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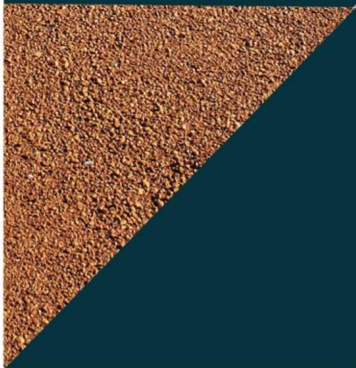
WESTERN AUSTRALIAN ROAD RESEARCH AND INNOVATION PROGRAM



Review of Light-Emitting Lane Demarcation Technologies

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SUMMARY

This report presents the findings from a literature review of the potential application of light-emitting lane demarcation technologies and the relevant applications to MRWA that may maximise the value for money and safety benefits in WA. Key findings from the review include:

- Luminescent line marking and luminescent pavement marking:
  - With the technologies development still in an early stage no published road safety benefits, performance indicators or costs were found.
  - Previous field trials have demonstrated issues with inadequate charging, and limited performance in wet conditions, under vehicle headlights and does not appear to have retroreflectivity as a contingency for these issues.
  - Insufficient information was available to conduct a safety benefit analysis compared to current pavement line markings.
  - There has been no published information regarding applicability to autonomous vehicles.
- Solar-powered road studs and solar-powered guardrail lights:
  - Literature indicates that solar road studs have been applied at a number of locations in Australia and internationally, including South Africa and the UK. Studies found that implementation reduced the number of accidents along the trial sections of road.
  - Solar-powered road studs are available as hybrid solar-powered LEDs and retroreflective pavement markers at a cost ranging from $29 to $58 each.
  - Solar-powered guardrail lights are available as hybrid solar-powered LEDs and retroreflective delineators at approximately $45 each from one Australian supplier.
- Insufficient information was available for any of the road delineation technologies to identify potential safety benefits or undertake an economic or sustainability analysis.
- There has been no published information regarding applicability to autonomous vehicles.

In light of the findings from the literature review and the limited information available on the safety benefits of the reviewed technologies, it is recommended that MRWA considers the following:

- Due to the novelty of the luminescent line markings a trial is not recommended.
- Although some deficiencies are clearly identified, luminescent pavement markings may be suitable to be trialled or implemented on off-road pedestrian and cycle paths.
- Consideration should be given to undertaking performance trials on a low risk road for solar-powered road studs and solar-powered guardrail lights and to determine if these products fit into current specifications.

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1 INTRODUCTION

1.1 Background

The Western Australian state-controlled road network includes approximately 19,000 km of road connecting an area of roughly 2,500 km^2. Main Roads Western Australia (MRWA) is charged with the establishment and maintenance of the road network, significant portions of which are based rurally (MRWA 2018a). Due to the vastness of the state, the rural network often has limited access to roadside lighting, as a result demarcation technologies provide a self-explaining road at night by delineating the alignment, lane designation and formation width. Studies have shown that the primary cause of approximately 90% of traffic crashes was due to human factors while nearly 28% are due to infrastructure, and most cases are a combination of these two factors (Lopez et al. 2016). Low visibility may be one of the reasons that annual road fatalities are typically higher on Western Australian regional roads than metropolitan roads although the population density is much lower in these areas (Road Safety Commission 2019). Improving the visibility of line delineation on the WA rural road network is critical to ensuring the safety of motorists is optimised.

The Western Australian climate is well suited to capitalise on technology powered by solar energy. Solar energy is currently used by MRWA and several other Australian state road agencies to power road lighting poles. However, recent evidence suggests that solar powered light-emitting lane demarcation technologies may have the potential to enhance delineation at night , providing a safety benefit on the rural road network which may reduce crashes thus providing an economic benefit to WA. The use of solar-powered light-emitting lane demarcation technologies offers an environmentally friendly, sustainable solution to delineating the road in areas that are difficult to access with conventional power sources to provide road lighting. Therefore, it is proposed that the long-term safety of WA roads can be enhanced through the incorporation of light-emitting lane demarcation technologies.

