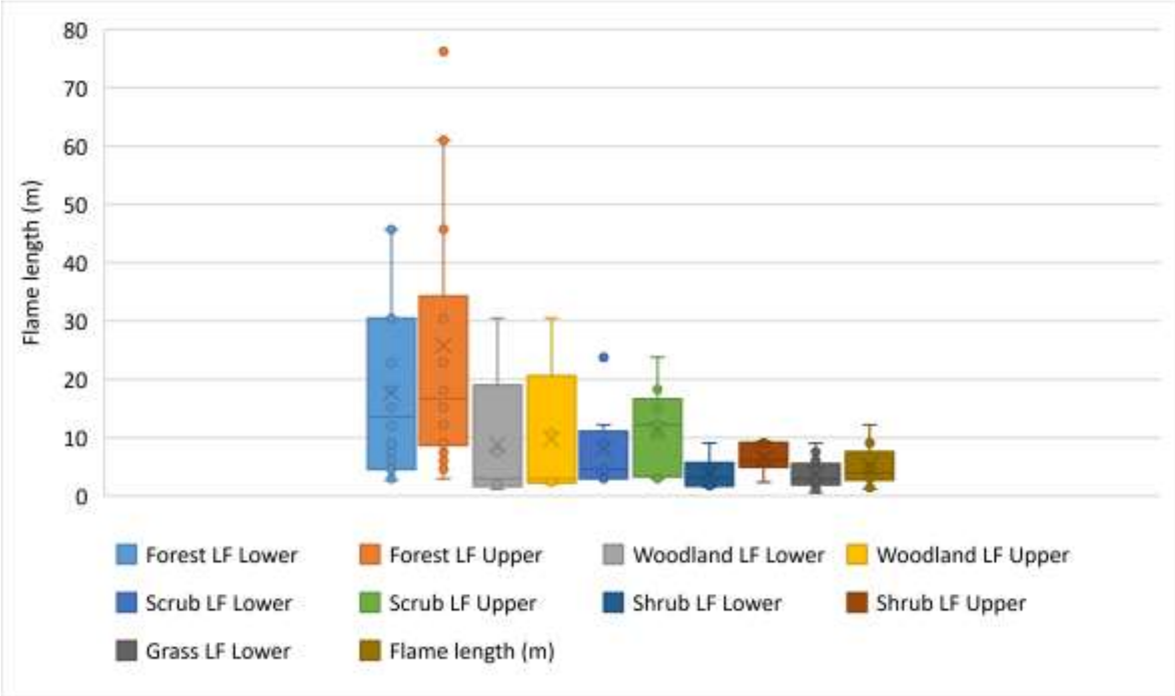
I lower reported / calculated value (kWm^{-1})	253	318990	47860	67687
I upper reported / calculated value (kWm^{-1})	850	318990	64453	73373
L_F lower reported value (m)	0.6	45.7	10.6	11.9
L_F upper reported value (m)	1.2	76.2	15.0	17.1



(a) RoS all incidents by vegetation



(b) Intensity all incidents by vegetation



(c) L_F all incidents by vegetation

Figure 4. Wildfire behaviour all incidents by vegetation type **(a)** RoS; **(b)** Intensity; **(c)** L_F

Efficacy is the ability of a fire safety system to successfully achieve its required objective, assuming it functions as intended [32,42,43]. Table 4 details the efficacy of vehicle protection systems against Performance Threshold 1 to 4 using the results from the historical entrapments analysed. Vehicle protection systems designed to operate up to an intensity 7,500 kWm^{-1} (i.e. Performance Threshold 1) have an efficacy between 0.12 to a maximum of 0.36. An increase in efficacy from 0.12 to 0.42 is observed when vehicle protection systems performing to Performance Threshold 2, i.e. 10,000 kWm^{-1}, are considered. Vehicle protection systems designed to operate up to an intensity of 12,000 kWm^{-1} (i.e. Performance Threshold 3) demonstrate an efficacy between 0.12 to 0.47. Applying Performance Threshold 4 (i.e. performance threshold equal to the mean historical upper recorded / calculated intensity of 64453 kWm^{-1}), efficacy of vehicle protection systems increases to between 0.62 to 0.81. By comparison, Yung [42] reports the efficacy of sprinklers in suppressing a 'large' fire in buildings as between 0.89 to 1.00, with an overall effectiveness (efficacy multiplied by reliability) of 0.77 to 0.96. In conjunction with the analysis of historical entrapments, this suggests that existing vehicle protection systems may be unreliable in protecting vehicle occupants from entrapment and burnover. Improvements in vehicle protection system efficacy could be achieved by increasing the performance standard they are required to meet, whilst further research into the reliability of vehicle protection systems will facilitate greater understanding of overall effectiveness.

Table 4. Vehicle protection system efficacy based on historical entrapments considering lower and upper recorded / calculated intensity

Fatality only incidents (n=26)		
Performance Threshold	**lower intensity**	**upper intensity**
PT 1 (intensity <7500kWm^{-1})	0.19 (n=5)	0.12 (n=3)
PT 2 (intensity <10000kWm^{-1})	0.31 (n=8)	0.12 (n=3)
PT 3 (intensity <12000kWm^{-1})	0.31 (n=8)	0.12 (n=3)
PT 4 (intensity <64453kWm^{-1})	0.69 (n=18)	0.62 (n=16)
Injury only incidents (n=36)		
Performance Threshold	**lower intensity**	**upper intensity**

PT1 (intensity <7500kWm^{-1})	0.36 (n=13)	0.22 (n=8)
PT 2 (intensity <10000kWm^{-1})	0.42 (n=15)	0.28 (n=10)
PT 3 (intensity <12000kWm^{-1})	0.47 (n=17)	0.33 (n=12)
PT 4 (intensity <64453kWm^{-1})	0.81 (n=29)	0.67 (n=24)
	All incidents (n=62)	
Performance Threshold	**lower intensity**	**upper intensity**
PT 1 (intensity <7500kWm^{-1})	0.29 (n=18)	0.18 (n=11)
PT 2 (intensity <10000kWm^{-1})	0.37 (n=23)	0.21 (n=13)
PT 3 (intensity <12000kWm^{-1})	0.42 (n=26)	0.24 (n=15)
PT 4 (intensity <64453kWm^{-1})	0.76 (n=47)	0.66 (n=41)

3. Phase 2 – Design wildfire analysis

3.1 Study Design

Where full scale fire safety systems testing is prohibitive (e.g. testing vehicle protection systems against an out of control wildfire in elevated fire weather conditions), fire safety systems analysis using design fire simulation is required [30-32]. Design fires are prescribed fires that can be used by fire protection engineers for performance-based fire safety designs [42]. Parameters and justification for the design wildfire simulated in the study are detailed in Table 6. Modelling was completed using the methodology described in AS3959 *Construction of buildings in bushfire prone areas Annexure B* [51] which details the calculation of wildfire Rate of Spread (*RoS*), intensity (*I*) and radiant heat flux (*RHF*) for multiple vegetation structures. This approach enabled vehicle protection systems designed to Performance Threshold 1 to 6 (i.e. intensities of 7,500 kWm^{-1}, 10,000 kWm^{-1}, 12,000 kWm^{-1}, 64,453 kWm^{-1}; and radiant heat flux of 15 kWm^{-2} and 30 kWm^{-2}) to be assessed across Forest, Woodland, Scrub, Shrub and Grassland fuel structures, fuel loads, forest and grassland fire danger indices, windspeeds, slope and fuel age.

