The University of Queensland
AUSTRALIA
CREATE CHANGE

UQ Materials Performance

Project No. D04489-001

Report for: **Resources Safety and Health Queensland**
PO Box 3221,
Rockhampton Qld 4703

Attention: **Mr Neville Atkinson**
Inspector of Mines - Electrical

Subject: **Assessing the Risk of Operating Mining Equipment During Lightning Storms**

Date: **6 September 2022**

Prepared By: **R. Low**, BE(Hons), PhD, RPEQ
J. Zhou, BE(Elec. Hons), MEng (Electronics)

Reviewer 1 (UQ Materials Performance)	Reviewer 2 (Electrical Engineering)
....	....
Philip Bennet, RPEQ	Chandima Ekanayake

Executive Summary

Mines in Queensland are currently do not operate heavy machinery and vehicles outdoors while lightning is present in the area. However, Resources Safety and Health Queensland (RSHQ) is aware that some mines have recently introduced (or are proposing to introduce) amendments to their Safety and Health Management Systems to allow operations to continue during lightning events. It is contended by these mine operators that the outer metal skin of the vehicle's cabin acts like a Faraday cage and protects the operator from potential electrocution. RSHQ engaged The University of Queensland to provide a report assessing the safety risks to operators of heavy machinery and emergency response teams working during lightning weather events.

It is acknowledged that every mine and mine vehicle will have a different level of exposure to lightning hazards. Nevertheless, in order for a meaningful assessment to be carried out, this assessment sought to qualify <u>the change in risk</u> from continued operation in a lightning storm. That is, what hazards are present during a lightning storm and how do the risk levels change by continuing to operate vehicles. The change in risk was assessed by evaluating the potential modes of injury and the case history of such injuries/near misses occurring in mining and in common society. Case history data was taken from RSHQ and NSW Resources Regulator incident database. Case histories available in the public domain were also noted.

Table 1 summarises the findings of our hazard assessment. A total of ten (10) hazards were identified to have an increased risk when mining vehicles are operating in lightning storms. With regard to the premise that the vehicle's cabin provides protection, it was found that the cabin is an imperfect Faraday cage and provides only partial protection. That is, there is a moderate increased risk of a direct strike to the windshield or windows owing to the large opening size. Touch potential and side flash (through open windows) are also a possible injury mechanism due to the imperfect Faraday cage. Moreover, a moderate to high/substantial change in the level of risk was deemed to be present from other mechanisms such as:

- Tyre rupture or explosion via pyrolysis (High/substantial increase from normal)
- Exposure to high voltage (HV) via UHF-radio wiring or other conductive surfaces. That is, touch voltage. (Moderate increase from normal)
- Initiation of other fires. That is, combustion of wiring, electronics, batteries, fuel, interior furnishings, etc. (Moderate increase from normal)

The same ten (10) hazards were identified to be present when emergency response vehicles and personnel are required to operate in lightning storms (Table 2). These crews have a higher likelihood of needing to leave the vehicle to carry out their duty. In addition to the hazards identified above, a moderate to high/substantial increased risk of injury or death was deemed to be present from the following mechanisms:

- Exposure to HV while outside and in close quarters to vehicles. That is, flashover injury, touch potential and step potential. (Moderate increase from normal)
- Exposure to HV while in an open area. That is, direct strike, step potential, side flash. (Moderate increase from normal)

Each individual mine may have their own Triggered Action Response Plan (TARP) for lightning. Nevertheless, it is recommended that the minimum requirements below remain implemented to ensure that the hazards identified in this report are mitigated:

- Halting production when lightning is detected within a specified distance from the mine (typically 20km or 30 second delay to hearing thunder clap),
- Driving mobile mining equipment to a designated safe lay-down area,
- Transporting the operators to a safe shelter away from the equipment, and

- Awaiting the “All Clear” once lightning is beyond the exclusion distance (typically no lightning detected within 40 km for a period of 30 minutes).

Controls to significantly reduce the risk of the identified lightning hazards would be required before a change to the status quo would be acceptable. It is expected that this would require significant design changes/modifications to mining vehicles. That said, some of the hazards are unlikely to be sufficiently controllable even with major redesign. Therefore, reduced activity is the current primary control.

Table 1 Summary of hazards present while operating a mining vehicle in a lightning storm. (*) The normal scenario is that personnel stop work and seek shelter in a lightning storm.

Scenario or Task	Hazard from operating in lightning	Is it a reasonable probability?	Summary of Comments and Case History	Qualitative change in risk level from normal*
Normal operation of mining vehicle	Exposure to HV while sitting in cabin (Section 4.2) I.e. Direct strike, touch voltage, side flash	Yes	The vehicle chassis and metal shell are an imperfect faraday cage. Several direct strikes to mining vehicles have been reported in the past although none have explicitly reported penetration of the cabin. Nevertheless, direct strikes to the windshields are the fourth most common type of damage to non-mining vehicles.	2 Moderate increase from normal while inside the vehicle
	Exposure to HV via UHF wiring or other conductive surfaces (Section 4.3) I.e. touch voltage	Yes	The antenna is the most common attachment points for lightning. The surge protection devices are not able to absorb the full energy of lightning. Furthermore, the metal surfaces of vehicles are conductive. There are cases of injuries to people via the UHF radio or while touching the mining vehicle.	2 Moderate increase from normal while inside the vehicle
	Exposure to HV while in close quarters to vehicles (Section 4.4) I.e. flashover injury, touch and step potential voltage	Yes, however the need for an operator to leave a mining vehicle under normal conditions is low	There are several cases in mining where personnel working with severe weather present in the area was shocked by lightning up to 1.5 km away. Owing to the large area of effect, the step potential currents cause the most lightning deaths and injuries in common society. Step potential currents also kills many farm animals.	3 High/substantial increase from normal while outside the vehicle

Scenario or Task	Hazard from operating in lightning	Is it a reasonable probability?	Summary of Comments and Case History	Qualitative change in risk level from normal*
Normal operation of mining vehicle cont.	Exposure to HV while in an open area (Section 4.5) I.e. direct strike, step potential, side flash	Yes, however the need for an operator to leave a mining vehicle under normal conditions is low	Studies show that the overwhelming majority of lightning fatalities occur while outdoors and most of these incidents occur while in an exposed-unsheltered scenario.	3 High/substantial increase from normal while outside the vehicle
	Tyre rupture or explosion via pyrolysis (Section 4.6) I.e. projectiles, shockwaves, loss of vehicle control	Yes	Numerous past cases of pyrolysis of truck tyres in mining due to lightning.	3 High/substantial increase from normal
	Initiation of other fires (Section 4.7) I.e. wiring, electronics, batteries, fuel, interior furnishings, etc.	Yes	Around 9% of non-mining vehicles struck by lightning catch on fire or experience significant smoke inside the cabin (see Section 4.7). In the mining industry, there are reports of vehicles being completely destroyed by fire caused by lightning.	1-2 Low/slight to moderate increase from normal due to vehicle evacuation required.
	Driver exposed to projectiles (Section 4.8) I.e. fallen trees and branches or projectile rocks and pavement	Yes	In the mining industry, there are no reports of such injuries likely because vegetation is often cleared on such sites.	0-1 Negligible to low/slight increase from normal

Scenario or Task	Hazard from operating in lightning	Is it a reasonable probability?	Summary of Comments and Case History	Qualitative change in risk level from normal*
Normal operation of mining vehicle cont.	Hearing loss, shock and mental trauma (Section 4.9)	Yes	The probability of a lightning strike and thunder causing mental trauma or hearing loss is deemed to be similar whether the operator is in a lightning-safe shelter or in a vehicle cabin. However, if an operator is required to leave the vehicle, the risk increases slightly from normal.	0-1 Negligible to low/slight increase from normal
	Loss of electrical systems and controls leading to collision (Section 4.10)	Yes	In the mining industry, there are reports of vehicle fires and damage of electronics caused by lightning. However, the low speeds and wide roads somewhat mitigates the risk of collision caused by a loss of electronics.	0-1 Negligible to low/slight increase from normal
	Driver distraction and human error leading to collision (Section 4.11)	Yes	There are no reports of this occurring in the mining industry likely owing the low speeds and wide, clear roads that are generally present on mine sites.	0-1 Negligible to low/slight increase from normal

Table 2 Summary of hazards present while attending to an emergency in a lightning storm. (*) The normal scenario is that personnel stop work and seek shelter in a lightning storm.

Scenario or Task	Hazard from operating in lightning	Is it a reasonable probability?	Summary of Comments and Case History	Qualitative change in risk level from normal*
Operation of Emergency Response Vehicle (4WD, Ambulance, Fire truck etc)	Exposure to HV while sitting in vehicle (Section 4.2) I.e. Direct strike, touch voltage, side flash	Yes	Same as above for mining vehicles.	2 Moderate increase from normal
	Exposure to HV via UHF wiring or other conductive surfaces (Section 4.3) I.e. touch voltage	Yes	Same as above for mining vehicles.	2 Moderate increase from normal
	Exposure to HV while in close quarters to vehicles (Section 4.4) I.e. flashover injury, touch potential and step potential	Yes	Same as above for mining vehicles. Additionally, the probability of an emergency response personnel needing to leave an ERV to carry out duties is inherent higher than the need for an operator to leave a mining vehicle.	2 Moderate increase from normal while outside the vehicle
	Exposure to HV while in an open area (Section 4.5) I.e. direct strike, step potential, side flash	Yes	Same as above for mining vehicles. Additionally, the probability of an emergency response personnel needing to leave an ERV to carry out duties is inherent higher than the need for an operator to leave a mining vehicle.	3 High/substantial increase from normal while outside the vehicle

Scenario or Task	Hazard from operating in lightning	Is it a reasonable probability?	Summary of Comments and Case History	Qualitative change in risk level from normal*
Operation of Emergency Response Vehicle (4WD, Ambulance, Fire truck etc)	Tyre rupture or explosion via pyrolysis (Section 4.6) I.e. projectiles, shockwaves, loss of vehicle control	Yes	Same as above for mining vehicles.	3 High/substantial increase from normal
	Initiation of other fires (Section 4.7) I.e. wiring, electronics, batteries, fuel, furnishings, etc.	Yes	Same as above for mining vehicles.	1-2 Low/slight to moderate increase from normal due to vehicle evacuation required.
	Driver exposed to projectiles (Section 4.8) I.e. fallen trees and branches or projectile rocks and pavement	Yes	Blunt trauma was the third frequent mode of injury (approximately 27%) among non-mining incidents involving trees and lightning.	1 Low/slight increase from normal
	Hearing Loss, Shock and Mental Trauma (Section 4.9)	Yes	Same as above for mining vehicles. Additionally, the probability of an emergency response personnel needing to leave an ERV to carry out duties is inherent higher than the need for an operator to leave a mining vehicle.	0-1 Negligible to low/slight increase from normal
	Loss of electrical systems and controls leading to collision (Section 4.10)	Yes	Same as above for mining vehicles. Additionally, these vehicles are more likely to be travelling at higher speeds, on narrower roads and are probably also fitted with airbags	1 Low/slight increase from normal

Scenario or Task	Hazard from operating in lightning	Is it a reasonable probability?	Summary of Comments and Case History	Qualitative change in risk level from normal*
Operation of Emergency Response Vehicle (4WD, Ambulance, Fire truck etc)	Driver distraction and human error leading to collision (Section 4.11)	Yes	In non-mining vehicles, swerving and having a collision is a known mode of injury– in approximately 7% of cases. Additionally, emergency vehicles are more likely to be travelling at higher speeds and on narrower roads.	1 Low/slight increase from normal

Contents

PROJECT D04489-001 — REPORT

Assessing the Risk of Operating Mining Equipment During Lightning Storms

1. Introduction

1.1 Background

Mines in Queensland are currently not permitted to operate heavy machinery and vehicles outdoors while lightning is present in the area. However, Resources Safety and Health Queensland (RSHQ) is aware that some mines have recently introduced (or are proposing) amendments to their Safety and Health Management Systems to allow operations to continue during lightning events. It is contended by these mine operators that the outer metal skin of the vehicle's cabin acts like a Faraday cage and protects the operator from potential electrocution. RSHQ engaged The University of Queensland to provide a report assessing the safety risks to operators of heavy machinery and emergency response teams working during lightning weather events.

1.2 Scope of Works

The following scope of works was carried out by UQ Materials Performance (UQMP):

- Discussions with RSHQ staff to determine requirements, background, expectations etc.
- Review relevant literature on the topic of lightning strikes on vehicles and personnel.
- Review of existing industry guidelines, protocols, action plans, etc.
- Focus areas for the literature review were:
  - Effectiveness of vehicles to act as Faraday cages.
  - Any reported or simulated incidents where drivers/passengers were injured, or personnel from emergency response teams responding to emergencies during a lightning storm were injured.
  - Any published methods or studies which investigated the safety of drivers in this scenario (test methods, concepts, critical electrical parameters etc).

1.3 Purpose of this Report

This report addresses the following key questions:

- Is it safe to continue to operate a mining vehicle (e.g. dump truck, excavator) during a lightning storm?
- Is it safe for Emergency Response Teams to attend to an emergency incident during a lightning storm?

The report contains:

- A summary of relevant electrical concepts to assist non-electrical engineers to interpret the report.
- A list of the identified literature found in the focus areas listed above and a summary of the key findings.
- A discussion of the general implications based on the literature findings, addressing the key questions above.
- A discussion of any identified unknowns or where further work is required.