The effectiveness (of delineation) and value for money (crash costs reduction and lifecycle of the technology, supplementing the use for roadside lighting) of different solar technologies is still debated. This report seeks to identify if further information regarding the effectiveness and value for money for the solar powered pavement-lane demarcation technologies is available and if these should be considered for trial and use on WA rural roads.

1.2 Purpose and Objective

The purpose of this review is to present a preliminary overview of the potential use of solar powered pavement-lane demarcation technologies identified in the WARRIP 'Review of Future Pavement Technologies' (Sharp et al. 2017). These technologies include:

- luminescent line markings
- luminescent pavement markings
- solar-powered road studs
- solar-powered guardrail lights.

The objective of the review was to identify if the technologies meet the following criteria:

- Applicability/performance: expected lifecycle, maintainability, implications for autonomous vehicle technology, reflectivity performance in dry conditions, reflectivity performance in wet conditions.
- Compliance with AS and MRWA standards: visible ahead of a vehicle, retroreflectivity, diffused reflectivity (line and pavement marking only), skid resistance value (BPN).

- Availability/cost: supplier location, cost
- Potential safety benefits: self-explaining road through improved delineation beyond the reach of headlights
- Financial benefits: implementation and maintenance, crash reduction
- Relevance to current MRWA practice

1.3 Approach and Report Outline

The approach used included the following:

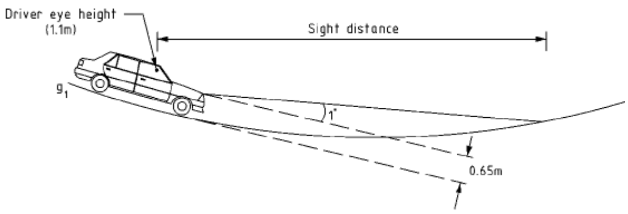
- evaluating recent research and literature that addresses identified products, their likely application in practice and their implementation both in Australia and overseas – Section 2
- outlining the requirements of a performance trial of selected technologies – Section 3
- documenting a summary of the review and recommended areas that may require further investigation – Section 4.

2 INVESTIGATION OF POTENTIAL APPLICATION OF LIGHT-EMITTING DEMARCATION TECHNOLOGIES

Solar technologies in Australia and New Zealand are typically adopted to power roadside lighting, help phones, traffic monitoring stations and electronic speed limit signs. Solar panels are secured to the top of the poles and placed at an angle that maximise the sun adsorption during winter and summer, generally oriented in a north-facing direction. The MWRA *Solar-powered LED Lighting Policy* (MRWA 2016) provides guidance on the provision of solar-powered lighting in remote and isolated locations where it is not economical to provide traditional sources of power supply. Similarly, in 2017, MRTS98 *Standalone Solar (PV) Powered Lighting* (QDTMR 2017) outlining the design, supply, installation, testing and commissioning of solar-powered lights at isolated intersections.

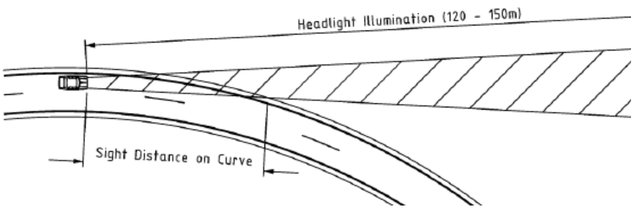
Solar-powered technologies are an emerging field which are demonstrating improvement on photovoltaic (PV) systems, that is converting light into electricity. These improvements may have the potential to provide delineation, which is not dependent on retroreflectivity (from vehicle headlights). This has the potential to the alignment, lane designation and formation width ahead of the reach of a vehicles headlights, particularly where headlights are not able to illuminate the road ahead, e.g. in sags and on horizontal curves as per Figure 2.1 and Figure 2.2. The potential for solar powered technologies to assist drivers by providing delineation beyond the reach of headlights delineating should greatly contribute to providing a self-explaining road at night. .