Table 6. Design wildfire specifications AS3959 Annexure B simulations

Component	**Model / Value**	**Justification**
Wildfire models	AS3959 Annexure B	Acknowledging the limitations of empirical models [65] the models selected are those currently used by fire services across Australia [10,67] as well as the Australian Building Codes Board [69,70] by adopting Australian Standard 3959 [51]. They have also been successfully utilised in recent related research [10,52], and are therefore considered suitable for the study.
Vegetation	Forest, Woodland, Scrub, Shrub & Grassland	Captures all fuel structures associated with historical entrapment and burnover. Understory fuel loads (*w*), total fuel loads (*W*), vegetation heights (*VH*) and wind speed (*V*) sourced AS3959 [51] Table B3: Forest: w = 25tha^{-1}; W = 35tha^{-1}; Woodland: w = 15tha^{-1}; W = 25tha^{-1}; Scrub: w = 25tha^{-1}; W = 25tha^{-1}; VH = 3m; V = 45kmh^{-1}; Shrub: w = 15tha^{-1}; W = 15tha^{-1}; VH = 1.5m; V = 45kmh^{-1}; Grassland: w = 4.5tha^{-1}; W = 4.5tha^{-1} Sensitivity analysis completed for W at 10% increments for Forest and Woodland, assuming flat slope and FDI = 80. Additional radiant heat flux sensitivity analysis was

		completed for Forest and Woodland for w at 5tha^{-1} increments across all Fire Danger Indices.
Fire Danger Index (*FDI*)	10-100	Assessed at increments of 10. Represents the 99th percentile of fire weather conditions [71] across Australia. Note: only applicable to Forest and Woodland.
Grassland Fire Danger Index (*GFDI*)	50-130	Represents the 99th percentile of fire weather conditions [71] across Australia. Note: only applicable to Grassland. GFDI distribution in accordance with AS3959 [51] default values.
Heat of Combustion (H_C)	18600kJkg^{-1}	Within ranges reported in AS3959[51] and the SFPE Handbook [32]
Flame temperature (T_F)	1090K	Within the wildfire flame temperature ranges reported [51,61,62]
Emissivity (ε)	0.95	Within emissivity ranges reported [51,61,62,72] (and reflects the optically thick flame of a significant wildfire head fire.
Head fire width	100m	Consistent with that required for radiant heat flux modelling of wildfire reported in AS3959 [51] and Penney & Stevenson [52].
Wind speed (V)	45kmh^{-1}	Average wind speed at 10m above ground (kmh^{-1}) in the open AS3959 [51]. Sensitivity analysis at 10kmh^{-1} increments. Note: only applicable to Scrub and Shrub fire models.
Slope	0°	Positive slope (aligned with wind direction) assumed to be 0° with sensitivity analysis at 5° increments across Forest and Woodland vegetation at FDI = 80; Grassland at GFDI =110 (equivalent to FDI of 80); at 45kph^{-1} windspeed for Scrub and Shrub.
Separation distance	0-100m	Radiant heat flux (RHF) diminishes with separation of the receiver from the radiant heat panel. RHF is calculated at 5m increments from 0 to 100m separation.

3.2. Results

Fire line intensity – AS3959

Applying the parameters detailed in Table 6, a total of 90 simulations were completed. As expected wildfire intensity increased with slope, windspeed (V) and Forest / Grassland Fire Danger Indices (Figure 5a-j), which is consistent with the principles of established wildfire behaviour.

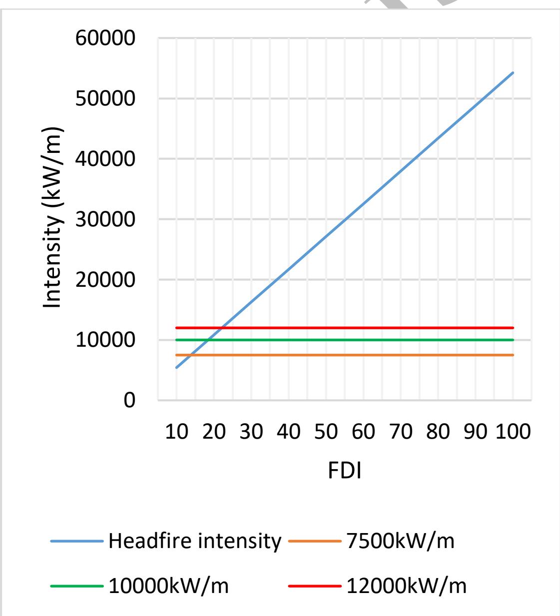
Forest simulations on flat ground resulted in intensity exceeding Performance Threshold 1 (7,500 kWm^{-1}) and Performance Threshold 2 (10,000 kWm^{-1}) between a Fire Danger Index of 10 to 20, and Performance Threshold 3 (12,000 kWm^{-1}) being exceeded between a Fire Danger Index of 20 to 30. Performance Threshold 4 (i.e. performance threshold equal to the mean historical upper recorded / calculated intensity of 64,453 kWm^{-1}) was not exceeded regardless of the Fire Danger Index. By comparison Woodland simulations on flat ground resulted in intensity exceeding Performance Threshold 1 (7,500 kWm^{-1}) between a Fire Danger Index of 30 to 40, intensity exceeding Performance Threshold 2 (10,000 kWm^{-1}) between a FDI of 40 to 50, and Performance Threshold 3 (12,000 kWm^{-1}) being exceeded between a Fire Danger Index of 50 to 60. Echoing the results of Forest simulations, Performance Threshold 4 (64,453 kWm^{-1}) was not exceeded in Woodland regardless of the Fire Danger Index. In Grassland under equivalent conditions, intensity exceeded Performance

Threshold 1-3 prior to a Grassland Fire Danger Index of 50 while Performance Threshold 4 was not exceeded at any Fire Danger Index.

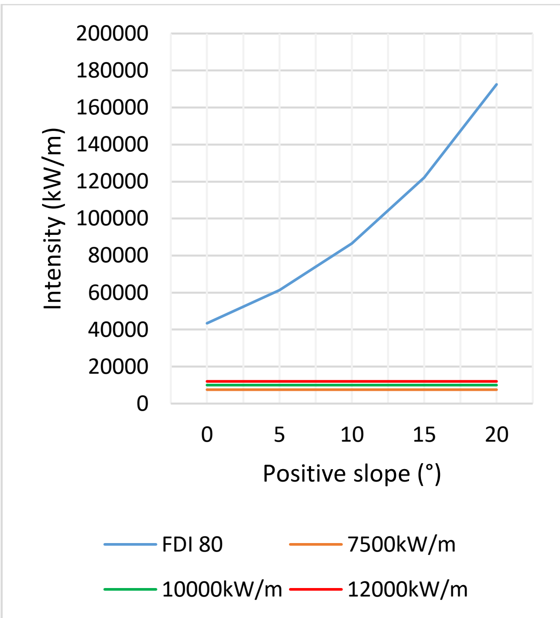
The influence of windspeed on fire line intensity in Scrub and Shrub wildfires is illustrated in Figures 5g and 5i. Scrub simulations on flat ground resulted in intensity exceeding Performance Threshold 1 to 3 between windspeeds (*V*) of 5 to 15 kmh^{-1}. Unlike all other simulations, intensity exceeded Performance Threshold 4 in simulated Scrub wildfire, but only once windspeed exceeded approximately 55 kmh^{-1}. By comparison, Shrub simulations in equivalent conditions resulted in intensity exceeding Performance Threshold 1 and 2 between windspeeds of 5 to 15 kmh^{-1}, and Performance Threshold 3 being exceeded between windspeeds of 25 to 35 kmh^{-1}. Intensity did not exceed Performance Threshold 4 regardless of windspeed in Shrub simulations.