2. Technical Background

2.1 How Lightning Works

A simplified explanation is included below of the ionisation and charge exchange process that occurs during a lightning strike [1]:

> *Lightning is a sudden discharge of electric charges between clouds, inside a cloud or between cloud and earth. Electric discharge is caused by the disparity of charges in two locations and charge movement between these two locations help to equalize the charged sites. Lightning strike is associated with a random process of ionisation of air and therefore hard to predict.*
>
> *Due to wind in the atmosphere clouds are charged in such a way that negative charges are trapped at the bottom of the cloud and positive charges at the top. When the amount of charge trapped at the bottom of the cloud increases in the ground beneath the cloud positive charges are formed and increases.*
>
> *The negative charges in the cloud ionised the air in the vicinity of the cloud and a negatively charge channel is developed towards the earth. In each step these channels travel for 50 – 100 m. In fact, there are usually many separate paths of ionized air stemming from the cloud. These paths are typically referred to as stepped leaders. Multiple stepped leaders are formed and some of these channels are terminated on the way towards the earth. Process of forming these stepped leader channels depends on many factors such as presence of dust, moisture, level of atmospheric pressure etc.*
>
> *When stepped leader approaches the ground a positively charged streamer start to develop from the ground to air. When streamer and leader are met a high conductive channel is formed between the cloud and the ground through which charge flow from ground to neutralise the cloud. This is seen as the lightning strike. Typically, a single lightning strike is not sufficient to neutralise the charges in the cloud and therefore repeated strikes occur through the same channel. The resulting flash is both bright and incredibly hot. Air temperature in the vicinity of the lightning can reach to about 20 000 °C. Due to this heat air expand rapidly and explode. This explosion is called as thunder.*

2.2 How Lightning Causes Injury

The intense energy and the pathological features of lightning strikes are summarised by Seidl [2].

> *Typical median current associated with a lightning strike is in the range of 25 kA. As 50 mA of current through body is sufficient to create a cardiac arrest the damage that could be caused by passing the lightning current through body is unrecoverable. Therefore, lightning that travels for 10's of kms can still cause injuries and death.*
>
> *The power of lightning is estimated to be between 10,000 and 200,000A of current, with estimated voltage ranging from 20 million to 1 billion V. A strike produces an intense burst of thermal radiation of up to 30,000K within milliseconds and is accompanied by a shock wave of up to 20 atm that can contuse or perforate human organs. Electrical energy follows the path of least resistance. Because tissues that have a low water and electrolyte content have a higher resistance, tissue resistance decreases in the following order: bone, fat, tendon, skin, muscle, blood vessel, and nerve. The most important resistor to the flow of current is skin. Skin resistance varies from 1000 ohms on a sweaty palm to 1 million ohms on a dry, calloused hand. When skin is exposed to a high voltage a current can travel on the surface of wet skin without much penetration to deeper tissues. If it is raining or the person is perspiring, the water can vaporize with such force that the clothes are shredded and the shoes are blown off.*

The different mechanisms of how people are struck by lightning are summarised by the US National Weather Service [3, 4].

1. *Direct Strike*

A person struck directly by lightning becomes a part of the main lightning discharge channel. Most often, direct strikes occur to victims who are in open areas. Direct strikes are not as common as the other ways people are struck by lightning, but they are potentially the most deadly. In most direct strikes, a portion of the current moves along and just over the skin surface (called flashover) and a portion of the current moves through the body--usually through the cardiovascular and/or nervous systems. The heat produced when lightning moves over the skin can produce burns, but the current moving through the body is of greatest concern. While the ability to survive any lightning strike is related to immediate medical attention, the amount of current moving through the body is also a factor.

2. *Side Flash (In direct strike)*

*A side flash (also called a side splash) occurs when lightning strikes an object near the victim and a portion of the charge jumps from the object to the victim. In essence, the person acts as a "short circuit" for some of the energy in the lightning discharge. Side flashes generally occur when the victim is within a foot or two of the object that is struck. Most often, side flash victims have taken shelter under a tree to avoid rain or hail (*Figure 1*).*

Figure 1 Example of a side flash fatality site near a tall tree [3]

In 2011, a man took shelter under this tall tree. When lightning struck the tree, the man was killed by a side flash.

3. *Ground Current or Step Potential*

When lightning strikes an object on the ground, which is not specifically designed for absorbing lightning current, much of the energy travels outward from the strike into the ground and along the ground surface. This is known as the ground current. The current travels alone the ground creates potential difference between points on the ground surface due to the surface resistance. As a result, if the victim stands on ground closer to a lightning strike an electric potential could develop between the victims' feet. This potential is called as step potential. In some cases, step potential is high enough to drive a harmful level of current through victims' body.

Level of step potential depends on the magnitude of lightning current, ground surface resistance, thickness of the topsoil layer and distance of the foot span. Typically, lightning current through ground surface is high closer to the striking point hence could experience large step potentials if the victim stands closer to the lightning strike. Very high step potentials could be experienced when the surface resistivity is smaller (very conductive) and bottom layers of the soil have higher resistivity. Magnitude *of current passing through the body depends on the level of step potential as well as the resistance between the two contact points. Wearing high resistive shoes may sometimes help to reduce the body current caused by the step voltage.*

Because the ground current affects a much larger area than the other causes of lightning casualties, the ground current causes the most lightning deaths and injuries. Ground current also kills many farm animals. The greater the distance between contact points, the greater the potential for death or serious injury. Because large farm animals have a relatively large body-span, ground current from a nearby lightning strike is often fatal to livestock.

4. Conduction or Touch Voltage

Wires and metal objects provide low resistive paths for lightning current to travel. When lightning current is passing through these conductive objects their potential level with respect to ground potential increases substantially. If a victim touches such object a voltage develops between the tough point and the feet, which is called as the touch potential. A harmful level of current could travel through body due touch potential.

Conduction is responsible for most indoor lightning casualties. Lightning can enter a home through wires or pipes. Anyone that touches plumbing or anything plugged into an electrical outlet is at risk of being struck.

5. Lightning Back Stroke

Lighting back strokes may be considered as a subset of direct strikes. *While not as common as the other types of lightning injuries, people caught in "streamers" are at risk of being killed or injured by lightning. Streamers develop as the downward-moving leader approaches the ground. Typically, only one of the streamers makes contact with the leader as it approaches the ground and provides the path for the bright return stroke – also called back stroke; however, when the main channel discharges, so do all the other streamers in the area. If a person is part of one of these streamers, they could be killed or injured during the streamer discharge even though the lightning channel was not completed between the cloud and the upward streamer.*

2.3 Summary of Cases

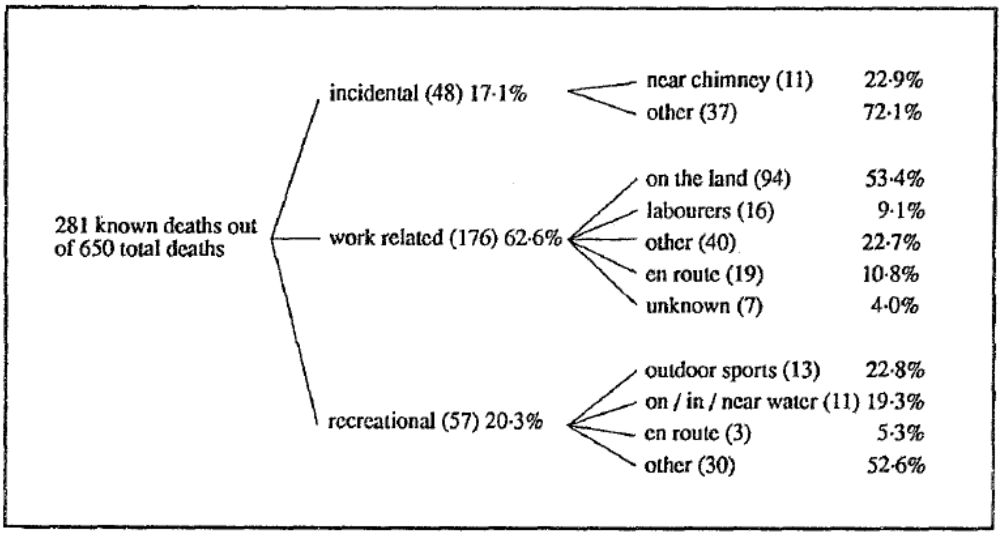
Lightning strikes cause more deaths in USA than other natural disasters, such as hurricanes, tornadoes, volcanoes, and floods [2]. Furthermore, the approximate number of lightning strike fatalities in different countries each year are summarise below:

- Australia: 5 to 10 deaths each year [5]
- USA: 20 to 30 deaths each year [6]
- Canada: 9 to 10 deaths each year [7]
- China: about 180 deaths each year [8]
- UK: about 18 deaths each year [9]

On top of the fatalities, there may be another 9 times more people injured or disabled as a result of lightning strikes [10]. Coates et al. [11] studied, the lightning fatalities in Australia and found the most number of deaths were work related and while on the land (53.4%). This is the most relevant activity category to which open cut mining pertains.

However, it is also noted that lightning fatalities are avoidable with appropriate engineering intervention. For example, an airplane may be struck by lightning on average every 1,000 to 3,000 flight hours. For a commercial aircraft, that is equivalent to one strike per aircraft per year. However, since the 1980's there have been a negligible number of fatalities in commercial flights from lightning strikes. This is due to the strict certification standards for lightning protection [12].

Figure 2 Activity of lightning fatalities in Australia at time of strike, 1824-1991 [11]



3. Existing Industry Practices and Guidelines

QLD Work Health and Safety Act 2011 [13], Clause 20.2 states:

> *The person with management or control of a workplace must ensure, **so far as is reasonably practicable**, that the workplace, the means of entering and exiting the workplace and anything arising from the workplace are **without risks to the health and safety of any person**.*

Moreover, Clause 18 states:

> *In this Act, **reasonably practicable**, in relation to a duty to ensure health and safety, means that which is, or was at a particular time, reasonably able to be done in relation to ensuring health and safety, taking into account and weighing up all relevant matters including—*
>
> *(a) the likelihood of the hazard or the risk concerned occurring; and*
>
> *(b) the degree of harm that might result from the hazard or the risk; and*
>
> *(c) what the person concerned knows, or ought reasonably to know, about—*
>
> > *(i) the hazard or the risk; and*
> >
> > *(ii) ways of eliminating or minimising the risk; and*
>
> *(d) the availability and suitability of ways to eliminate or minimise the risk; and*
>
> *(e) after assessing the extent of the risk and the available ways of eliminating or minimising the risk, the cost associated with available ways of eliminating or minimising the risk, including whether the cost is grossly disproportionate to the risk.*

This requirement, to provide a safe workplace, so far as is reasonably practical, is a similar requirement in other Australian states. The Western Australian Department of Mines, Industry Regulation and Safety has addressed the hazards of lightning in a 2-page factsheet [14]. It is the duty of the employer as part of the risk management process to:

- *identify hazards associated with lightning, assess the risk and implement control measures to prevent workers exposure to lightning;*
- *monitor the latest weather forecast and warnings and take action when required;*
- *provide instruction and training to outdoor workers on lightning risks and actions to be taken when lightning is forecasted or occurs; and*
- *develop an evacuation plan, detailing actions to be followed when outdoor work is affected by lightning.*

Regarding outdoor workers at risk of exposure to lightning, including mine workers, the following precautions are recommended when working outdoors and there is a risk of lightning [14]:

- *Seek shelter in a substantial building or a metal bodied car when the lightning-thunder gap is less than 30 seconds.*
- *Never shelter under trees.*
- *If boating or engaged in aquatic activities, head for shore straight away. If this is not practicable when on a boat deck, keep a low profile and avoid contact with or being close to masts, rails, stay wires or metallic objects, avoid unnecessary contact with communication or navigations equipment and avoid contact with water.*

- *Avoid touching, handling and proximity to metal objects that may become part of the discharge path, for example towers, mobile plant, power lines, fences and pipes.*
- *Avoid using electrical equipment, hand tools and landline telephones.*
- *Avoid handling fishing rods, umbrellas, golf clubs or any metal objects and stay clear of sheet metal, wire fences, clotheslines, streams, pools of water and so on.*
- *If caught in the open, crouch down with your feet together as low as possible with minimal contact with the ground. Do not lie down. If in a group, stay approximately three meters from other persons.*

Each individual mine may have their own Triggered Action Response Plan (TARP) for lightning which are not available to UQMP. Nevertheless, these TARPs are understood to generally include:

- Halting production when lightning is detected within a specified distance from the mine (typically 20km or 30 second delay to hearing thunder clap),
- Driving mobile mining equipment to a designated safe lay-down area,
- Transporting the operators to a safe shelter away from the equipment, and
- Awaiting the “All Clear” once lightning is beyond the exclusion distance (typically no lightning detected within 40 km for a period of 30 minutes).