Figure 2.1: Headlight sight distance limitations on vertical sags



Source: Austroads (2016)

Figure 2.2: Headlight sight distance limitations on horizontal curves



Source: Austroads (2016)

The findings for each light-emitting demarcation technology are provided as follows:

- 2.1 Luminescent Line Markings
- 2.2 Luminescent Pavement Markings
- 2.3 Solar-powered Road Studs
- 2.4 Solar–powered Guardrail Lights
- 2.5 Summary and Discussion

2.1 Luminescent Line Markings

Line markings are used to delineate the road alignment (horizontal geometry), separate opposing traffic flows (on undivided roads) and provide lane designation (multi-lane roads and passing lanes etc.). Retroreflective line marking is used to provide delineation at night (provided by glass beads embedded on top of the linemarking). The limitation with traditional linemarking is that it is retroreflective meaning that the lines will only illuminate when a light source (e.g. headlights) strikes the glass beads embedded on the paint. Additionally, in wet conditions a film of water on the road surface diminishes the retroreflectivity performance.

Retroreflective line marking on Australian roads is typically accomplished using waterborne paint and glass beads (typically Type B or C), and some thermoplastic paints and glass beads are also used. An ongoing National Asset Centre of Excellence (NACOE) project is currently trialling higher-performing combinations of cold applied plastic paint and Type D glass which are demonstrating high levels of retroreflectivity in dry and wet conditions (NACOE 2018).

It is postulated that as luminescent line marking is self-illuminating and not reliant on a light source (at night) it should delineate the carriageway as far as the eye and road alignment allow. Potential benefits include identifying the road alignment lane drops and where lanes diverge beyond the limitations of headlight reach. Additionally, it is thought that the performance should not be affected by a film of water (in wet conditions) resulting in line markings providing a more self-explaining road at night.

2.1.1 Domestic and International Applications

The use of (solar charged) photo-luminescent pavement line markings was developed by Dutch artist Daan Roosegaarde and the construction services company Heijmans (based in the Netherlands), to provide ‘glow-in-the-dark’ line marking (BBC 2014). The luminescent line marking (Figure 2.3 and Figure 2.4), dubbed ‘Glowing Lines’ aims to enhance delineation of the road and improve visibility and safety in poor weather conditions to provide an alternative to conventional lighting in areas away from the power grid (Heijmans n.d.a). The glow-in-the-dark paint uses strontium aluminate pigments that can glow throughout the night on a single charge for 8 to 10 hours of illumination (SRRB 2014).

Figure 2.3: Heijmans Glowing Lines, Netherlands trial: demonstrating illumination

Source: BBC (2014).

Figure 2.4: Heijmans Glowing Lines, Netherlands trial: demonstrating illumination around a curve

Source: Studio Roosegaarde (n.d.b).

The Australian company Moon Deck offers a resin-based product called Glow Line (Figure 2.5) that is luminous and can be applied to a multitude of different surfaces, including asphalt and concrete. The supplier claims that the resin formula makes the product highly resistant to wear compared to epoxy products and that it meets the highest rating class P5 in accordance with AS 4586 Slip Resistance Classification of New Pedestrian Surface Materials. The product also comes in multiple colours to make the marking discernible in daylight hours (Moon Deck 2015). An article in McCosker (2017) reported that the Moon Deck product was trialled on Ferny Grove Cycle Link in 2017 and in Canberra in 2015, with reports that the technology was effective for walkers and riders with no lights.

Figure 2.5: Moon Deck line marking

Source: Moon Deck (2018).