Sensitivity analysis was completed to determine the effect of changing slope across all vegetation structures. Simulations in each fuel structure were completed at 0° to 20°. When simulating the effect of increase in slope (Figures 5b,d,f,h,j), a positive relationship was confirmed between slope and wildfire intensity (Table 8). This subsequently resulted in Performance Threshold 1-3 thresholds being exceeded more rapidly as slope increased. Increased slope may also result in Performance Threshold 4 being exceeded where it previously provided adequate protection. These outcomes were expected given the mathematical relationship between slope, rate of spread and intensity detailed in equations 1-8.

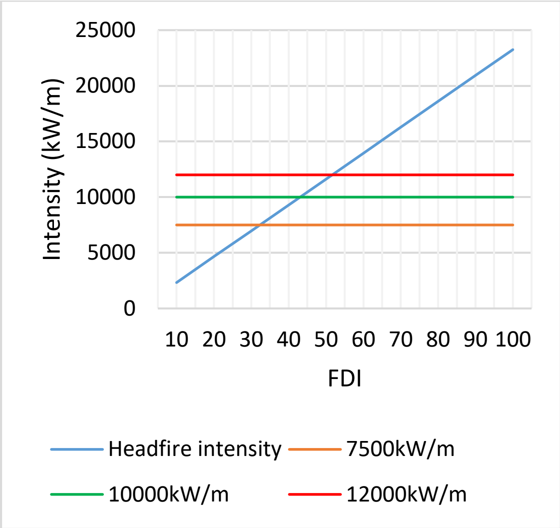
Sensitivity analysis of intensity to fuel load in Forest and Woodland also confirmed consistent increase of intensity as understory (*w*) and total fuel (*W*) load increased (Figure 6). At a Fire Danger Index of 80 and assuming flat ground, fire line intensities exceeded Performance Threshold 1 and 2 when Forest fuels reached 40-50% of their default design wildfire values (*w*= 10-12.5 tha^{-1} and *W*= 14-17.5 tha^{-1}) and Performance Threshold 3 was exceeded once Forest fuels reached 50-60% (w= 15-17.5 tha^{-1} and W= 21-24.5 tha^{-1}) of default design wildfire values. Under the same conditions, Performance Threshold 1 was exceeded when Woodland fuels reached 60-70% (*w*= 7.4-9 tha^{-1} and *W*= 12.5-15 tha^{-1}) of default design wildfire values and both Performance Threshold 2 and 3 were exceeded once Woodland fuels reached 70-80% (*w*= 10.5-12 tha^{-1} and *W*= 17.5-20 tha^{-1}) of their default design wildfire values (the fuel loads assigned in AS3959). Performance Threshold 4 was not exceeded in Forest or Woodland simulations at any fuel load. These results indicate that whilst sparser fuels result in reduced intensity, vehicle protection systems designed to existing performance threshold may still be exceeded, however vehicle protection systems designed to Performance Threshold 4 would provide a significantly higher level of firefighter protection.



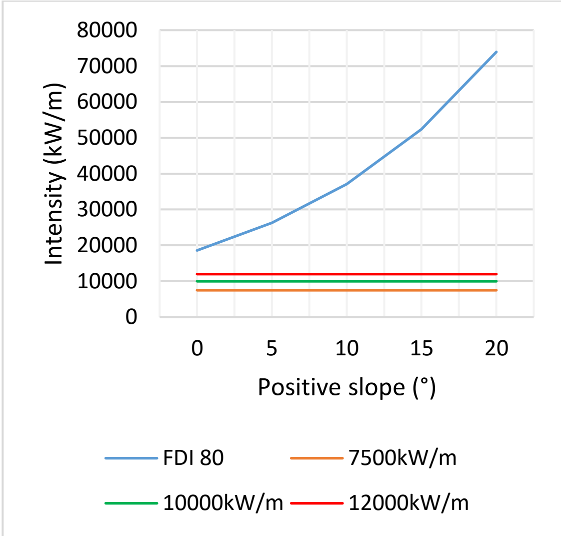
(a) *Forest headfire intensity FDI sensitivity*



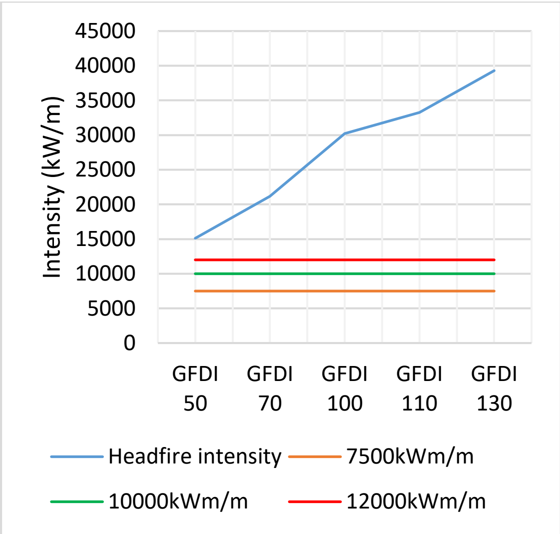
(b) *Forest headfire intensity slope sensitivity (FDI 80)*



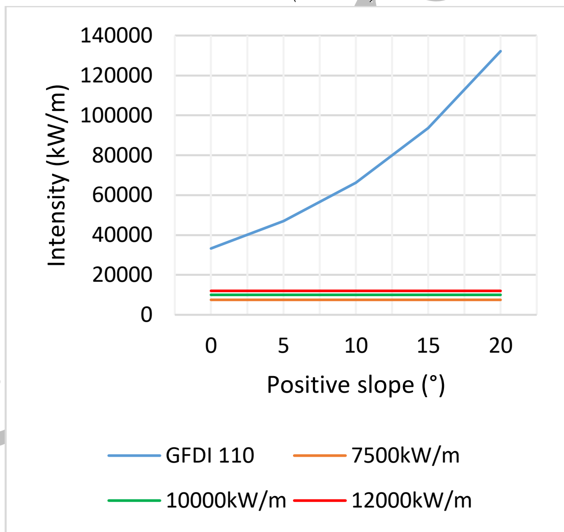
(c) *Woodlands headfire FDI sensitivity*



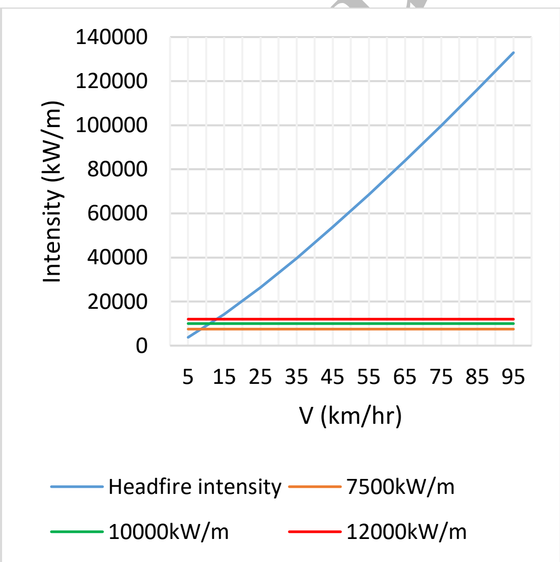
(d) *Woodland headfire intensity slope sensitivity (FDI 80)*