These risk mitigation measures are endorsed by tyre manufacturers such as Otraco [15]. They are also consistent with other industries such as port operators [16, 17]. For example, the Lightning Response Plan employed by ports pertaining to *driving, operating earth moving equipment with ground engaging tools, operating mobile plant outdoors* involves [16]:

- *All personnel immediately seek a safe location (i.e. large buildings, offices and control rooms) and remain in place until the alert is downgraded.*
- *Suspend all out-door surface mobile plant with ground engaging tools, for example but not limited to front end loader and excavator operations.*
- *Use of wired radios in vehicles or buildings to be kept to a minimum.*

During the lightning storm, personnel at the port are to seek refuge in large buildings, offices or control rooms. However, if they cannot reach a safe location, they are instructed to remain inside a vehicle or mobile plant, if possible [16]. Furthermore, they are instructed to [17]:

> *Fold your hands in your lap and avoid touching metal components inside the vehicle. Do not operate a radio or any electrical device which is connected to the vehicle.*

This is because *there are some portions of the vehicle which current can flow through such as the vehicle’s electrical systems and metal appendages such as radios, phone chargers, GPS units, door handles, foot pedals, the steering column and the steering wheel [17].*

4. Evaluation of Vehicle Operations in Lightning

4.1 Methodology

Since each mine, vehicle and their operating conditions are unique, the level of exposure to lightning hazards will also vary with each scenario. Thus, it is not possible to carry out a formal risk assessment (e.g. in accordance with AS1768 – Lightning Protection) that describes all mines and that quantifies the absolute risk levels for each hazard.

In order for a meaningful assessment to be carried out, this report seeks to qualify <u>the change in risk</u> from continued operation in a lightning storm. That is, what hazards are present during a lightning storm and how do the risk levels change by continuing to operate vehicles. The change in risk level is described qualitatively according to the following ratings:

0 Negligible

1 Low or Slight increase

2 Moderate increase

3 High or substantial increase

The change in risk was assessed by evaluating the potential modes of injury and the case history of such injuries/near misses occurring in mining and in common society. Case history data was taken from RSHQ and NSW Resources Regulator incident database. Case histories available in the public domain were also noted.

4.1.1 Assumptions and Exclusions

It is acknowledged that every mine and mine vehicle will have a different level of exposure to lightning hazards. Nevertheless, in order for a meaningful assessment to be carried out, the following general assumptions or stereotypes are considered:

- The type of mine sites generally discussed in this report is envisaged to be a cleared, open cut mine or quarry with wide roads and negligible vegetation. The primary mining activity being considered is open cut mining, quarrying and excavation. The vehicle speeds are assumed to be relatively low.
- The type of mining vehicles being considered are primarily haul trucks, bull dozers, excavators and drag-lines.
- The type of emergency response vehicle being considered are primarily, light trucks, utes, 4WDs, vans and SUVs. In an emergency, it is conceivable that these vehicles may need to mobilise from areas outside the mine site boundary. The vehicle speeds are assumed to be relatively high.
- The risk assessments below are all in comparison to the 'normal' scenario. That is, in a lightning storm, crews are required to park the vehicle in a safe place and seek shelter until the storm passes.
- Other assumptions are detailed in the text as they occur.

Other mining activities that do not involve vehicles are excluded from the assessment, including but not limited to, blasting, long-wall mining, drilling, surveying, etc.

4.2 Overview of Hazards

In this assessment, the following hazards have been considered as a result of continued operation of a mining vehicle (e.g. dump truck, excavator) during a lightning storm:

1. Exposure to high voltage
    a. To personnel in the cabin
    b. To personnel in close quarters to the vehicle
    c. To personnel while in an open area
2. Lightning-related fire, explosion and projectiles
3. Human errors, which refers to lightning causing operator misjudgement while operating a vehicle.
4. Machine failures, which refers to malfunction of a vehicle's electrical and electronics control system due to a lightning strike.

Consequential safety risks to emergency response personnel are also considered.

4.3 Exposure to HV While Sitting in Cabin

4.3.1 Background

A familiar example of the Faraday cage effects is the *door of a microwave oven with its metal screen with holes. The screen keeps the microwaves from getting out while allowing light, with its much shorter wavelength, to pass through. Science museums sometimes dramatize the effect with electric sparks, as illustrated in Figure 3 [18].*

Figure 3 Dramatization of the Faraday cage effect, taken from Ref. [18]

Reference [19] provides a clear explanation of what is a Faraday cage:

> *In [Michael] Faraday's original studies and experiments regarding charge, magnetism, and their interaction, he found that charge on a conductor only resided on the outer surface. Furthermore, Faraday discovered that nothing inside that conductor was affected by any change in electrical charge on the outside. Later, field theory was based on Faraday's work, and he did believe, contrary to the accepted view at the time, that an electric field extended into space beyond a charge. Having somewhat better understanding of things now, we know that the electrostatic repulsion of like charges causes a redistribution of charge to the outside of a conductor* ***resulting in a net electrostatic field within the conductor of zero****. "Within the conductor" means any space enclosed by a* ***continuously*** *conducting layer.*

It is understood that this is the basis by which certain mining operators are contending the continued use of vehicles in an electrical storm. That is, the outer metal skin of the vehicle's cabin acts like a Faraday cage and protects the operator from potential electrocution.

4.3.2 Mode of Injury

Direct strike

It is well-known among electrical and electronics engineers that a Faraday cage can also be used to reduce noise while neutralising electric charges created by an electromagnetic field. One example of these applications is EMC (electromagnetic compatibility) tests for industrial and commercial equipment in a NATA lab. According to test requirements, such as the frequency range and energy level parameters of the equipment under testing, some Faraday cages are designed with mesh metal wires or metal sheets with punched holes which are used for routing wire or cable through, as well as for observation purposes. Certain frequency of signals can escape through these holes, especially when the energy level is extremely high with these frequencies; therefore, the mesh hole sizes must comply with test requirements. A general rule of thumb is that the opening in a Faraday cage should be smaller than 1/10th of the wavelength to be blocked. For example, in order to block EM fields with frequencies of 10 GHz and lower (wavelength = 30 mm), the hole size of the Faraday cage should be smaller than 3 mm.

It is well known that lightning strikes are associated with ultra-high energy. Another characteristic of the lightning strike is that its energy, in terms of discharge current, has a very wide frequency range. According to Rakov [20], lightning is known to emit significant electromagnetic energy in the radio-frequency range from below 1 Hz to near 300 MHz, with a peak in the spectrum near 5 to 10 kHz for lightning at distances beyond 50 km or so.

For a lightning strike that contains significant energy in the 100 MHz frequency (wavelength = 3 metres), the hole size should therefore be smaller than 30cm (like the windows on passenger planes). Windows in most ground vehicles are bigger than half a meter (50cm), and can be significantly larger in mining vehicles. Therefore, <u>most ground vehicles are imperfect Faraday cages and there is the potential for lightning to strike objects inside the vehicle, especially through large non-conductive areas (e.g. windows).</u>

Based on the above facts, it is believed that lightning striking the driver inside the vehicle is a reasonable possibility, especially in vehicles with large windows. The windows do not need to be open for this risk to exist, however if vehicles are operated with the windows open this would further increase the risk to the operator. If the driver is operating the steering wheel, brake pedal, gear handles, actuating levers or other devices containing metal connected to or near the outer shell this will further increase the risk (as discussed in section 4.3).

Touch Potential

A vehicle's body consists of an imperfect conductor. As extremely large current passing through the imperfectly conducting metal body in the event of a lightning strike, the impedance of the metal shell will create a large hazardous touch potential.

An example of touch potential shock is if a person has one hand rested on a vehicle's metal surface (e.g., edge of a door near the window) and their other hand touching (or near) exposed metal on a steering wheel or hand brake. In this case, the lightning strike will use the person as a conductor to dump the energy in the discharge process, in which current flow will be adequate to cause fatal electric shock. *A current of as little as 0.007 amps (7mA) across the heart for three seconds is enough to kill. A current of 0.1 amps (100mA) passing through the body will almost certainly be fatal [21].*

The point of contact of a lightning strike to a vehicle may be very close to the metal frame of doors or windows, as these points represent discontinuity gaps in the vehicle's metal surface, where electrical fields can be much greater than the average value on the metal body surface. Therefore, touch potential is one of the largest risks for the operator when lightning strikes a ground vehicle.

<u>During a lightning event, an operator touching or near to a vehicle's windows is at risk of a touch voltage shock</u> or side flash hazard, which is described below.

4.3.3 Case History

An example of a lightning strike occurring through the windshield has been documented in the public domain [22]. According to the report, the unoccupied car (Ford Super Duty) was struck while parked at a dealership in Michigan, USA. The lightning strike appears to have first struck the windshield before passing through into the dashboard below the windshield where gross localised melting of plastic was observed.

Figure 4 Photographs of an apparent direct lightning strike to the windshield of a stationary utility vehicle, Ford Super Duty [22].

(a)

(b)

(c)

Holle [23] characterised the different types of damage sustained to non-mining vehicles struck by lightning in North America. "Broken, flying or etched glass" was found to be the fourth most common type of damage to vehicles (see Figure 15, page 40).

The cases of mining vehicles that were apparently struck directly by lightning in NSW and QLD are summarised in Table 2 although none have explicitly reported HV penetration of the cabin. It is noted that these cases ostensibly did not lead to any injuries and the vehicles in many cases were unmanned.

Table 3 Cases of direct lightning strikes to mining vehicles or mobile plant in NSW and QLD

Date and location	Vehicle Type	Incident details	Source
18/10/2021; Meandu Mine, QLD	Hitachi EH5000 Rear Dump	RSHQ HPI#148373: *Suspected lightning strike of rear dump truck parked on go-line 150m away from CMWs in cribhut. CMWs saw lightning and heard thunder very close by while in the Crib Hut during a wet weather TARP. The OCE and shift supervisor were contacted. Mine Control was asked to review the CCTV footage. The footage suggested that lightning had struck a parked, <u>unoccupied</u>, rear dump truck. Preventative action: The CMWs were retrieved from the crib hut and the Go-Line was isolated with an exclusion zone for 24 hours. After 24 hours of monitoring …the tyre fitters inspected the tyres/truck for heating and damage… No evidence of a strike was found. Hazard description: No unidentified Hazards were identified as a result of this event*	RSHQ
5/03/2020; Rolleston Mine, QLD	130t Link-Belt Mobile Crane	RSHQ HPI#144631: *Lightning Strike 135t Link Belt all terrain crane. A rain event passed over Rolleston Coal mine in the evening of Thursday the 05/03/20. A CMW was at the warehouse at approximately 1900hrs when he witnessed the potential event occurrence. The Link-Belt 135t all-terrain crane was parked at the hardstand (approximately 300m from the warehouse), with the boom elevated in the air. The CMW has stated he saw sparks directly after a lightning strike in the vicinity of the crane. Preventative action: Develop mobile crane park up standard - investigate crane park up process to reduce risk of equipment damage from lightning strikes.*	RSHQ
22/01/2020; Dawson Mine, QLD	Cat D11R Dozer	RSHQ HPI# 144525: *Fire on TD27; Dozer was parked upon during rain event. Appear that the dozer has been struck by lightning which has caused the dozer to completely burn as no personnel were in the vicinity*	RSHQ
14/12/2018; Cameby Downs Coal Mine, QLD	DT109 1500 Komatsu haul truck	RSHQ HPI#141000: *DT109 struck by lightning while <u>unmanned</u> and parked at in pit go line; Lightning and or storms had not been triggered in the area when an operator on a grader in the area reported to the OCE that a lightning bolt had struck a parked haul truck that was unmanned; need to improve the alert of a rough storm, lighting event in the area. As a result in the process of arranging for an AP lightning alert in area to be installed on OCE phone. Preventative action: Severe weather TARP reviewed. IT looking to arrange new support AP on OCE phone for lightning warnings in area.*	RSHQ

Date and location	Vehicle Type	Incident details	Source
3/12/2018; Kestrel Coal Mine, QLD	Reclaimer and 80t crane	RSHQ HPI#140783: *A Storm had passed to the North of the plant, and it is believed that lightning may have struck the Product Reclaimer RCR03 or the 80 tonne crane working on the reclaimer or has struck somewhere in that area causing an electric shock. Preventative action: Grounding of cranes when potential storm conditions exist.*	RSHQ
5/11/2015; NSW	Dump truck	*Suspected lightning strike of dump truck - as a precautionary measure the site was evacuated of non-essential personnel.*	NSW Resources Regulator
14/11/2010, NSW	Excavator	*Excavator caught fire, hit by lightning. The unmanned machine was destroyed by the fire.*	NSW Resources Regulator

4.3.4 Overall Evaluation and Change in Risk Level

It is a misconception that a driver is 100% safe while staying in a vehicle during lightning storms because the vehicle's metal body is an imperfect Faraday cage. A metal shell with charges distributed on its surface is not safe for a person to be near it when the charges are not neutralized. For effective lightning strike charge neutralization, a solid ground path for absorbing the large amount of energy from a lightning discharge with minimum resistance is required. A good lightning protection system usually consists of designated air terminations (i.e. lightning rods) as well as a good ground path, as discussed in AS1768:2021 [24].

A vehicle's metal shell is not a perfect conductor, and it has no good earth ground connection (through tyres); therefore, it is not an ideal faraday cage for lightning protection.

When a vehicle attracts a lightning strike, it absorbs energy from an unpredictable spot, discharges through the metal shell and passes it to the ground via the tyres or nearby air. In most instances, insulation of air or tyres breaks down and causes back strokes which create dangerous situations for vehicle operators [25].

A person is safe if they remain in a Faraday cage; however, most vehicle metal bodies are not perfect Faraday cages. Therefore, it is not 100% safe to use them as a shelter for lightning storms. However, it is relatively safer to stay in a vehicle compared to remaining outside when an alternative, safer shelter cannot be found. A safe shelter for lightning storms is a place which has been designed with lightning protection systems as required in industrial standards, such as AS1768:2021 [24].