The potential use of Heijmans' luminescent Glowing Lines has been restricted by a number of limitations identified in an initial trial in Oss, the Netherlands, conducted in April 2014 and by a subsequent investigation conducted by the Scottish Road Research Board (SRRB). The initial trial in April 2014 found that the road markings were sensitive to large amounts of moisture due to rainfall, resulting in insufficient light output. Additionally, the study also identified that some drivers drove without headlights to experience the glow-in-the-dark effect (BBC 2014). Due to these identified drawbacks Heijmans developed Glowing Lines 2.0, and application in the same trial area in Oss was carried out in October 2014 (Heijmans 2015). In addition to the limitations uncovered in the initial trial, the investigation by the SRRB into the potential for glowing lines in Scotland (SRRB 2014) also uncovered the following shortcomings that may impact the effectiveness of the glow-in-the-dark paint:

- Modern grade strontium aluminate pigments may allow the glow to be bright enough for the first two to three hours but will begin discharging as soon as daylight falls. This may result in the paint only being illuminated for an hour or so after the sun is fully set.
- Ambient light emitted by the vehicle headlights has the potential to overpower the glow-in-the-dark effect.

In addition to the ambient light mentioned in the SRRB report, direct light from headlights shone on the lines appeared to overpower the luminosity of the lines, as shown in Figure 2.6. If the technology is only dependent on its luminosity for visibility, the area lit by the headlights would diminish the visual cues guiding the driver.

Figure 2.6: Headlights overpowering luminescent line marking

Source: Studio Roosegaarde (n.d.c).

2.1.2 Compliance with Pavement Marking Standards

The performance criteria for longitudinal and transverse lines as well as other road markings used are outlined in MRWA Specification 604 *Pavement Markings* (MRWA 2017a) and AS 4049.3, as summarised in Table 2.1. It is important to note that MRWA has successfully moved towards performance-based contracts and the minimum performance criteria outlined in Specification 604 is significantly lower than what is typically required.

Of the products reviewed non provided information demonstrating that the light-emitting technology would meet the MRWA specifications for retroreflectivity or skid resistance. Information could also not be found that provides an indication of the diffused reflectivity (Qd) performance (luminosity), durability and expected lifecycles.

Table 2.1: Minimum performance criteria for longitudinal lines

Performance criteria	White markings (MRWA)	Yellow markings (MRWA)	White markings (AS 4049.3)	Yellow markings (AS 4049.3)
Retroreflectivity (millicandela per lux (mcd/lx)/m^2)	100	70	150	Not available.
Luminance (%)	40	30	80	45-50
Skid resistance value (British Pendulum Number (BPN))	45	45	45	45

Source: MRWA (2017a) and AS 4049.3.

Note: Yellow line marking results were not available at the time the specification was written

2.1.3 Implications for Autonomous Vehicle Technology

The rapidly advancing vehicle automation technologies must be addressed by MRWA to predict changes in demand patterns and any required retrofitting required for the existing infrastructure network (MWRA 2014). Autonomous technology relies in part on road markings and signs to provide the vehicle with clear lane delineation during day and night, therefore the road markings must be maintained to a high standard (Turley 2017). In 2016, Volvo's semi-autonomous prototype vehicle would not operate during a press event because of the poor quality of road markings (Sage 2016). However, are in their early development and implementation stages manufacturers have not determined or specified the minimum quality and visibility of road markings necessary for safe travel (Turley 2017).

In terms of the implementation of autonomous vehicles, new lane delineation technologies can only be considered as a suitable countermeasure for run-off-road crashes if the in-vehicle machine vision can identify the line marking to ensure the vehicle does not unintentionally depart from the designated lane (Milling 2018). For a machine vision algorithm to detect pavement marking it must be able to identify the contrast between the pavement marking and pavement surface. On a typical high-speed rural road where white linemarking was on a black sprayed seal only 35% of edge lines and 45% of centrelines were identified when using current generation lane detection warning systems (LDWS) (Milling 2018), this may have been due to a combination of both the linemarking being in poor condition or indeed the linemarking was in good condition and above intervention levels however the machine vision technology could not adequately identify the presence of the linemarking.