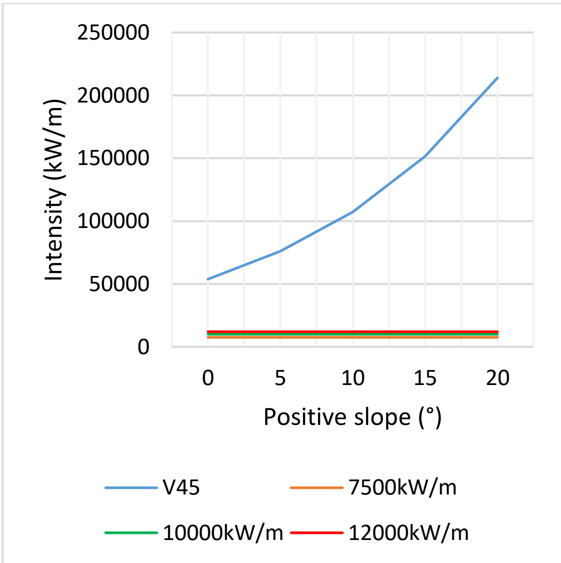
(e) *Grass headfire FDI sensitivity*



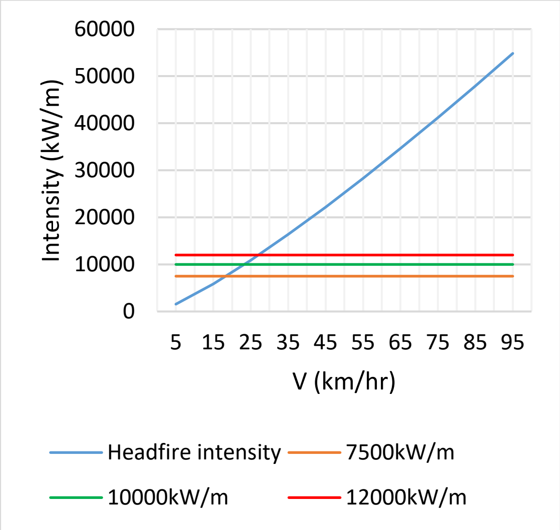
(f) *Grass headfire intensity slope sensitivity (GFDI 110)*



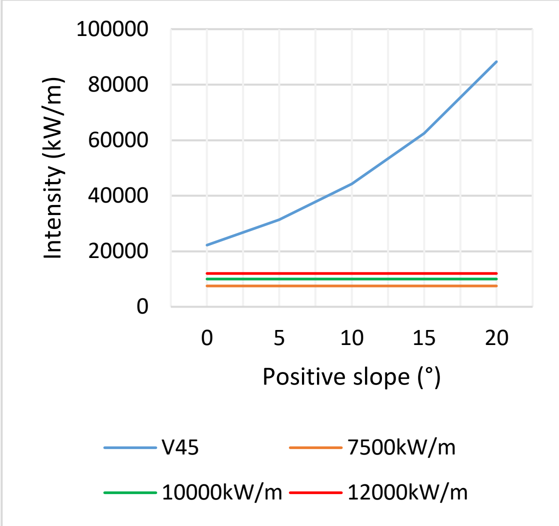
(g) *Scrub headfire V sensitivity*



(h) *Scrub headfire intensity slope sensitivity (V=45)*



(i) *Shrub headfire V sensitivity*



(j) *Shrub headfire intensity slope sensitivity (V=45)*

Figure 5. Wildfire intensity by vegetation type

Table 8. Relationship between slope and intensity, all vegetation types

Slope	Intensity factor compared to flat ground
Flat	1
5°	1.4
10°	2.0
15°	2.8
20°	4

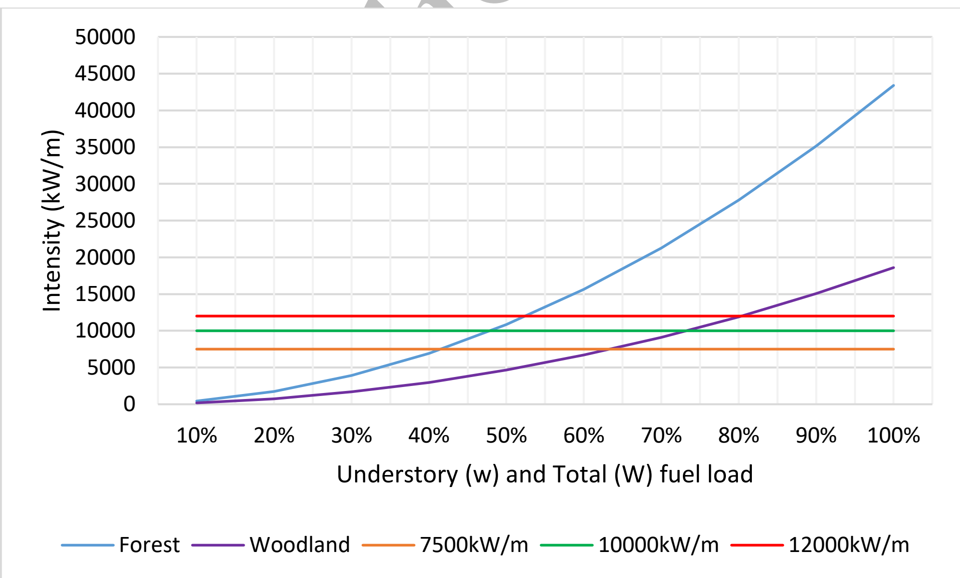


Figure 6. Sensitivity to fuel load - Forest & Woodland

Radiant Heat Flux

Wildfire simulations (n=45) enabled radiant heat flux (RHF) to be calculated at 5 m increments for 0 to 100 m of separation from the headfire for Forest, Woodland, Scrub, Shrub and Grassland vegetation structures (Figure 7). As expected, due to the mathematical relationships established in Equations (1) to (9), radiant heat flux at each unit of separation increases with slope, Fire Danger Index (FDI), Grassland Fire Danger Index (GFDI) and windspeed (V).

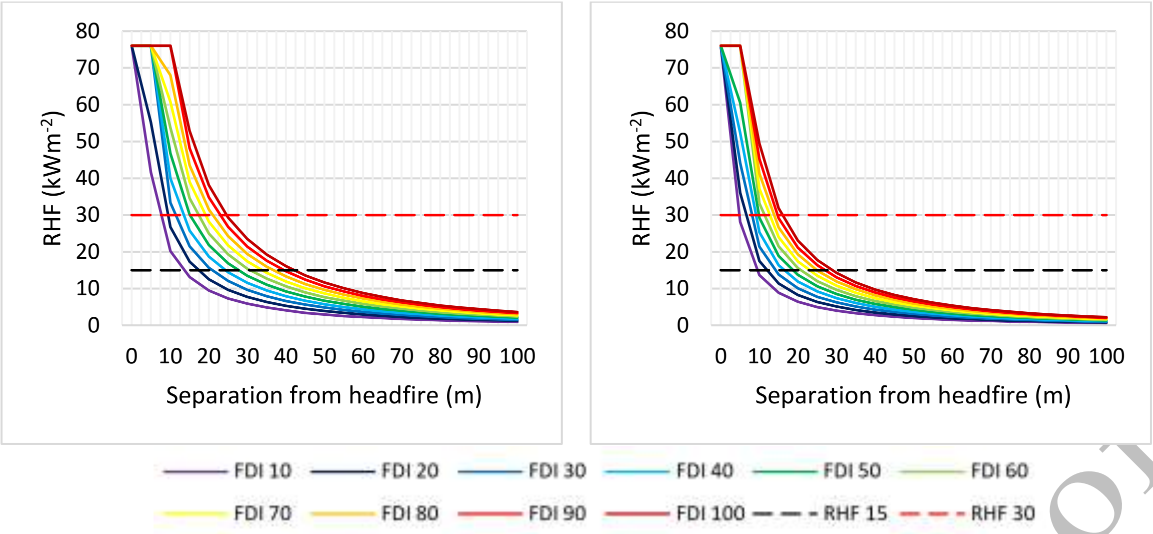
In all simulations, regardless of FDI, GFDI, V, slope or fuel load, Performance Threshold 5 (15 kWm^{-2}) and Performance Threshold 6 (30 kWm^{-2}) were exceeded for 0 to 5m separation from the wildfire front. Historical analysis (Table 3) identifies the mean flame length during entrapments and burnover resulting in either injury or fatality is 10.6 to 15 m, with a maximum flame length of 45.7 to 76.2 m. This indicates vehicle protection systems would likely fail in the event of protracted flame immersion associated with engulfment and burnover during the passage of the headfire.