The case history has shown that lightning strikes to mining vehicles do occur albeit infrequently. The general approach of leaving vehicles unmanned in designated lay-down area during a lightning storm has thus far avoided injuries and death. However, there is a moderate increased risk of a direct strike or side flash to an operator while in the cabin if this approach is abandoned. Moreover, as discussed later, the risk of injury or death from tyre pyrolysis and explosion and other mechanism are another significant consideration.

4.4 Exposure to HV via UHF wiring or other conductive surfaces

4.4.1 Mode of Injury

Most lightning strike comes with multiple strikes, including an initial flash and back strokes. These strikes can cause various and mostly permanent damage to the insulation material, even to properly designed lightning protection systems.

When lightning comes into contact with a vehicle, it tends to attach at the point where the lowest impedance to earth is. These attachment points can be the vehicle's metal surface, where there is higher density of opposite electrical charges to the incoming charges behind the stepped leaders. For a cloud to ground lightning strike, the charges in the cloud are normally negative and therefore the charges on the vehicle's surface are positive.

One of the common attachment points is the UHF or VHF antenna installed on the vehicle, which is used for voice communication channels like CB radios or for data telemetry purposes. The antenna is either a vertical elevated radial rod or an extruded shark fin module. Although they are moulded over with insulation material, they are still a likely point for major lightning strikes to break down. For this reason, lightning surge protection devices (referred as lightning arresters) are commonly fitted between the antenna input and the vehicle's chassis. As their names imply, these devices are supposed to absorb the energy and route hazardous current flow through the vehicle's metal body if lightning strikes the antenna. The arrester uses a gas-filled gap that acts as an open circuit to low potentials but becomes ionized and conducts at very high potentials. Thus, there is some protection if the lightning hits the line; the gas gap will conduct the current safely to ground.

When a lightning arresters work properly, the hazardous energy or current is routed to the vehicle's chassis and then flows to earth through tyres or air, which protects radio electronics systems as well as the occupants and drivers. As a ground vehicle has no solid and reliable ground connection (with low impedance which capable of absorbing large lightning discharge current), there will be a large voltage and current surge can be created on the vehicle chassis when lightning discharge through the vehicle. In this scenario, surge protection devices will absorb the energy to protect the human as well as electrical system.

All lightning arrester and SPD have their service life cycle, which can be reduced greatly for a vehicle working in opening lightning storms with no servicing. When they are out of service or damaged by a major lightning strike, the operator, if using the handheld radio, could be exposed to a direct lightning strike(s), as they can be in the lightning discharge path if their body impedance is lower than the non-functional SPD to the vehicle's metal shell.

When this happens, antenna cables usually induce a high inductive voltage that breaks down the insulation layer between the radio speaker and the driver's hand; the lightning discharge current will then pass through the operator to another end of the connection, such as the other hand on a steering wheel or feet on a brake, then finally to ground.

More details regarding the SPD failure mode are discussed in section 4.10.

4.4.2 Case History

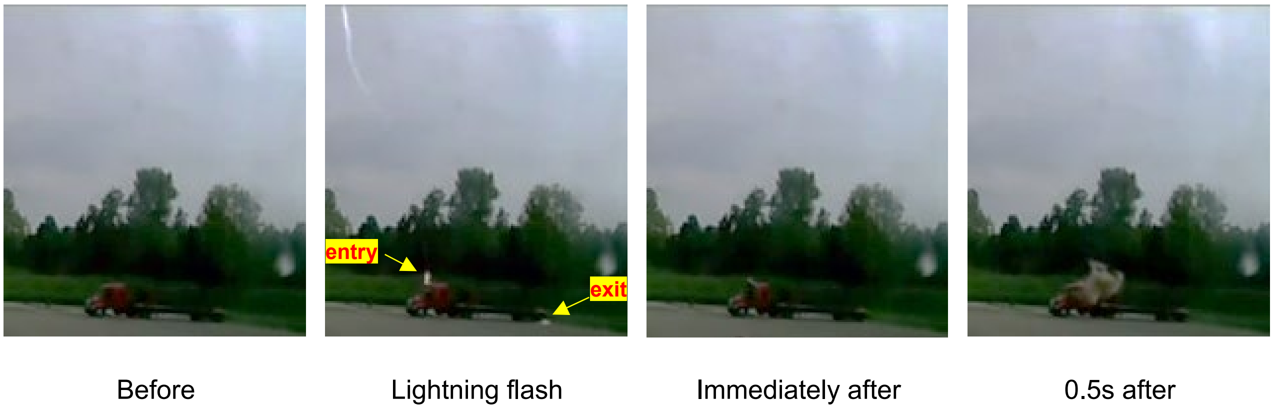
The cases of electric shock to NSW and QLD mining personnel in contact with vehicles and conductive surfaces during a lightning storm are summarised in Table 3. It is noted that the cases had a common preventative recommendation – to stop work during a lighting event.

Table 4 Cases of lightning shock caused by UHF wiring or other conductive surfaces in the NSW and QLD mining industry

Date and location	Vehicle Type	Incident details	Source
3/02/2022; Zappala Quarries, QLD	Terex TC1150 Cone Crusher	RSHQ HPI#148984: *While clearing rocks from a blocked cone crusher lightning strike on mountains behind crushing plant. Operator was touching metal hopper at time and felt an electric shock through his body. Preventative action: Carry out take 5; No manual work to be permitted in adverse weather conditions*	RSHQ
22/03/2017; Newlands Open Cut, QLD	BE1370 Walking Dragline (DL01)	RSHQ HPI#136558: *Lightning struck Dragline with two contractors in contact with structure; - 2x CMW's taking shelter from rain underneath the house, touching structure of the Dragline. - Inclement weather (Storm activity) - Lightning suspected to have struck Dragline affecting 2x CMW's; Servicing DL01 completed. Personnel waiting to be mobilised delayed due to inclement weather. Lightning TARP not followed. Preventative action: All site personnel to be familiarised with the requirements and responsibilities of the Lightning TARP.*	RSHQ
17/01/2007	Mobile crushing plant	*While beneath a mobile crushing plant removing jammed material with a 1 meter bar, lightning struck the mobile plant and the victim received shock injuries. 4 other persons were exposed in the vicinity.*	NSW Resources Regulator

Lightning strikes to the antenna are the most common type of damage to non-mining vehicles from lightning (see Figure 15, page 40). Further examples of lightning strike to non-mining vehicles have been reported in the public domain. This includes a video of a truck that was struck by lightning while parked at a truck stop [26]. The incident occurred in South Carolina, USA on 1 August 2012 and was captured by another truck's dashcam. The lightning is believed to have struck the trucks front antenna and then travelled through the driver's shoulder, out the back of his left arm and then grounded at the back of the trailer (see Figure 5). The driver survived with some minor burns. The truck would not start and almost all internal electronics were burnt out.

Figure 5 Frame captures of a lightning strike to a truck, taken from Ref. [26].



4.4.3 Change in Risk Level

Electrical theory supports the claim that a vehicle operator can be struck by lightning due to contact with a UHF radio or other conductive device/surface during a lightning strike. This was further supported by documented cases of operator injuries or near misses in these scenarios. Therefore, if a mine site continues operation of vehicles during a lightning storm, a moderate increase in the risk of electric shock from a lightning strike via contact with UHF wiring or other conductive surfaces will occur.

4.5 Exposure to HV while in close quarters to vehicles

4.5.1 Mode of Injury

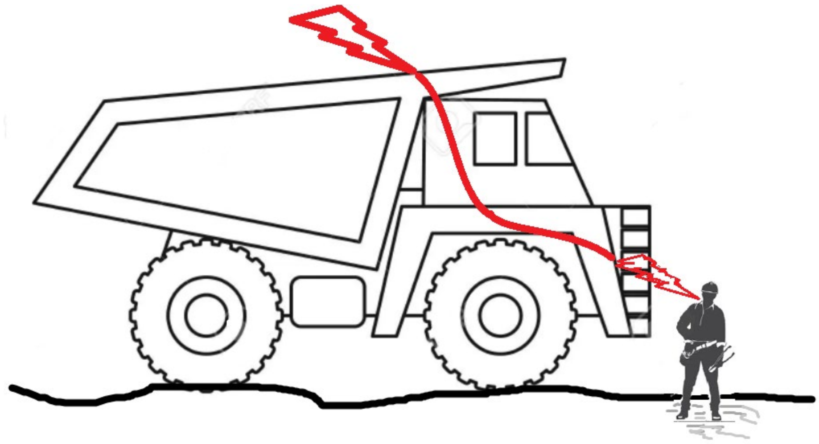
In addition to tyre explosions discussed later in Section 4.6, there are further potential electrical hazards when personnel are outside and close to the vehicle.

- Touch potential is when a person touches an electrified object that has higher potential than the other part of the person, normally the ground potential.
- The step potential is when a person stands or walks on a ground or surface that carries electric current.

The person can also be subjected to side flash if lightning strikes the vehicle. As shown in Figure 7, a side flash can occur when a person is in close proximity to the vehicle. This can occur even if the operator is not touching the vehicle. The lightning strike hits the vehicle and then breaks down the air gap between the vehicle and the person. This happens when the electrical resistance of the tyres-to-earth path is larger than the resistance of the air gap-to-human-to-earth path. The electrical resistance of a human is normally between 1 to 10 kOhms. It is judged likely that the resistance of a mine tyre could be considerably larger than that of a human, especially if the soil under the tyre is drier than that the location where the person is standing (e.g. due to rain). Therefore, it is quite possible that person in close proximity to a vehicle which is struck by lightning, could be exposed to a side flash.

The resulting voltage applied on the person would be similar to the scenario where they are touching the vehicle, however, flashover events (i.e. electrical discharge through air) are more likely to cause skin burns on exposed parts such as the face and hands.

Figure 6 Illustration of a side flash injury mechanism via the vehicle



Touch and Step Potential shocks

Lightning striking a vehicle is equivalent to, or much worse than a serious electrical ground fault (e.g. contact with overhead power lines), when a huge current 1 to 200kA flows through a vehicle's metal shell and tyres to the ground. All ground faults can inevitably introduce step and touch potentials. Huge ground current induces excessive dangerous potential on the object it passes through as well as ground potential lift to higher local voltage than ground potential. Therefore, in addition to flashover injury, people who are working on or near the stricken vehicle can be severely injured from electric shock.

This is especially true (and complex) as vehicles normally have no solid safety ground connection. A safe ground termination ensures lightning currents pass through a relatively low impedance path to ground. Vehicle shells are made of steel, and steel is not a good conductor (in contrast to copper) especially when it is coated with paint; the tyre is made of rubber, which is a poor conductor compared to metal or a human.

Touch potential occurs when a person touches a charged metallic object, causing a current to flow through their body to the ground. When the person touches a vehicle hit by a lightning strike, the person would be subjected to touching voltage. This is indicated in Figure 8, which shows the lightning current flowing from top of the vehicle, through the vehicle's metal shell, to the human body, then to the ground (following the red line). With 1kA lightning discharge current, according to Ohm's law, the person would suffer from a shock voltage of 50MVpeak, assuming that resistances for the metal shell, human body and shoes are 50Ohm,1kOhm and 1kOhm. The voltage is enormous, >1MegaV, which is lethal to the person.

Figure 7 Illustration of a touch potential injury mechanism

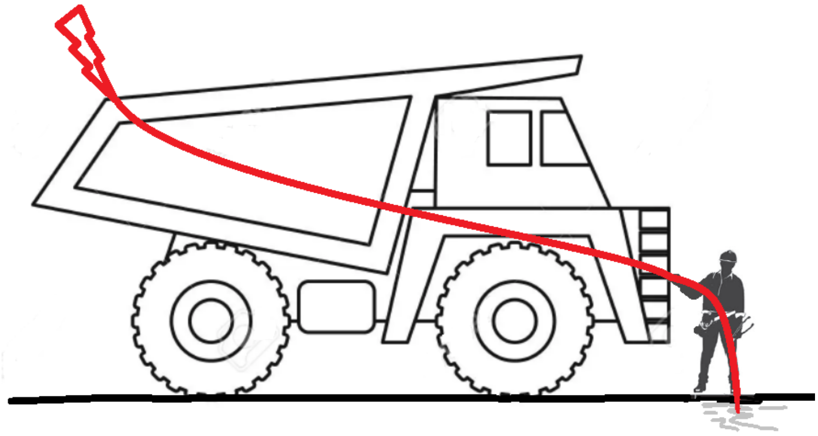
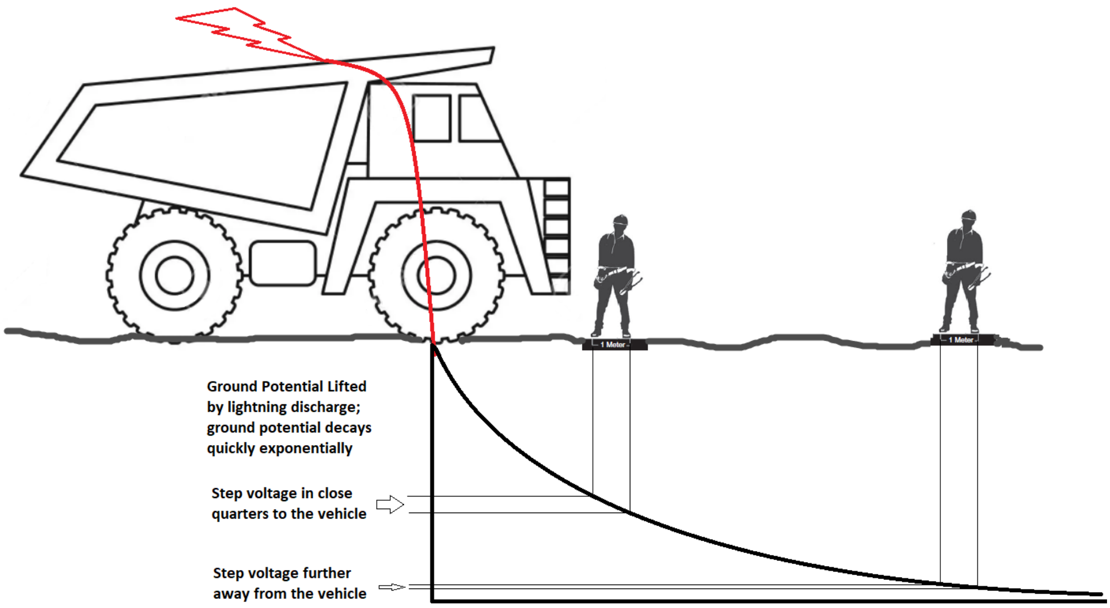


Figure 9 illustrates a step potential injury mechanism that may occur in the ground near a vehicle struck by lightning. According to Ohm's law, voltage induced on the ground is dependent on the earth resistance at that location. If a person is standing nearby the vehicle, the voltage gradient may be significant such that the distance between their feet is able to span an appreciable voltage drop. This in turn facilitates a potentially lethal level of current to flow through their body. However, the step potential reduces rapidly as it decays exponentially from the point of current input into the ground. Thus, a person a long distance away (>100 m) may have a non-lethal voltage drop between their feet [27].