The ability for machine vision to identify green coloured, light-emitting linemarking is unknown. Logic would indicate the task would be more difficult and that high levels of luminance would be required. Furthermore, as identified in Figure 2.4 a vehicles headlights appear to diminish the presence of the linemarking which is likely to further reduce the contrast and thus the ability for machine vision to identify linemarking.

2.1.4 Suitability for Implementation

The review of luminescent line markings indicates that although they can provide a luminous effect that would assist in providing a self-explaining road at night by delineating the alignment, lane designation and formation width beyond the head lights of a vehicle, the technologies are still in the early stages of development and a number of limitations were identified. Based on the information that was available to review the limitations are summarised as follows:

- News reports on trials conducted to date have shown little success, furthermore, published information on the use of luminescent products for pavement markings available to date has been very limited.
- The solar charging requirements (e.g. hours of daylight, UV intensity) and time self-emitting light will be provided are not known.
- Luminescent linemarking was not identified to be retroreflective. Therefore, may not function at night if:
  - solar charge does not provide self-illuminated light throughout the duration of the night (particularly if sunlight hours are limited during the day).
  - A vehicles headlights or street lights overpower the self-illuminating light
- The diffused reflectivity levels (day time luminosity/contrast) of luminescent line marking's green colour levels on asphalt, sprayed seals and concrete surfaces is unknown. Without knowing the diffused reflectivity at installation and subsequent change in performance over time, it is unknown if the products will meet Australian and MRWA standards or if automated vehicles will be able to detect line marking.
- Vehicle headlights and streetlights have the potential to overpower the luminescent line marking, which may be more evident with different light bulb types. The line marking should be visible within the headlights so that the lines are visible to clearly indicate lane designation for lane changes, merges, divergences, overtaking and in situations where a vehicle is stopping on the shoulder.

Table 2.2 presents a summary of the luminescent line marking evaluation.

Due to the limited published results and lack of quantifiable performance of reflectivity levels (day and night) a trial would need to be undertaken to gain an understanding of performance before widespread installation could be undertaken. As the products are proprietary and still in development it is unlikely that reliable performance data would be able to be provided from a supplier or installer.

Table 2.2: Evaluation of luminescent line markings

Review criteria		Luminescent line markings
Current practice domestically and internationally		▪ Netherlands-based trial only – unsuccessful and not implemented on a large scale.
Applicability/performance	Expected lifecycle	▪ 25 years (product dependent and unconfirmed).
	Maintainability	▪ No published information.
	Implications for autonomous vehicle technology	▪ No published information.
	Reflectivity performance in dry conditions	▪ No noted reflectivity, although visibility is high when adequate charge is received during daylight and during the limited time frame before the charge is exhausted. ▪ Quantified Qd levels are could not be sourced.
	Reflectivity performance in wet conditions	▪ No noted reflectivity. ▪ Visibility diminishes in wet conditions which has been indicated to be inadequate for road delineation.
Compliance with AS and MRWA standards	Visible ahead of a vehicle	▪ Yes, when charge is not exhausted. However, visibility is diminished immediately in front of the vehicle under headlights.
	Retroreflectivity	▪ No published information.
	Diffused reflectivity (Qd)	▪ No published information.
	Skid resistance value (BPN)	▪ No published information.
Availability/cost	Supplier location	▪ Australia (Moon Deck) and the Netherlands (Heijmans).
	Cost	▪ No published information.
Potential safety benefits	Self-explaining road	▪ The safety benefits may be related to the road user's ability to see the road curvature at a greater distance than current retroreflective road markings allow, although trials have shown this can have adverse effects on driver behaviour. ▪ No quantitative data could be sourced.
Financial benefits	Implementation and maintenance	▪ No published information.
	Crash reduction	▪ As the performance and compliance with existing linemarking is unknown it is difficult to hypothesise the safety benefits. For example, the ability to delineate the road beyond the reach of headlights is highly advantageous, however the longevity of that delineation throughout the night, unknown performance in wet weather and potentially reduced visibility of linemarking within range of the headlights would be disadvantageous. ▪ There are no published studies reporting the safety benefits or disbenefits.
Relevance to current MRWA practice		▪ MRWA Specification 604 Clause 52 *Performance Criteria for Longitudinal Lines* – although there are currently no reported performance criteria.