In Forest simulations (Figure 7a), radiant heat flux exceeded Performance Threshold 5 (15 kWm^{-2}) for approximately 14 m separation from the headfire at a Fire Danger Index of 10, increasing to approximately 44 m at a Fire Danger Index of 100. Radiant heat flux exceeded Performance Threshold 6 (30 kWm^{-2}) for approximately 8 m separation from the headfire at a Fire Danger Index of 10, increasing to approximately 25 m at a Fire Danger Index of 100.

As expected, the efficacy of vehicle suppression systems in Woodlands fuels was slightly higher by comparison, Woodlands having less understory fuel (15 tha^{-1}) compared to Forest (25 tha^{-1}). Radiant heat flux exceeded Performance Threshold 5 (15 kWm^{-2}) for approximately 10m separation from the headfire at a Fire Danger Index of 10, increasing to approximately 30m at a Fire Danger Index of 100 (Figure 7b). Radiant heat flux exceeded Performance Threshold 6 (30 kWm^{-2}) for approximately 5 m separation from the headfire at a Fire Danger Index of 10, increasing to approximately 17 m at a Fire Danger Index of 100.

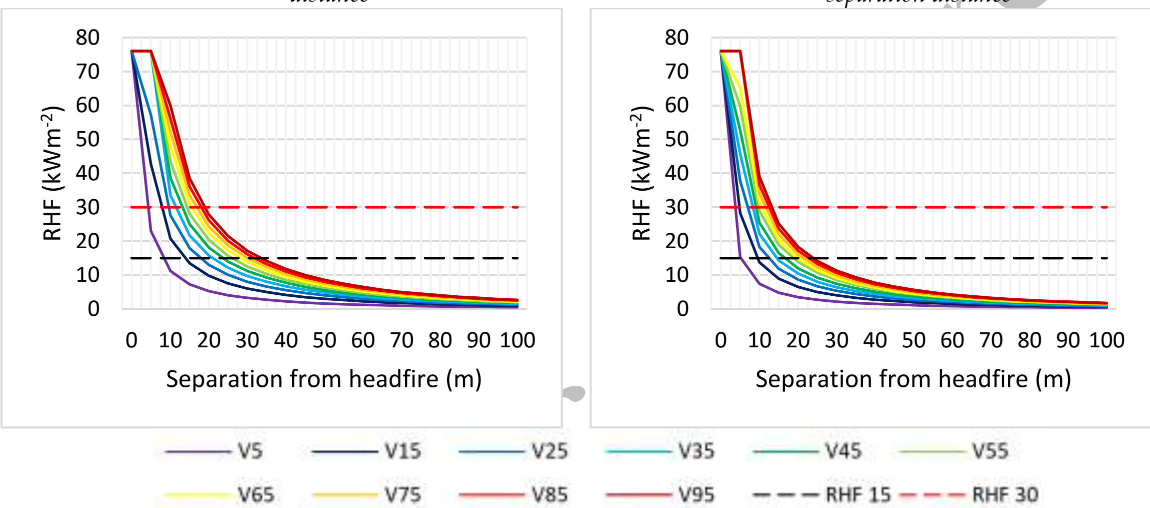
In Scrub simulations (Figure 7c), radiant heat flux exceeded Performance Threshold 5 (15 kWm^{-2}) for approximately 8 m from the headfire at a windspeed of 5kmh^{-1}, increasing to approximately 35 m at a windspeed of 95 kmh^{-1}. Radiant heat flux exceeded Performance Threshold 6 (30 kWm^{-2}) for approximately 5 m from the headfire at a windspeed of 5 kmh^{-1}, increasing to approximately 20 m at a windspeed of 95 kmh^{-1}. By comparison, in Shrub simulations (Figure 7d), radiant heat flux exceeded Performance Threshold 5 (15 kWm^{-2}) for approximately 5 m from the headfire at a windspeed of 5 kmh^{-1}, increasing to approximately 25 m at a windspeed of 95 kmh^{-1}. Radiant heat flux exceeded Performance Threshold 6 (30 kWm^{-2})for approximately 4m from the headfire at a windspeed of 5 kmh^{-1}, increasing to approximately 13 m at a windspeed of 95 kmh^{-1}.

In Grassland simulations (Figure 7e) radiant heat flux exceeded Performance Threshold 5 (15 kWm^{-2}) for approximately 10 m from the headfire at a Grassland Fire Danger Index of 50, increasing to approximately 17 m at a Grassland Fire Danger Index of 130. Radiant heat flux exceeded Performance Threshold 6 (30 kWm^{-2}) for approximately 5m from the headfire at a Grassland Fire Danger Index of 50, increasing to approximately 10m at a Grassland Fire Danger Index of 130.



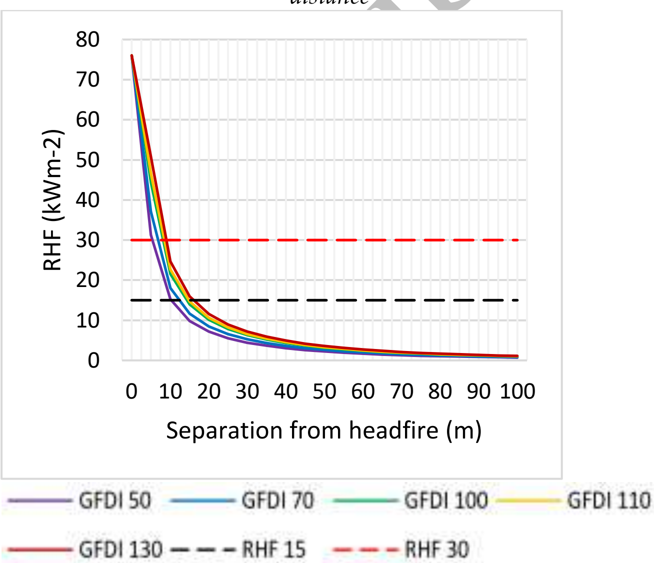
(a) *Forest headfire RHF as a function of separation distance*