Figure 8 Illustration of a step potential injury mechanism



4.5.2 Case History

The suspected cases of electric shock to NSW and QLD mining personnel from a step potential mechanism are summarised in Table 4. The Gregory Crinum Coal Mine is of particular interest as a step potential was experienced despite the lightning strike occurring approximately 1.5 km from personnel. Had the severe weather TARP been initiated the incident would have been avoided. Similarly, the incident in NSW on 11/12/2014 with boom-type concrete pump also experienced a step potential when lightning stuck approximately 1 km from the vehicle. Both of these incidents demonstrate the wide proximity that a lightning strike can create an adverse step potential.

Table 5 Suspected cases of step potential shock while personnel were close to lightning strikes in the NSW and QLD mining industry

Date and location	Vehicle Type	Incident details	Source
21/02/2020; Gregory Crinum Coal Mine	Terex MT4400 DT05	RSHQ HPI#144357: *CMWs reported feeling an electric shock following a lightning event. Two (2) CMWs were conducting maintenance activities on a Terex MT4400 DT05 on the 21st February 2020 within the hardstand area of the Gregory Mine Workshop. The hardstand area is immediately adjacent to the workshop and is not undercover. There was a storm approaching the area at the time and the CMWs were using a mechanical torque tool to torque up the lower service brake calliper mounting bolts. The CMWs reported feeling a mild tingling sensation, one CMW through their lower hands and the other CMW through their upper arms while utilising the torque tool. … At the time of the incident, a lightning storm was approaching the work area. The investigation team determined that the closest lightning strike recorded at the time of the event was approximately <u>1.5km from the work area</u>. …Technical advice sought by the Investigation Team identified that this event is likely the result of the indirect effect of a lightning strike. A lightning strike 1.5km away is unlikely to give rise to step and touch potentials issues for current dissipated through the ground alone. There is a possibility that the voltage was transferred from the lighting strike location to where the two personnel were (via pipes/conveyors etc), causing a touch potential large enough to give a tingling sensation. … If the TARP had been initiated, level three trigger conditions would have seen all CMWs moved to a safe location if lightning activity occurred within 0-15km of the mining lease… The Severe Weather TARP has failed to work as intended to ensure all CMWs are moved to a safe location during a lightning event.*	RSHQ
11/12/2014; NSW	Boom type concrete pumpers	*Site was monitoring lightning activity in area, and had initiated lightning procedure when strikes were recorded within 10kms of site, instructing all booms to be lowered. Six boom type concrete pumpers were in operation at the time. The workers involved were holding the hose while the boom was being flushed prior to lowering, when lightning struck at a point approximately 1km from the site. Both workers reported immediately that they felt a shock at the time the lightning struck.*	NSW Resources Regulator
28/3/2014; NSW	NA	*Approaching storm clouds caused geophysical surveying team to cease work and while packing up equipment one technician received an electric shock. The generator had already been switched off and the induction loop disconnected at the generator. While walking with the down-hole probe in hand, with in-excess of 40 metres of connected signal lead laid out on the ground, a lightning strike occurred overhead and the technician felt tingling in hand and arm.*	NSW Resources Regulator
12/11/2013; NSW	NA	*Electric Shock caused by a lightning strike hitting our overhead 11kv aerial system and transferring to ground through the earth system causing step / touch potential.*	NSW Resources Regulator

Date and location	Vehicle Type	Incident details	Source
8/01/2012; NSW	Haul truck	*Lightning strike near the haul truck go line*	NSW Resources Regulator
1/09/2011; NSW	Unknown	*Three exploration drillers were leaving a drill site when a lightning strike occurred approximately 10 metres from the vehicle.*	NSW Resources Regulator

4.5.3 Change in Risk Level

Currently, a mine site equipped with appropriate weather monitoring and a "stop work, seek shelter" severe weather TARP will have a negligible risk of step potential injuries. By continuing operation of vehicles in a lightning storm, the risk of touch and step potential voltages and flashovers is an important consideration if an operator needs to leave the vehicle. That is, there will not be a step potential current path if an operator is not touching or standing on the ground. However, the change in risk level of such injury is deemed to be high/substantial if operators are required to leave the vehicle. For example, at a change of shift, during pre-start checks, while refuelling, during regular maintenance, while opening/closing gates, while securing loads, etc.

Similarly, emergency personnel required to leave their vehicles will be exposed to a high/substantial change in risk level due to a step potential shock from a lightning strike in the area. These personnel have a higher likelihood of needing to leave the vehicle to carry out their duty.

4.6 Exposure to HV while in an open area

4.6.1 Mode of Injury

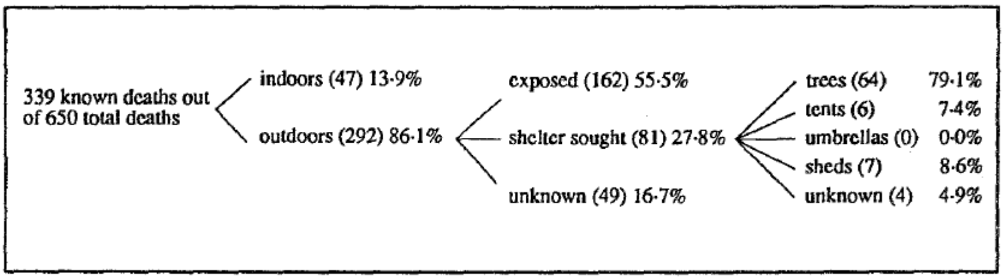
When a person is a long distance away from a vehicle, the risk of a direct strike is significant (Figure 10). Step potential and side flash injuries, as discussed above, are also a possibility if a person seeks shelter near a tree, power pole or some other unsuitable shelter.

Figure 9 Illustration of a direct strike injury mechanism

4.6.2 Case History

An outdoor, full exposed scenario is where most lightning injuries and fatalities occur in Australia. Figure 11 shows that the overwhelming majority of fatalities occur while outdoors (86.1%) and most of these incidents occur while in an exposed-unsheltered scenario (55.5%). For this reason, this scenario is considered the most hazardous – more hazardous than taking shelter in a vehicle.

Figure 10 Whereabouts of lightning fatalities in Australia at time of strike, 1824-1991 [11]



4.6.3 Change in Risk Level

Mine sites in Queensland generally have "stop work, seek shelter" TARPs for severe weather events. This prevents a person from being in an outdoor exposed environment during a lightning storm. However, if there are changes to existing protocols that require personnel to work outside of a vehicle or shelter during a lightning storm, then the change in risk of injury or death is deemed to be high/substantial.

Similarly, emergency personnel required to leave their vehicles or shelter during a lightning storm will be exposed to a high risk of a direct lightning strike. These personnel have a higher likelihood of needing to leave the vehicle to carry out their duty.

4.7 Tyre Rupture or Explosion via Pyrolysis

4.7.1 Background

When a vehicle is struck by lightning (or comes into contact with high voltage power lines), a current path to the ground via the tyres or the rims is often established. The energy from this event is capable of causing tyre rupture or explosions by a process broadly known as "pyrolysis"; although the pyrolysis reaction is just one of a number of chemical reactions and degradation processes that lead to the final failure event.

Tyre pyrolysis is now a well-known phenomenon in mining and has been comprehensively reviewed and summarised by RSHQ [28, 29] and other safety regulators [30, 31]. Lightning strikes are just one of a number of known causes. In brief, after a lightning strike, the hot spot created by the current path in the tyre or rim initiates exothermic degradation reactions in the rubber tyre or inner tube; some of which can proceed apart from oxygen. These chemical reactions produce heat which in turn causes gas expansion. However, more significantly, the degradation reactions produce several gases such as *steam, carbon dioxide, carbon monoxide, carbon black, oil and a <u>mixture of volatile, explosive vapours</u> including methane, hydrogen and a number of hydrocarbons [32]*. In some scenarios, *it has been calculated that the chemical degradation of only 20g of rubber produces enough gas to reach the standard blowout pressure of tyres [33].*

Thus, tyre rupture is one possible outcome of tyre pyrolysis. However, a tyre explosion is another possible, more severe outcome which will occur when the mixture of flammable gases with oxygen reaches a critical concentration and the auto-ignition temperature is reached [33]. Such an explosion can occur even after the heat source has been removed or sometimes long after the lightning strike, since the chemical reactions involved are highly exothermic [33]. Moreover, depressurising the tyre after pyrolysis has initiated does not remove the risk of an explosion [15]. Such an explosion may generate shock waves and pressures of about 7 MPa [33].

Pyrolysis-related explosion and ruptures are unpredictable due to the rapid, autocatalytic, run-away exothermic degradation reactions that take place. Due to the kinetics of the pyrolysis degradation reactions, a delay between the initial lightning strike and the final tyre explosion is possible. Most lightning strikes cause tyre failure immediately, however, t*here are records of large tyres having catastrophic air loss up to 21.5 hours after electrical contact as a result of pyrolysis [34]*. Notably, a delay of a few minutes seems to be the deadliest since this is the time period when unaware crew or operators are carrying out a close inspection of the vehicle and tyres.

4.7.2 Case History

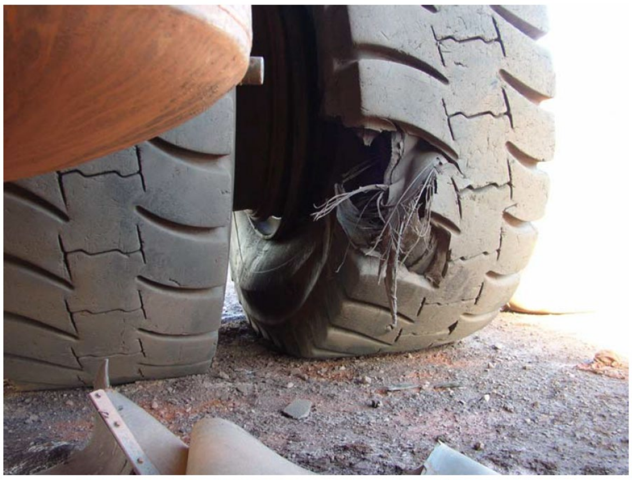
There are numerous past cases of pyrolysis in mining or truck tyres due to lightning (Table 5). Notably, a common outcome of a tyre explosion or rupture is gross projectile damage of surrounding structures and equipment. Some fragments were reportedly propelled up to 300 m. Moreover, the truck operator is not necessarily safe from injury even while in the cabin, as shown in Figure 12c, where the windshield was found to have been blown outwards due to the shockwave.

Table 6 Examples of tyre pyrolysis incidents caused by lightning strikes

Date and location	Vehicle Type	Incident details	Source
2004; Pilbara, WA	Terex/Unit Rig MT4400 haultruck	On April 10 2004, the incident haultruck was found, after a lightning storm at Pilbara Iron's Hamersley Iron Channar minesite, with a catastrophically failed outside rear tyre (40.00R57 size) and severe damage to the truck. The truck has been parked (in an outdoor lay-down area) because of the impending lightning activity and the operator had been taken to a safe area until the storm had passed. No one was injured in the incident. When an operator returned to the truck three hours later, the operator found that the position 3 (left outside rear) tyre had failed catastrophically (Figure 12a) and that severe damage had been caused to the truck – including damage to the main hydraulic tank (Figure 12b), the operator cabin (Figure 12c), the walk-platform over the engine (Figure 12d), and other areas. Subsequently, while the truck was being repaired and undergoing further examination, damage to the electrical wiring and circuitry components was discovered. It was also found that the inner liner of the failed position 3 tyre had undergone extensive pyrolysis. The inner liner of the position 2 (right front) tyre had also suffered pyrolysis, although not as severely as for the position 3 tyre, and had not failed.	[15]
Unknown	Caterpillar 777F haultruck	The four rear tyres blew out immediately (see Figure 13). The left rear out tyre was propelled 250 m and the wheel 300 m.	[34]
1987; Ipswich, QLD	Caterpillar 777 haultruck	The tyre exploded after lightning struck the truck.	[15]

Date and location	Vehicle Type	Incident details	Source
1989; Pine Creek Mine, NT	Caterpillar 773 haultruck	According to eyewitnesses, the tyre exploded at the same instant that the truck was struck by lightning. The tyre, bead seat band and lock ring were reportedly propelled 45 m, 40m and 70 m from the truck, respectively. The projectiles caused significant damage to the nearby equipment and structures. A section of the liner in the incident liner was pyrolyzed. Two other tyres also suffered pyrolysis of the inner liner.	[15]
2008, NSW	Large rear dump truck	*A large rear dump truck (RDT) was struck by lightning while stationary and unattended (Figure 14). No employees or personnel were injured.* *Three tyres were blown off the truck between 2 to 5 minutes after the lightning strike. Two tyres exploded (position 1 and 3 tyres) on the driver's side of the truck, sending debris several hundred metres from the vehicle and causing extensive damage to the truck and other equipment. One complete wheel base (weighing 1.6 tonnes) was thrown about 100 metres from the truck. A solid wheel flange (weighing 250kg) was thrown to the top of the stockpile about 275 metres from the truck. The air blast and shock wave caused damage to the operator's cabin, other equipment and buildings up to 230 metres from the truck. The tyres were ejected and finished between 50 to 60 metres from the truck.* *The operator's cabin windscreen of a water truck parked 20 metres from the incident truck was blown out.* Several other nearby building windows and windshields were also broken.	[35]
2018, WA	Large rear dump truck	*An unloaded autonomous truck was ascending a ramp when it was struck by lightning. The strike caused the position 2 tyre (front right) to explode, resulting in extensive damage to the upper structure of the truck including the deck, autonomy cabinet, engine and cab. No workers were injured.* *Preliminary findings from a tyre specialist concluded that the explosion was caused by extensive pyrolysis (chemical decomposition by heat). There was no pre-existing tyre damage that contributed to the event.*	[36]
2020, Lake Vermont Mine, QLD	Liebherr T282C Rear dump truck	*A severe weather storm converged on the mine operations. Lightning strike to a Rear Dump Truck. Pos- 5 Tyre failed as a result of the strike. The tyre failed due to rapid gas expansion by the pyrolysis. The failed tyre impacted on nearby crib huts where CMWs were sheltered from the storm. Significant damage occurred to the crib huts and minor injures recorded for a group of CMWs.*	RSHQ HPI# 146440

Figure 11 Photographs of tyre explosion after lightning strike in Pilbara, WA in 2004 [15].



Exploded position 3, left outside rear tyre *(note torn mud-flap in foreground)*

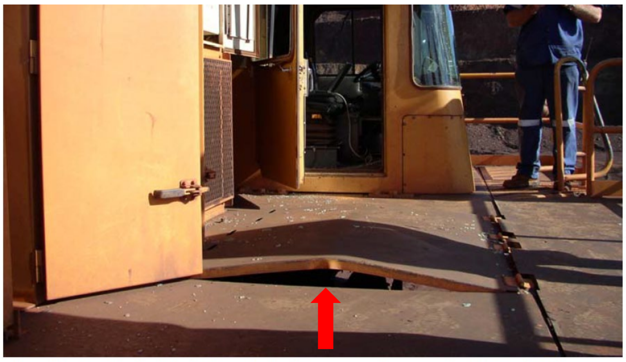
(a)

Damaged hydraulic tank & blown-off left wheel cover *(the right side wheel cover was also blown off)*

(b)

Damaged driver's cabin *(note outwardly deformed windscreen & rear window)*

(c)



Buckled walk-platform *(note blown-open doors on electrical cabinet)*

(d)

Figure 12 Photographs of tyre explosion after lightning strike [34]. Unknown incident date and location.

Figure 13 Photographs of tyre explosion after lightning strike in NSW in 2008 [35].

(a) Incident truck

(b) Truck and debris

(c) Tyre side wall from position number 1

In non-mining vehicles, a significant number of tyre failures as a result of lightning strikes have been reported. Holle [23] characterised the damage to non-mining vehicles in 76 incidents reported in North America (see Figure 15). Flat tyres were the third most common type of damage that was reported in 14 vehicles (18%). However, it is unclear from the statistics what percentage of the tyres merely ruptured and what proportion of tyres exploded from pyrolysis.

Figure 14 Damages to fully-enclosed metal-topped vehicles with people inside them from a sample of 76 incidents reported in North America. Some events had more than one type of damage [23].

Damage	Events
Antenna	**20**
--Destroyed	*9*
--Hit	*7*
--Damaged	*4*
Electrical System	**17**
--Destroyed	*9*
--Damaged	*8*
Tire(s) flat	14
Broken, flying, or etched glass	13
Engine stopped or racing	13
Burn marks on exterior	10
Smoke inside vehicle's passenger cabin	9
Pavement damaged	7
Radio/CD player destroyed/damaged	7
Caught fire	4
Airbags deployed	3
Tree or utility box fell on vehicle	3
Stuck horn	2
Total loss of vehicle	2
Air conditioner stopped	1
Battery failed	1
Brakes died	1
Cruise control and speedometer stopped	1
Luggage rack melted	1
Power locks and windows disabled	1
Side mirror blown off	1
Stuck siren	1
Weld marks on tire rim	1

4.7.3 Possible Modes of Injury

Thus, from a review of the literature and case histories, it is evident that the following modes of injury are plausible if a lightning strike causes pyrolysis of the tyres.

- Operator struck by moving object or shockwave while in the cabin. Even while inside the cabin, there is a known history of shockwaves travelling through the cabin during a tyre explosion (Figure 12c). It is also conceivable for projectiles to penetrate the cabin walls owing to the extreme energy involved. In addition to being hit by a projectile, there is also the risk of hearing loss or shock.
- Personnel struck by moving object or shockwave while outside the cabin. After the lightning strike, there may be a need for the operator to leave the vehicle urgently (e.g. due to a fire, as discussed later in Section 4.7). It is possible, as discussed earlier, for the pyrolysis kinetics to delay an explosion. Thus, there is a risk, the operator is struck by a delayed explosion after they have left the vehicle. Furthermore,

emergency response personnel that might be initially attending to an injured operator or the fire may also be at risk of a delayed explosion.

- Loss of vehicle control. There is risk that a tyre rupture, especially while a vehicle is in motion, could cause a dramatic decline in tyre function leading to a crash. Moreover, it is not uncommon for the explosion to cause the vehicle to lift[1]. This also has the potential to contribute to a crash.

4.7.4 Change in Risk Level

Currently, the principal countermeasure against injury from pyrolysis-related tyre explosions from lightning strikes is isolation (Section 3). That is, parking the vehicle in a safe location where a potential tyre explosion is not near people or structures and evacuating the vehicle operator all before the lightning storm arrives.

By continuing operation of vehicles in a lightning storm, the above risks which were previously negligible are now deemed to be '*high/substantial increase from normal*'.

It is noted that some mines are in the practice of filling haul truck tyres with nitrogen, in an attempt to reduce the risks associated with tyre pyrolysis. However, this is judged by the tyre manufacturers to be an unreliable means of reducing the risk of tyre pyrolysis and explosion [37, 38]. This is due to the following reasons:

- Many of the chemical degradation processes involved in pyrolysis can proceed in a deoxygenated or low oxygen atmosphere [33].Thus, the generation of flammable gases is likely not prevented in such an atmosphere.
- Explosions can be avoided if the oxygen level in a tyre's inflation chamber is kept below 5% [33, 38]. However, to achieve this will require strict measures including pre-purging tyres prior to filling, filling with high purity nitrogen, no 'top-up' inflation with air in the field and quality testing of oxygen levels inside the tyres.
- An initial tyre rupture may occur immediately as a result of a lightning strike (e.g. due to the flashover near the rim). However, after the rupture event, the pyrolysis reaction may proceed in the unseated tyre and fill the enclosed (albeit not sealed) tyre cavity with flammable gases. Since the tyre cavity is no longer sealed, some oxygen will be able to enter and mix with gases inside the enclosed cavity. As the pyrolysis reaction continues and the temperature rises, an explosive condition could be still created inside the tyre cavity after a delay. Tyre manufacturers are well aware that unseated tyres undergoing pyrolysis are still an explosion risk [38].

Thus, tyres inflated with nitrogen are generally considered to have a similar risk of pyrolysis-related tyre explosions as air-inflated tyres [37, 38]. It is noted that Bougainville Copper in Papua New Guinea, one of the largest mines in the world in the 1980s, had several tyre explosions despite implementation of nitrogen inflation, one of which resulted in a fatality [38].

4.8 Initiation of Other Fires

4.8.1 Background and Modes of Injury

Lightning is known as one of the major causes of fires and explosions of vehicles. When a vehicle receives a high energy strike, an extremely high level of energy is exchanged in a short period, usually less than 200ms,

[1] In 1993, in Timmins, Ontario, eye witnesses report contact between a Caterpillar Triple 87 surface haul truck and a power line caused a flash out. A short time later the first tyre exploded lifting the 60-tonne truck approximately one metre off the ground. The rest of the tyres began to explode at about 20-second intervals until all six were completely destroyed.

and this can ignite the vehicle and inflict serious burn injuries on the passengers. Tyre fires and explosion by pyrolysis have been treated separately above. Below is a list of other possible sources of fire.

Electrical Wiring

A lightning bolt striking a vehicle's antenna often starts a fire from inside of the vehicle. In this scenario, a huge current travels through a wire and quickly heats up the conductive core (which is not rated for the huge current) along its path to ground and initiates the fire.

Electronics and Circuit Boards

Another similar scenario is when the lightning bolt strikes the metal roof of the vehicle and current flows on the surface of car's body and then through tyres to the ground. In this case, the huge current can induce big surges in the vehicle's electrical and electronic circuits. This energy is strong enough to break the surge protection devices (SPD) in the system, and causes a short circuit or flashover in the circuit, which starts a fire from the inside of a vehicle.

Interior Furnishings

Separated metal shells such as doors and windows frames tend to concentrate an electric field, which emits streamers and attracts lightning stepped leaders, thus generating sparks and flashes. A spark or flash in contact with flammable material can result in a fire. Flammable material inside a vehicle includes anything other than metal; the plasma is extremely hot (i.e. >1000C) – oil, lubricant, bearing grease, paper, cloth, plastics, foam, leather, electrical wire insulation (150C ignition point), fiberglass and rubber are susceptible.

Battery explosion

Batteries are one of the high-density power sources used in vehicles. A battery creates hydrogen in normal usage, especially when the battery is heated or out of service. External or internal fires (initiated by lightning strikes as well as short circuits) can lead to rapid pressure build up inside the battery, thus resulting in an explosion. In any case when an automotive battery explodes, it can create severe injury, even fatal if the operator is close to the explosion.

Petrol or diesel fire

The petrol or diesel in the tanks and fuel lines is another possible source of fuel for a fire initiated by lightning. Although, in certain cases, the fuel may not be mixed with air at flammable concentrations.

4.8.2 Case History

In non-mining vehicles, a significant number of fires or smoke in the cabin as a result of lightning strikes have been reported. Holle [23] characterised the damage to non-mining vehicles in 76 incidents reported in North America (see Figure 15). Around 9% of vehicles struck by lightning catch on fire or experience significant smoke inside the cabin. Table 6 summarises some of these types of incidents.

Table 7 Summary of cases of vehicle fire or smoke inside the cabin as a result of lightning strike from a sample of 76 incidents reported in North America [23].

Date of event or report	Location	Deaths-Injuries	Description
August 1995	Jacksboro, Texas	0-0	Male storm chaser's car struck traveling down road; car stalled, amateur radio and battery blown, antenna melted, and hole burned in trunk.
03 March 1999	Central Minnesota	0-0	Woman driving on Interstate 74 when lightning struck car that filled with smoke after antenna hit; electrical components destroyed.
07 May 2000	Nebraska Panhandle	0-0	Male storm chaser driving in rain when flash vaporized two-meter amateur radio antenna; 3 flat tires, weld marks on tire rims, interior filled with smoke from burst cable connecting antenna to radio.
17 October 2000	Snyder, Texas	0-0	Male truck driver uninjured when flatbed trailer with roofing insulation struck and caught fire; engine stopped then electrical system restarted.
18 April 2001	Abeline, Kansas	0-0	Woman driving car on Interstate 70; antenna demolished, radio failure, smoke from dashboard, flat tire, stuck horn, and racing engine.
07 June 2001	Alliance, Nebraska	0-0	Man driving car on highway stopped immediately as electrical system destroyed, smoke from dashboard, small black hole in roof, windshield and rear window etched, and scorched tire rim; car total loss.
28 June 2001	Carmel, New York	0-0	Man and woman driving on Route 301 when SUV was hit in antenna; paint burned, filled with smoke, windshield cracked, two tires exploded, and airbags deployed. The highway was damaged.
27 April 2004	Baxter, Arkansas	0-0	17-year-old male on Highway 5 when pickup struck; the impact through metal gear shift left red mark on palm. Truck shut off, white smoke from under hood, left fender wall caught fire, windows blown out; truck destroyed by fire.
15 June 2005	Cochrane, Alberta	0-0	Driver uninjured when car struck while traveling on Highway 22; car lost power, smoke from dashboard, and caught fire.
28 December 2006	Port Arthur, Texas	0-0	Male driving car when struck; engine and brakes died, smoke filled inside, back passenger window blown out, metal frame around window twisted, and electrical system destroyed.