(b) *Woodland headfire RHF as a function of separation distance*



(c) *Scrub headfire RHF as a function of separation distance*

(d) *Shrub headfire RHF as a function of separation distance*



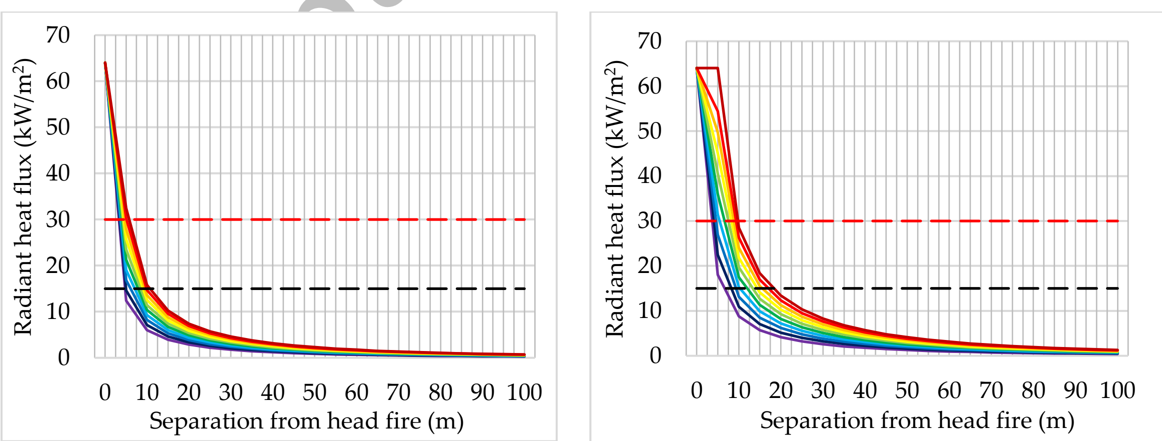
(e) *Grass headfire RHF as a function of separation distance*

Figure 7. Radiant heat flux (RHF) as a function of separation from headfire: (**a**) Forest; (**b**) Woodland; (**c**) Scrub; (**d**) Shrub; (**e**) Grassland

Sensitivity analysis (table 9) demonstrates the separation required from the headfire (all vegetation structures) in order for radiant heat flux to fall below Performance Threshold 5 and 6 increases with slope. Similarly, sensitivity analysis of understory fuel loads (*w)* in Forest/Woodland design wildfires (Figure 8a-f) demonstrates a positive relationship between the separation required from the headfire in order for radiant heat flux to fall below Performance Threshold 5 and 6, and understory fuel loads (*w*). At surface fuel loads (*w*) of 30 tha^{-1}, and a Fire Danger Index of 100, radiant heat flux exceeds Performance Threshold 5 (15 kWm^{-2}) until approximately 45 m separation from the forest head fire is achieved. Under the same conditions radiant heat flux exceeds Performance Threshold 6 (30 kWm^{-2}) until separation of approximately 25m is achieved. The required separation from the head fire for RHF decreases with FDI and *w*, with only approximately 6 m separation required for RHF to fall below 30 kWm^{-2} at a FDI of 100 when w is 5 tha^{-1}; and 10 m separation required for RHF to fall below 15 kWm^{-2} under the same conditions.

Table 9. Effect of slope on reparation from headfire required before Performance Threshold 5 & 6 are achieved.

			Slope		
Vegetation	**0°**	**5°**	**10°**	**15°**	**20°**
Performance Threshold 5 (*Radiant heat flux of 15kWm*$^{-2}$) exceeded					
Forest (*FDI*=80)	35-40m	45m	55m	65m	75-80m
Woodland (*FDI*=80)	25m	30m	35-40m	45-50m	55-60m
Scrub (*V*=45kmh^{-1})	20-25m	25-30m	30m	30-35m	35-40m
Shrub (*V*=45kmh^{-1})	15-20m	15-20m	20-25m	20-25m	25-30m
Grassland (*GFDI*=110)	15m	15-20m	20m	15-20m	25-30m
Performance Threshold 6 (*Radiant heat flux of 30kWm*$^{-2}$) exceeded					
Forest (*FDI*=80)	20-25m	25-30m	30-35m	40-45m	50-55m
Woodland (*FDI*=80)	10-15m	15-20m	20-25m	25-30m	30-35m
Scrub (*V*=45kmh^{-1})	10-15m	10-15m	15-20m	15-20m	20-25m
Shrub (*V*=45kmh^{-1})	5-10m	5-10m	10-15m	10-15m	10-15m
Grassland (*GFDI*=110)	5-10m	5-10m	10m	10-15m	10-15m



(a) *w* = 5tha^{-1} (b) *w* = 10tha^{-1}

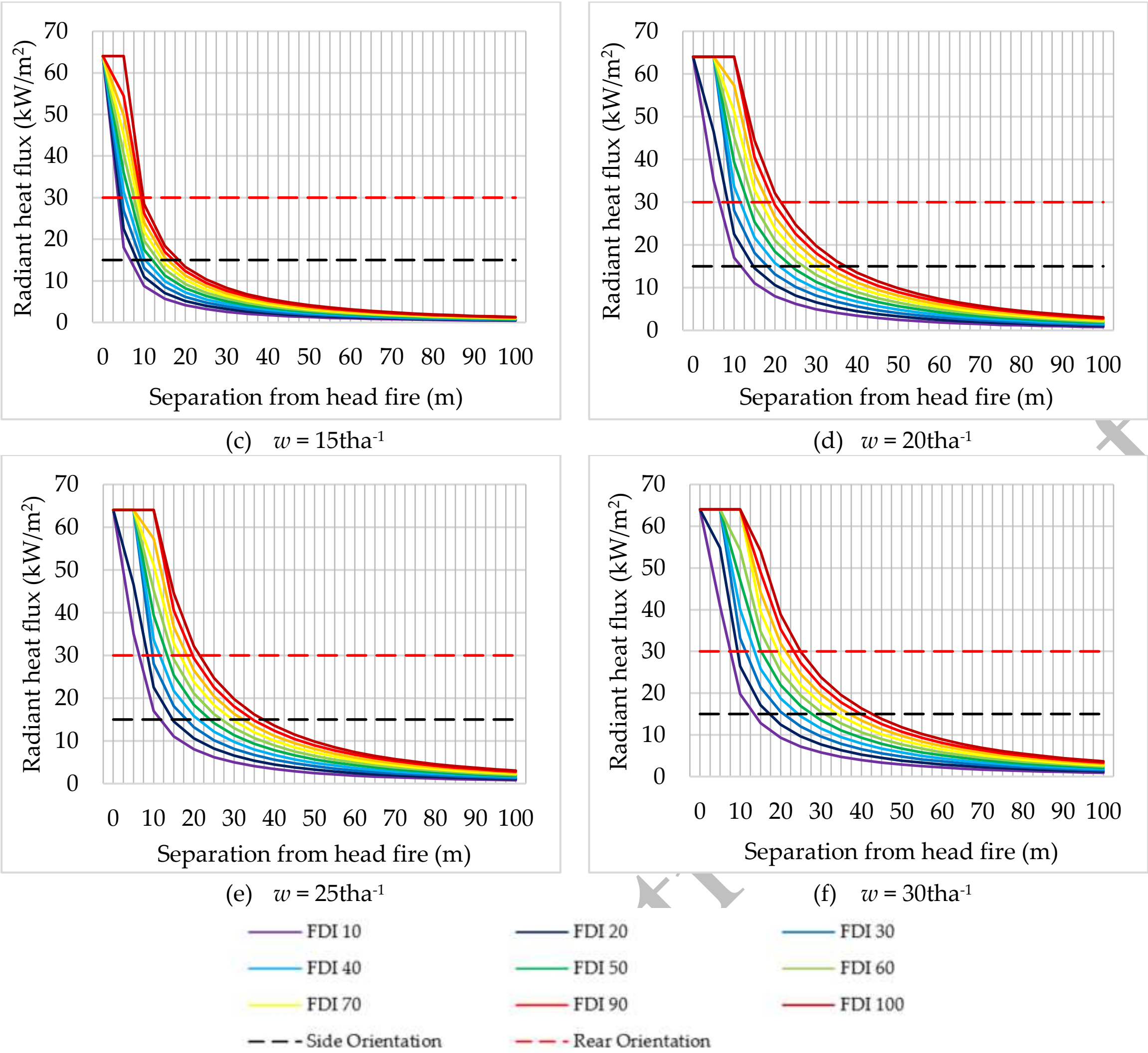


Figure 8. Effect of understory fuel load on RHF as a function of separation from the headfire: (**a**) w = 5tha^{-1}; (**b**) w = 10tha^{-1}; (**c**) w = 15tha^{-1}; (**d**) w = 20tha^{-1}; (**e**) w = 25tha^{-1}; (**f**) w = 30tha^{-1}