In the mining industry, there have been reports of vehicles being completely destroyed by fire caused by a lightning strike at Dawson Mine, QLD (22/01/2020) and in NSW (14/11/2010). These incidents are discussed in Table 2 (page 24). In both cases, the vehicle was unoccupied and no injuries or deaths occurred.

4.8.3 Change in Risk Level

Mines sites that have "stop work, seek shelter" TARPs for severe weather events will not exposed their operators to the risk of lightning related vehicle fires. However, if operations are allowed to continue in a lightning storm, then the risk of injury is deemed to be *low/slight* to *moderate increase from normal*. This is because the initial fire will consequently require the operator to evacuate the vehicle. Once outside of the vehicle, the operator and any emergency response personnel in attendance will be exposed to the many of the other electric shock hazards and tyre pyrolysis risks.

4.9 Driver Exposed to Projectiles

4.9.1 Background and Case History

Where there are tall trees, it is common for lightning strikes to cause branches or trees to fall to the ground or onto vehicles. Holle [39] analysed a total of 444 incidents near or around trees (in common society). Among these incidents, the mechanism of injury was clearly reported in 82 of these cases surveyed (Table 7). It was found that ground current and side flashes (as discussed above) were the most frequent mode of injury. Blunt trauma was the next most frequent mode of injury (approximately 27%). This includes *reports of trees or branches falling on people or vehicles with people inside, the explosion of tree parts or gas lines, concussive effects such as being thrown, and a motorcycle running into a lightning-felled tree [39]*.

Table 8 Mechanisms of lightning injury from a sample of 82 incidents in the vicinity of trees [39]

Mechanism	Events
Ground	30
Side flash	23
Blunt trauma	22
Contact	7

In addition to fallen trees and branches, it has also been reported that lightning strikes have thrown up ground debris and heavy fragments of pavement [40]. These projectiles have hit fast moving cars and windshields and caused significant injury to the occupants. Figure 16 shows the damage caused by a fragment of pavement thrown up by a lightning strike. The fragment broke both the front and back windshield. The rear middle seat was also damaged – the headrest bent back more than six inches. No passengers were seated there at the time. It is thought that the lightning may have instantaneously vaporised water trapped within or beneath the surface of the roadway.

Figure 15 Photos of a ute in Florida damaged after pavement was thrown by a lightning strike through the front and back windshield before coming to rest atop of the covered tray [40]

Lightning strikes have also caused significant damage and thrown up debris at various runways around the world including Pittsburgh International Airport [41], Sao Paulo-Guarulhos International Airport [42] and Hutchinson Regional Airport in Kansas [43].

4.9.2 Possible Modes of Injury and Change in Risk Level

The risk of an operator of a mining vehicle being hit by a projectile caused by a lightning strike has been considered. From a review of the literature and case histories, it seems that there would be two main sources of projectiles, trees and pavement.

Regarding tree, each mine site will have differing levels of vegetation. Nevertheless, it is acknowledged that mines generally have very sparse levels of vegetation owing to land clearing. Thus, the change in the risk level of an operator being hit by a tree or branch during a lightning storm is deemed to be low or negligible.

Regarding pavement or rocks, each mine site may have a differing level of risk. Areas of mine where truck passes below a steep wall or cliff may arguably have a higher risk of being struck by a dislodged rock. Nevertheless, it is acknowledged from the case studies that projectile fragments of pavement and rocks are a very low probability event among the general public still less in mining. Moreover, the elevated cabin positions and the slow-moving speeds (compared to light vehicles on the highway) further reduces the potential consequences and risks of a projectile created by a lightning strike. Thus, the change in the risk level of an operator being hit by a projectile pavement or rock is deemed '*low/slight increase from normal*' or '*negligible change*'.

Similarly, the risk of emergency response personnel being hit by a projectile caused by a lightning strike has also been considered. It is conceivable that such emergency crews may be mobilising from areas off the mine site where the level of trees are higher. Such emergency crews may also be using light vehicles and may be required to travel at higher speeds or on the highway where the consequence of a projectile pavement or tree branch would be more significant. Thus, the change in the risk level of emergency response personnel being hit by a tree or other projectile from a lightning strike is deemed to be '*low/slight increase from normal*'.

4.10 Hearing Loss, Shock and Mental Trauma

4.10.1 Background and Case History

A lightning strike is essentially an explosion in an open space. In a cloud-to-ground lightning strike, back stroke plasma is formed as the lightning stepped leader finds its way to the ground. The back-stroke plasma, carrying huge current (1-200kA), can create extremely high temperature flashes >30,000°C in a period within 1 ms. Due to this ultra-high temperature, air around the plasma expands fiercely and rapidly, and this causes huge air pressure surges around the plasma (10,000 kPa), known as thunder. An eardrum can be ruptured when the pressure exceeds 275 kPa and lethal injury can occur when the pressure exceeds 635 kPa.

Holle [23] characterised the injuries associated with 76 lightning strike incidents in the vicinity of vehicles in North America. In approximately 5% of total cases, short or long-term hearing loss occurred as a result of the incident. There was also a further seven accounts (9% of total cases) of cognitive impairment (i.e. dizzy, stuttering, unconscious, headache). However, it is unclear if some of these injuries were also associated with exposure to high voltages. Long-term trauma such as nightmares was also noted in one case.

Figure 16 Injuries reported to people inside fully-enclosed metal-topped vehicles from a sample of 76 incidents reported in North America [23]. Some events had more than one symptom.

Symptom	Events
Arms or elbows tingling, tickling, burned, struck, or numb	7
Ears ringing, hearing loss, or earphone damage	4
Shaken, jolted, or dizzy	4
Skin marks	2
Headache	1
Knocked unconscious	1
Left side injured	1
Minor cuts by flying glass	1
Nightmares	1
Pressure in chest	1
Struck in head by wood from exploded tree	1
Stuttering	1

Another secondary source of hearing loss is a lightning strike may cause the airbags to deploy particularly to passenger vehicles used by emergency response vehicles. This phenomenon is further described in Section 4.10 and Figure 15. This phenomenon has been reported in 4% of cases in passenger vehicles struck by lightning.

Apart from the initial injury to the ear, the lightning strike may lead to a loss of vehicle control due to the distraction or misjudgement of the driver. This is discussed in detail in the next section.

4.10.2 Change in Risk Level

The risk of an operator losing hearing or being traumatised by a lightning strike and thunder while continuing operation of a vehicle has been considered. The current practise in the event of a lightning storm is for operators to wait in a lightning-safe shelter. However, the probability of a lightning strike and thunder causing mental trauma or hearing loss while in the vehicle is likely identical regardless of whether the operator is in a lightning-safe shelter. Thus, the change in the risk level to an operator or an emergency response personnel is deemed '*negligible change*'.

However, if vehicle operators or emergency personnel are required to leave the vehicle then the noise protection offered by the vehicle will be removed. In this scenario, the change in the risk level to an operator or an emergency response personnel is deemed to be '*low/slight increase from normal*'.

4.11 Loss of Electrical Systems and Controls Leading to Collision

4.11.1 Background

A typical lightning strike carries enormous electrical energy and generates intense electrostatic and magnetic fields which can potentially paralyse the electrical and electronic control systems. All electrical and electronics equipment and control systems must work reliably in an electromagnetic environment with no defects. Therefore, it is required that all electrical and electronics appliances be certified for electromagnetic compatibility before they are used in the vehicle. However, these certifications do not address the intense and unpredictable conditions which occur during lightning strikes.

When conducting electromagnetic compatibility certification tests, the electrical and electronics sub system are tested according to standards in a testing house. The sub-systems under test include vehicle AC and DC power supplies, power train control sub-system, charging circuit, sensor circuit, information systems such as communication radio, cameras, GPS, display panel, antenna, and interfaces between these sub-systems. Surge protection devices (SPD) are used inside the system in order to divert or absorb the energy created from inside and outside the vehicle. SPDs including spark gap discharge devices, varistors, transient absorbers (TVS diode and SCR diode) and fuses are used in electrical control systems in vehicles.

As required in automotive industrial standards, these automotive grade SPDs are more reliable than commercial devices, however, they provide less capabilities for protecting the system from a major lightning strike.

For example, as defined in DIN 40839 or ISO 40839, emission from the electrical system inside the vehicle are determined by following models:

- Human Body Model using the MIL-STD-883, Method 3015.7
- Machine Model using EIAJIC121
- Human Body model using the IEC 1000-4-2 standard

This means all tests are based on emulating effects from these objects. For example, for electrostatic discharge (ESD) immunity, only included are the device under test (DUT), human body and electrical systems in the vehicle. Intensive effects caused by lightning strike are not. Therefore, the ESD test criteria only considers direct contact, and air discharge methods of testing are used with four discrete steps in the severity level ranging up to 8 and 15kV, which is far less than the static electrical field introduced by a lightning strike. As a result of the standards for SPDs in the 24V powered circuit in vehicles, an SPD protection circuit can normally provide 240V positive and negative voltage transients. However, voltage much higher than 300V can be induced in a small square circuit of 0.1x0.1m, which is very common on a printed circuit board or wiring arrangement in large vehicles [44]. In contrast, lightning strikes can create much higher voltage than the protection level which is designed to withstand.

4.11.2 Possible Modes of Injury and Case History

A direct lightning strike to the vehicle is capable of overloading the SPDs and damaging circuit boards and electronic components. That is, the lightning strike initially breaks the SPD which is used for protecting the circuit from voltage surges. By design, automotive SPD circuits absorb higher voltage or current surges generated by the system and ensures higher voltage or current tolerance compared to domestic products, as required in the automotive industry. SPD circuits being compromised by a lightning strike is extremely undesirable, especially in power supplies, which are vital parts for a vehicle's electrical and electronics systems. A failed power supply would render the vehicle's electrical control system paralysed, or in worse scenarios, cause malfunctioning of the vehicle, which could conceivably lead to a loss of control of the vehicle.

SPDs tend to stay in short or open circuit conditions when they fail due to extreme conditions. When the devices stay in a short circuit condition, they tend to cause burning on the circuit board. This usually starts a flame on the circuit board or connecting wires, and cause fire inside the vehicle if the circuit board is not in a fire-retardant enclosure. The initiation of fires and its consequences are discussed in more detail in Section 4.7.

Holle [23] characterised the damage to non-mining vehicles in 76 incidents reported in North America (see Figure 15). Damage or destruction of the electrical system was the second most common type of damage that was reported in 17 vehicles (22% of cases). The fifth most common type of damage was reported in vehicles was the engine stopped or racing (13 vehicles or 17% of cases). Some of the other less frequent types of damage include:

- Radio/CD player destroyed/damaged (7 vehicles or 9% of cases)
- Airbags Deployed (3 vehicles or 4% of cases)

- Stuck horn (2 vehicles or 3% of cases)
- Power locks and windows disabled (1 vehicle or 1% of cases)
- Cruise control and speedometer stopped (1 vehicle or 1% of cases)
- Stuck siren (1 vehicle or 1% of cases)
- Brakes died (1 vehicle or 1% of cases)

Notably, in approximately 4% of cases, the airbags had deployed when struck by lightning. This could cause significant hearing loss (as discussed in Section 4.9) or be a severe distraction especially to emergency response personnel (to be discussed in Section 4.11).

It is also noted that lightning strikes in the past have disabled the central locking system in a passenger vehicle. This could conceivably lead to serious consequences in the event of a fire (Section 4.6 and 4.7) or some other emergency where an emergency response personnel is prevented or delayed from evacuating their vehicle.

4.11.3 Change in Risk Level

The risk of operator of a mining vehicle having a collision or being adversely affected by the loss of electrical systems (such as the scenarios discussed above) has been considered. It is acknowledged that each mine vehicle is different and due to the various relationships between electrical mechanical, pneumatic or hydraulic systems some vehicles are more or less at risk of a lightning-related incident than others. For example, in the event that a lightning strike causes the engine to shutdown, vehicles with steering and/or braking systems dependent on engine power could be at risk of a collision. Alternatively, in the event that a lightning strike causes the engine to race, a mechanically controlled vehicle is more likely to be able to disengage the drive and prevent the vehicle from losing control.

Owing to the low probabilities, the predominantly stationary or low speeds used by mining vehicles and wide roads that are available, the change in risk of an operator having a serious collision due to a lightning strike disabling the engine or electrical systems is deemed to be '*negligible to low/slight increase from normal*'.

Similarly, the risk of an emergency response vehicle having a collision or being adversely affected by the loss of electrical systems (such as the scenarios discussed above) has also been considered. These vehicles are more likely to be travelling at higher speeds on narrower roads. These vehicles are probably also fitted with airbags. Thus, the change in risk of an emergency response vehicle having a serious collision due to a lightning strike disabling the engine or electrical systems is deemed to be '*low/slight increase from normal*'.

4.12 Driver Distraction and Human Error Leading to Collision

4.12.1 Background and Case History

Any of the events describe above are capable of having a secondary effect of distracting the operator into carrying out an unsafe or unintended manoeuvre even if vehicle controls are still sound. Alternatively, the operator due to injury or distraction is unable to respond appropriately to a normal hazard. For example, the sudden flash, noise and alarm caused by a lightning strike could conceivably startle an operator into carry out an unsafe manoeuvre.

Holle [23] characterised 76 incidents involving lightning strikes to non-mining vehicles in North America. Table 8 summarises the crashes that have occurred as a result of driver distraction of some type. From this list, swerving and hitting a power pole seems to be a known mode of injury in passenger vehicles – in approximately 7% of cases.

Table 9 Summary of cases of driver distraction from a sample of 76 lightning strike incidents reported in North America [23].