4. Discussion

The results of Phase 1 of the study identify that vehicle protection systems designed to operate in fire line intensities of 7,500 kWm^{-1} (i.e. Performance Threshold 1) could reasonably be expected to be effective in 0.12 to 0.36 of historical entrapments and burnovers, assuming they operate without fault 100% of the time (i.e. a reliability factor of 1.00). An increase in efficacy from 0.12 to 0.42 was observed when vehicle protection systems performing to Performance Threshold 2, i.e. 10,000 kWm^{-1}, were considered. Vehicle protection systems designed to operate up to an intensity of 12,000 kWm^{-1} (i.e. Performance Threshold 3) demonstrate an efficacy between 0.12 to 0.47. To put this into perspective, these figures are well below the expected efficacy of commercial fire safety systems [32,40], and support Hypothesis 1 (i.e. Existing vehicle protection systems would have been effective in less than 50% of historical burnovers resulting in firefighter injury or fatality.)

The results of Phase 2 of the study further highlight the performance limitations of existing vehicle protection systems. The simulations completed in the study demonstrated Performance Threshold 1-3 (i.e. intensity of 7,500 kWm^{-1}, 10,000 kWm^{-1} and 12,000 kWm^{-1} respectively) were exceeded on flat terrain in Forest below a Fire Danger Index of 30; in Woodlands at Fire Danger Indices between 30 to 60; in Grassland at a Grassland Fire Danger Index of less than 50 (equivalent to a Fire Danger Index of 40); and in Scrub and Scrub at windspeeds of less than 15 kmh^{-1}. By

comparison, the mean historical upper recorded / calculated intensity of 64,453 kWm^{-1} (i.e. Performance Threshold 4) was not exceeded in any simulation, regardless of Fire Danger Index or windspeed except for Scrub fuels once windspeed reached approximately 55 kmh^{-1}. Radiant heat flux modelling completed in Phase 2 demonstrated that vehicle protection system Performance Threshold 5 and 6 (i.e. 15 kWm^{-2} and 30kWm^{-2}) are likely to be exceeded in all cases of entrapment where flame immersion occurs, and, remains a distinct possibility for significant distances of separation from the headfire. The results of these simulations support Hypothesis 2 (i.e. Existing vehicle protection systems would not be effective in simulated wildfires during conditions representative of days when house loss is expected (i.e. Fire Danger Index exceeding 50).

Increasing the operational performance standard of vehicle protection systems to the mean historical upper recorded / calculated intensity of 64,453 kWm^{-1} (i.e. Performance Threshold 4) would result in an increase in the efficacy of vehicle protection systems to between 0.62 to 0.81. Adopting this performance threshold represents an increase in the performance demands of vehicle protection systems of 52,453 to 56,953 kWm^{-1} (an increase by a factor of 5.16 to 8.59 compared to existing thresholds). Similarly, enhancing existing vehicle protection systems to withstand peak calculated radiant heat flux of 76 kWm^{-2} would require a performance increase of a factor of 2.53 to 5.07 compared to existing systems. While determining whether existing vehicle protection systems can be modified to meet this requirement is outside the scope of this study, materials and testing standards for houses required to maintain tenable interiors during sustained flame immersion and burnover have been used in Australia for over a decade [51,73]. Given the limitations of water in reducing headfire intensity we have previously reported [11], achieving the required level of protection may require passive protection, enhanced construction and alternatives to water deluge systems to be considered by fire services when designing future wildfire fighting vehicles and fleet. To address the low levels of vehicle protection system performance identified in the study, fire services should also work towards establishing a standard or minimum required efficacy, not just for vehicle protection systems but for all firefighting safety systems.

To improve firefighter safety during entrapment and burnover it is recommended that a significantly higher standard of fire line intensity resilience is adopted across fire services for vehicle protection systems. Further research into the reliability of vehicle protection systems is also recommended to determine the effectiveness of each system as part of a detailed fire safety system validation and fire engineering analysis. This will help a better assessment of the required safety systems for firefighters during entrapment and burnover and will reduce injuries or fatalities during wildfire suppression. To increase firefighter safety further research and development is recommended into vehicle protection systems satisfying Australian Standard 1530.8.2 *Methods for fire tests on building materials, components and structures – Part 8.2 Tests on elements of construction for buildings exposed to simulated bushfire attack – large flaming sources* [73], which specifically identifies performance threshold for prolonged radiant heat flux exceeding 40 kWm^{-2}.

This study investigates the efficacy of vehicle protection systems as currently fitted to Australian wildfire appliances. Whilst it does not investigate impacts of specific designs or the effects of various water sprays and droplet size on attenuation, the study does identify suitable performance threshold for future vehicle protection systems to be assessed against. Building on findings and recommendations by Roberts [74], Turco et al., [75] and SAI Global [73,77] future research into specific components of vehicle protection system design may further improve the effectiveness of various systems and ultimately improve firefighter safety. Whilst data was collected across three countries and over 40 years, it is also acknowledged that incidents in some jurisdictions and fuel types are limited, particularly from Australia and New Zealand and in shrub and grassland fuel structures. For this reason, care should be taken when interpreting the findings in these specific areas until further data becomes available for analysis.

5. Conclusion

This study involved analysis of the potential effectiveness of wildfire fighting vehicle protection systems in increasing the tenability of firefighters during entrapment and burnover using 62 historical international entrapment and burnover reports, and 135 simulated wildfires encompassing the 99th percentile of Australian fire weather conditions, fuel structures and terrain. Acknowledging existing models relied on in the study simplify the chaotic geometry and propagation of wildfire, the results suggest that existing vehicle protection systems designed to withstand up to 12,000 kWm^{-1} are unlikely to have been effective in improving firefighter tenability in more than 50% of historical entrapments and burnovers resulting in firefighter injury or fatality. Further, the study suggests these systems would not be effective during entrapment and burnovers in conditions representative of days when house loss is expected (i.e. Fire Danger Index exceeding 50).

Improving the effectiveness of vehicle protection systems in these conditions would require an increase in intensity performance thresholds by a factor of 5.16 to 8.59, and an increase in radiant heat flux thresholds by a factor of 2.53 to 5.07 compared to existing systems. To improve firefighter tenability during entrapment and burnovers it is recommended future vehicle protection system designs adopt a suitable performance criteria, being Australian Standard 1530.8.2 Methods for fire tests on building materials, components and structures – Part 8.2 Tests on elements of construction for buildings exposed to simulated bushfire attack – large flaming sources [73].