Date of event or report	Location	Deaths-Injuries	Description
04 July 2000	Augusta, Maine	0-1	63-year-old woman crashed into a utility pole while driving after being blinded by lightning in front of her.
03 August 2000	Chatham, Ontario	0-1	29 year-old male truck driver hit the cab's roof when lightning hit the top on Highway 401; all gauges and electrical system disabled.
10 March 2001	Casa de Fruta, California	2-2	37-year old man killed, as well as 74-year-old woman who started crash when flash struck very near vehicle on highway 152; 2 injured.
24 May 2001	Cumming, Georgia	0-0	18-year-old male driver swerved to avoid a lightning strike and slammed into a utility pole.
29 May 2001	Aylmer, Ontario	0-30	30 high school students injured when bus flipped into ditch at low speed after bus driver slammed on brakes behind van that stopped suddenly for dog crossing road after being frightened by thunder and lightning.

4.12.2 Possible Mode of Injury and Change in Risk Level

The risk of a mine truck operator being distracted by a lightning strike flash or thunder and having a collision has been considered. From a review of the past cases, the low speeds and wide, clear roads that are generally present on mine sites, this risk is deemed as '*negligible to low/slight increase from normal*'. This is a similar change in risk level as losing of electrical systems leading to collision, as discussed in Section 4.10.

Similarly, the risk of an emergency response vehicle being distracted by a lightning strike flash or thunder and having a collision has also been considered. These vehicles are more likely to be travelling at higher speeds on narrower roads. Nevertheless, the change in risk of an emergency response vehicle having a serious collision due to distraction by a lightning strike flash or thunder is deemed to be '*low/slight increase from normal*'. This is a similar risk level to an emergency response personnel being hit by a tree or other projectile from a lightning strike, as discussed in Section 4.8.

5. Conclusions

Table 1 summarises the findings of our hazard assessment. A total of ten (10) hazards were identified to have an increased risk when mining vehicles are operating in lightning storms. With regard to the premise that the vehicle's cabin provides protection, it was found that the cabin is an imperfect Faraday cage and provides only partial protection. That is, there is a moderate increased risk of a direct strike to the windshield or windows owing to the large opening size. Touch potential and side flash (through open windows) are also a possible injury mechanism due to the imperfect Faraday cage. Moreover, a moderate to high/substantial change in the level of risk was deemed to be present from other mechanisms such as:

- Tyre rupture or explosion via pyrolysis (High/substantial increase from normal)
- Exposure to high voltage (HV) via UHF-radio wiring or other conductive surfaces. That is, touch voltage. (Moderate increase from normal)
- Initiation of other fires. That is, combustion of wiring, electronics, batteries, fuel, interior furnishings, etc. (Moderate increase from normal)

The same ten (10) hazards were identified to be present when emergency response vehicles and personnel are required to operate in lightning storms (Table 2). These crews have a higher likelihood of needing to leave the vehicle to carry out their duty. In addition to the hazards identified above, a moderate to high/substantial increased risk of injury or death was deemed to be present from the following mechanisms:

- Exposure to HV while outside and in close quarters to vehicles. That is, flashover injury, touch potential and step potential. (Moderate increase from normal)
- Exposure to HV while in an open area. That is, direct strike, step potential, side flash. (Moderate increase from normal)

Each individual mine may have their own Triggered Action Response Plan (TARP) for lightning. Nevertheless, it is recommended that the minimum requirements below remain implemented to ensure that the hazards identified in this report are mitigated:

- Halting production when lightning is detected within a specified distance from the mine (typically 20km or 30 second delay to hearing thunder clap),
- Driving mobile mining equipment to a designated safe lay-down area,
- Transporting the operators to a safe shelter away from the equipment, and
- Awaiting the "All Clear" once lightning is beyond the exclusion distance (typically no lightning detected within 40 km for a period of 30 minutes).

Controls to significantly reduce the risk of the identified lightning hazards would be required before a change to the status quo would be acceptable. It is expected that this would require significant design changes/modifications to mining vehicles. That said, some of the hazards are unlikely to be sufficiently controllable even with major redesign. Therefore, reduced activity is the current primary control.

6. Disclaimer

This report is solely for the use of the individual or company to whom it is addressed. It is not intended to and should not be used by anyone else (Unintended Recipients). The University of Queensland will not be liable or otherwise responsible for any loss, damage, cost or expense incurred or arising out of or in connection with any use of this report by Unintended Recipients.

Information contained in this report may not reflect any event or circumstances which occur after the date of this report. Users of this report are responsible for assessing the relevance and accuracy of the content of this report.

7. References

1. Zavisa, J. and J. Shields. *How Lightning Works - Stepped Leaders*. 2022; Available from: https://science.howstuffworks.com/nature/natural-disasters/lightning3.htm.
2. Seidl, S., *Pathological Features of Death From Lightning Strike*, in *Forensic Pathology Reviews*, M. Tsokos, Editor. 2006, Humana Press: Totowa, NJ. p. 3-23.
3. Jensenius, J. *Dr. Lightning's Guide To Lightning and Thunder*. 2013; Available from: https://www.weather.gov/media/safety/Dr_Lightning_Guide-Victims.ppsx.
4. National Weather Service. *Lightning Science: Five Ways Lightning Strikes People*. US Dept of Commerce 2022; Available from: https://www.weather.gov/safety/lightning-struck.
5. The University of Western Australia. *Electrical circuits 1: Lightning facts (fact sheet)*. ast1378 2015; Available from: https://www.uwa.edu.au/science/-/media/Faculties/Science/Docs/Lightning-facts.pdf.
6. National Weather Service. *Lightning Victims*. US Dept of Commerce 2022; Available from: https://www.weather.gov/safety/lightning-victims.
7. Mills, B., *An updated assessment of lightning-related fatality and injury risk in Canada: 2002–2017.* Natural hazards (Dordrecht), 2020. **102**(3): p. 997-1009.
8. Qiyuan, Y.I.N., et al., *Lightning fatalities in China, 2009-2018.* Journal of Agricultural Meteorology, 2021. **77**(2): p. 150-159.
9. Elsom, D.M. and J.D.C. Webb, *Deaths and injuries from lightning in the UK, 1988–2012.* Weather, 2014. **69**(8): p. 221-226.
10. National Weather Service. *How Dangerous is Lightning?* US Dept of Commerce 2022; Available from: https://www.weather.gov/safety/lightning-odds.
11. Coates, L., R. Blong, and F. Siciliano, *Lightning fatalities in Australia, 1824–1991.* Natural Hazards, 1993. **8**(3): p. 217-233.
12. Rash, C.E. *When Lightning Strikes*. Aero Safety World 2010; Available from: https://flightsafety.org/wp-content/uploads/2016/11/asw_jun10_p18-23.pdf.
13. State of Queensland, *Work Health and Safety Act*. 2011.
14. Government of Western Australia Department of Mines Industry Regulation and Safety. *Lightning and outdoor work*. Fact sheet; Available from: https://www.commerce.wa.gov.au/sites/default/files/atoms/files/lightning_and_outdoor_work.pdf.
15. Otraco, *Final report to Hamersley Iron on catastrophic tyre incident on haul truck 06H1 at Channar on April 10*, editor. T. Cutler. 2004: Otraco.

16. Southern Ports. *Lightning Response Procedure*. 2020; Available from: https://www.southernports.com.au/sites/default/files/2019-09/Lightning%20Response%20Procedure.pdf.

17. Pilbara Ports Authority. *Lightning Preparedness and Response Plan A802593*. 2022; Available from: https://www.pilbaraports.com.au/about-ppa/publications/forms-and-publications/forms-publications/strategy-plan/2020/june/lightning-preparedness-and-response-plan.

18. Chapman, S.J., D.P. Hewett, and L.N. Trefethen, *Mathematics of the Faraday Cage.* SIAM Review, 2015. **57**(3): p. 398-417.

19. Gamry Instruments. *Faraday Cage: What Is It? How Does It Work?* Application note 2022; Available from: https://www.gamry.com/application-notes/instrumentation/faraday-cage/.

20. Rakov, V.A., *Electromagnetic Methods of Lightning Detection.* Surveys in Geophysics, 2013. **34**(6): p. 731-753.

21. *Fatal Electric Shock: What Voltage Causes Death?* Metroid Electrical Engineering Knowledge Center 2022; Available from: https://www.metroid.net.au/engineering/knowledge_center/fatal-electric-shock-what-voltage-causes-death/.

22. *Terrifying! This is how it looks like when a lightning bolt hits your car*. StrangeSounds.org 2021; Available from: https://strangesounds.org/2021/07/terrifying-pictures-lightning-melts-car-michigan-ford.html.

23. Holle, R.L. *Lightning-caused deaths and injuries in the vicinity of vehicles*. in *Third Conference on Meteorological Applications of Lightning Data*. 2008.

24. Standards Australia, *Lightning Protection.* Australian Standard, 2021. **AS 1768-2021**.

25. Naito, Y., S. Yanagawa, and K. Yamamoto. *High voltage impulse experiment on electric automobiles and its verification*. in *2014 International Conference on Lightning Protection (ICLP)*. 2014.

26. *Lightning strikes truck driver in his truck*. youtube video 2012; Available from: https://www.youtube.com/watch?v=b4HxAszLgXY.

27. Surgetek. *Explanation on Step Potentials due to a direct lightning strike*. Available from: https://studylib.net/download/18144141.

28. Resources Safety & Health Queensland. *Tyre fires, pyrolysis and explosions*. Mines safety bulletin 47 2004; Available from: https://www.rshq.qld.gov.au/safety-notices/mines/tyre-fires,-pyrolysis-and-explosions.

29. Resources Safety & Health Queensland. *Lightning strikes on rubber-tyred vehicles*. Mines safety bulletin 176 2018; Available from: https://www.rshq.qld.gov.au/safety-notices/mines/lightning-strikes-on-rubber-tyred-vehicles.

30. Government of Western Australia Department of Mines Industry Regulation and Safety. *Hazard of lightning strikes on vehicles*. Mines Safety Bulletin 183 2021; Available from: https://www.dmp.wa.gov.au/Documents/Safety/MSH_SB_183.pdf.

31. Government of Western Australia Department of Mines and Petroleum Resources Safety. *Tyre safety for earth-moving machinery on Western Australian mining operations*. Safety Guideline 2015; Available from: https://www.dmp.wa.gov.au/Documents/Safety/MSH_G_TyreSafetyEarthMovingMachineryWAMines.pdf.

32. Glenn, W., *The hazard nobody's heard of*, in *OH & S Canada*. 1997, Business Information Group: Don Mills. p. 42-44+.

33. Dolez, P.I., et al., *Exploring the chemical aspects of truck tire blowouts and explosions.* Safety Science, 2008. **46**(9): p. 1334-1344.

34. Balkrishna Industries Ltd. *Tire Dangers after Equipment Lightning Strike or Electric Transmission Line Contact*. Available from: https://www.roadsbridges.com/sites/rb/files/BKT%20Lightning%20Strike%20White%20Paper.pdf.

35. NSW Department of Primary Industries. *Lightning strikes stationary truck*. Safety Alert 2008; Available from: https://www.resourcesregulator.nsw.gov.au/__data/assets/pdf_file/0017/204047/SA08-03-Lightning-strikes-stationary-truck.pdf.

36. Government of Western Australia Department of Mines and Petroleum Resources Safety. *Autonomous truck significantly damaged by lightning strike*. Significant Incident Report No. 260 2018; Available from: https://www.dmp.wa.gov.au/Documents/Safety/MSH_SIR_260.pdf.

37. Rimex. *8 Essential Tips to Reduce the Risk of Tire Explosions*. 2017; Available from: https://www.rimex.com/blog/8-essential-tips-to-reduce-the-risk-of-tire-explosions/.

38. Cutler, T. *Dangerous Misconceptions about Earthmover Tyre Explosions*. OTR Global Technical Bulletin 2016; Available from: http://otrglobal.com.au/wp-content/uploads/2017/01/OTRG-Technical-bulletin-Tyre-explosion-misconceptions.pdf.

39. Holle, R.L. *Lightning-caused deaths and injuries in the vicinity of trees*. in *2012 International Conference on Lightning Protection (ICLP)*. 2012.

40. Cappucci, M. *Florida lightning strike blasts chunk of roadway into vehicle*. The Washington Post 2021; Available from: https://www.washingtonpost.com/weather/2021/05/11/florida-lightning-roadway-vehicle/.

41. *Lightning punches 3x3 foot hole in runway at Pittsburgh International Airport*. WPXI.com News 2020; Available from: https://www.wpxi.com/news/top-stories/lightning-punches-3x3-foot-hole-runway-pittsburgh-international-airport/ZTON3DYC2VCVDJAQC2FJWMHTTQ/.

42. Martínez Garbuno, D. *Video: Sao Paulo Runway Damaged By Direct Lightning Strike*. Simple Flying 2021; Available from: https://simpleflying.com/sao-paulo-lightning-strike-runway/.

43. *Lightning strike punches hole in runway*. The Weather Network 2019; Available from: https://www.theweathernetwork.com/ca/news/article/lightning-strike-punches-hole-in-runway-kansas.

44. Kanata, J., A. Ametani, and K. Yamamoto. *Threats of lightning current through an electric vehicle*. in *2012 International Conference on Lightning Protection (ICLP)*. 2012.

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

CREATE CHANGE

Contact details

UQ Materials Performance
T +61 7 **3365 6123**
E **uqmp**@uq.edu.au
W uqmp.com.au

ABN: 63 942 912 684