The results of this study should not be considered in isolation, but rather alongside the findings of our other recent research [10-13] into wildfire suppression strategies and the limitations of firefighters and the equipment they rely on. Active defense of houses will continue to be a central strategy of wildfire firefighting and will be required in periods of elevated fire weather. The chief question is, when can it be done safely and when should it be abandoned for alternate, safer strategies? Unfortunately there is no single rule of thumb. Fire services should ensure training in the limitations of firefighter tenability [10], suppression [11], rural urban interface defense [12], and firefighting vehicles are imbedded in the training of frontline firefighters and Incident Management Teams alike. In turn this may assist firefighters more accurately assess the likelihood of successful suppression, understand associated risks, and clearly articulate the severity of the approaching head fire to affected communities.

Author Contributions: Conceptualization, G.P.; Methodology, G.P.; Validation, G.P., D.H. and M.C.; Formal Analysis, G.P.; Investigation, G.P.; Writing-Original Draft Preparation, G.P.; Writing-Review & Editing, G.P., D.H. and M.C; Supervision, D.H. and M.C.; Project Administration, G.P.;

Funding: This research was supported by an Australian Government Research Training Program (RTP) Scholarship

Conflicts of Interest: The authors declare no conflict of interest.

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Appendix A

Table A1 – Entrapments and Burnover Fatalities

Report	Vegetation	Country
https://www.wildfirelessons.net/viewdocument/oaklandberkeley-hills-1991	Forest	USA
https://www.wildfirelessons.net/viewdocument/south-canyon-fire-fa	Forest	USA
https://www.wildfirelessons.net/viewdocument/dude-1990	Forest	USA
https://www.wildfirelessons.net/viewdocument/thirtymile-fire-fata	Forest	USA
https://www.wildfirelessons.net/viewdocument/rainbow-springs-1984	Forest	USA
https://www.wildfirelessons.net/viewdocument/california-1990	Forest	USA
https://www.wildfirelessons.net/viewdocument/station-fire-fatalities-2009	Forest	USA
https://www.wildfirelessons.net/viewdocument/blue-ribbon-fire-fatalities-2011	Forest	USA
https://www.wildfirelessons.net/viewdocument/mound-house-fire-1983	Forest	USA
https://www.wildfirelessons.net/viewdocument/golden-gates-estates-fire-1985	Forest	USA
https://www.wildfirelessons.net/viewdocument/cedar-mountain-1994	Forest	USA
https://www.wildfirelessons.net/viewdocument/daddy-ridge-fatality	Forest	USA
https://www.wildfirelessons.net/viewdocument/panther-fire-fatality-2008	Forest	USA
http://royalcommission.vic.gov.au/getdoc/1ef74588-457f-47ce-baa2-1c98f9fe10f2/TEN.132.001.0001.pdf	Forest	Australia
https://www.wildfirelessons.net/viewdocument/cramer-fire-entrapment-2003	Forest	USA
https://www.wildfirelessons.net/viewdocument/yarnell-hill-entrapm	Forest	USA
https://www.wildfirelessons.net/viewdocument/point-fire-1995	Grass	USA
https://www.wildfirelessons.net/viewdocument/kates-basin-2000	Grass	USA
https://www.wildfirelessons.net/viewdocument/esperanza-fire-fatal	Scrub	USA
https://www.wildfirelessons.net/viewdocument/glen-allen-entrapment-1993	Scrub	USA
https://www.wildfirelessons.net/viewdocument/cedar-2003	Scrub	USA
https://www.wildfirelessons.net/viewdocument/tuolumne-fire-entrap	Scrub	USA
https://www.dfes.wa.gov.au/publications/MajorIncidentReports/Major% 20Incident%20Review%20-%20Black%20Cat%20Creek%20Fire%20 (October%202012).pdf	Scrub	Australia
https://www.researchgate.net/publication/298346129_Fire_behaviour_and_firefighter_safety_implications_associated_with_the_Bucklands_Crossing_fire_burnover_of_24_March_1998	Scrub	New Zealand
https://www.wildfirelessons.net/viewdocument/county-road-u-fire-f	Shrub	USA
https://www.wildfirelessons.net/viewdocument/shaw-fire-entrapment-fatality-2018	Shrub	USA

Table A2 – Entrapments and Burnover Injuries

Report	Vegetation	Country
https://www.wildfirelessons.net/viewdocument/blue-cut-2002	Forest	USA
https://www.wildfirelessons.net/viewdocument/hochderffer-hills-1996	Forest	USA
https://www.wildfirelessons.net/viewdocument/dano-1996	Forest	USA
https://www.wildfirelessons.net/viewdocument/calabasas-1996	Forest	USA
https://www.wildfirelessons.net/viewdocument/pechanga-2000	Forest	USA
https://www.wildfirelessons.net/viewdocument/mendocino-fire-complex-injuries-and	Forest	USA
https://www.wildfirelessons.net/viewdocument/shrimp-fire-burn-inj	Forest	USA
https://www.wildfirelessons.net/viewdocument/seven-oak-fire-2007	Forest	USA

https://www.wildfirelessons.net/viewdocument/lauder-1987	Forest	USA
https://www.wildfirelessons.net/viewdocument/hyatt-1998	Grass	USA
https://www.wildfirelessons.net/viewdocument/deadman-flat-no-1298-1979	Grass	USA
https://www.wildfirelessons.net/viewdocument/jackson-burnover-2008	Grass	USA
https://www.wildfirelessons.net/viewdocument/grizzly-canyon-1981	Grass	USA
https://www.wildfirelessons.net/viewdocument/wagon-box-1999	Grass	USA
https://www.wildfirelessons.net/viewdocument/clubhouse-2006	Grass	USA
https://www.wildfirelessons.net/viewdocument/nicolaus-fire-2008	Grass	USA
https://www.wildfirelessons.net/viewdocument/dutch-flat-1996	Grass	USA
https://www.wildfirelessons.net/viewdocument/klamathon-entrapment-2018	Grass	USA
https://www.wildfirelessons.net/viewdocument/davin-road-fire-2010	Grass	USA
https://www.wildfirelessons.net/viewdocument/bull-fire-entrapment	Grass	USA
https://www.wildfirelessons.net/viewdocument/new-york-peak-2006	Grass	USA
https://www.wildfirelessons.net/viewdocument/pine-fire-dozer-entrapment-2007	scrub	USA
https://www.wildfirelessons.net/viewdocument/holloway-fire-entrap	Scrub	USA
https://www.wildfirelessons.net/viewdocument/tanner-railroad-1999	Scrub	USA
https://www.wildfirelessons.net/viewdocument/indians-fire-2008	Scrub	USA
https://www.wildfirelessons.net/viewdocument/ridgetop-fire-entrapment-2012	Shrub	USA
https://www.wildfirelessons.net/viewdocument/sadler-1999	Shrub	USA
https://www.wildfirelessons.net/viewdocument/mackenzie-1994	Shrub	USA
https://www.wildfirelessons.net/viewdocument/canyon-fire-entrapment-2016	Shrub	USA
https://www.wildfirelessons.net/viewdocument/grassy-ridge-fire-shelter-deploymen	Shrub	USA
https://www.wildfirelessons.net/viewdocument/old-topanga-1993	Shrub	USA
https://www.wildfirelessons.net/viewdocument/maple-road-1987	Woodland	USA
https://www.wildfirelessons.net/viewdocument/smokey-hill-wind-far	Woodland	USA
https://www.wildfirelessons.net/viewdocument/jesusita-fire-2009	Woodland	USA
https://www.wildfirelessons.net/viewdocument/hyde-1988	Woodland	USA
https://www.wildfirelessons.net/viewdocument/flat-fire-entrapment	Woodland	USA