2.2 Luminescent Pavement Marking

Pavement markings are used to provide information to drivers pertaining to decisions about travel paths and interactions with other road users (e.g. bus lane, cycle lane or pedestrian crossings etc). The limitation with traditional linemarking is that it is retroreflective meaning that the lines will only illuminate when a light source (e.g. headlights) strikes the glass beads embedded on the paint. Additionally, in wet conditions a film of water on the road surface diminishes the retroreflectivity performance.

It is postulated that as luminescent pavement markings are self-illuminating and not reliant on a light source (at night) the pavement (and messages) should be visible far as the eye and road alignment allow. Potential benefits include pavement messages in adjacent lanes (outside of headlights throw) being visible and these messages being visible to other road users without headlights (e.g. pedestrians and cyclists (vehicle standard headlights). Additionally, it is thought that the performance should not be affected by a film of water (in wet conditions) resulting in line markings providing a more self-explaining road at night.

2.2.1 Domestic and International Applications

Daan Roosegaarde (the artist mentioned in Section 2.1.1) had a second project named the Van Gogh path, an asphalt bicycle path 600 m in length which was scattered with thousands of luminous stones (Figure 2.7). The luminescence is produced using similar technology to the line markings described in Section 2.1, enabling the stones to charge during the day and emit light in the evening (Heijmans n.d.b). The Van Gogh path is a novel use of luminescent pavement marking technology and was intended for pathway use only, costing approximately €700 000 (approximately AUD $1.5 million based on XE (2019) exchange rates at path opening, 30 April 2014 (Heijmans n.d.b). Reports of any safety performance for the project could not be sourced.

Figure 2.7: Van Gogh path

Source: Studio Roosegaarde (n.d.d).

Figure 2.8: Pro-Teq Starpath

Source: STRABAG Press Office (2016b).

Similarly, a product named ‘Starpath’ (Figure 2.8) has been developed in the UK, which is a glow-in-the-dark quick drying, spray applied elastomeric coating manufactured, supplied and traded by Pro-Teq. Pro-Teq claims that the product can provide luminescence for up to 16 hours and is charged using UV light rather than direct sunlight (SRRB 2014). The product makes use of a photo-luminescent powder added to the aggregate that is then placed on a polyurethane layer and subsequently finished with a clear sealant topcoat.

Starpath costs approximately £45 per m^2 (approximately AUD $82.71 per m^2 based on XE (2019) exchange rates as at 21 March 2019) excluding importation and installation costs (Pro-Teq Surfacing n.d). There are no known suppliers/installers in Australia.

In 2016, a similar product to Starpath was implemented in Lidzbark, Warminski, Poland by a subsidiary of the STRABAG international group, named Technologies for the Future (TPA), which has an office in Brisbane, Queensland. STRABAG claims that the technology can provide luminescence for up to 10 hours. Phosphor is used to give the aggregate its luminescent properties, much like the Starpath product. A section 100 m long and 2 m wide was completed for 120 000 zł (Polish zloty) (STRABAG 2016), equivalent to approximately AUD $41 265 or $206/$m^2$ (XE 2019, current as at 30 April 2019). No additional information was found on the current development of the TPA product since its trial run in 2016 .

Moon Deck, previously mentioned, also offers a luminescent pavement surfacing product known as ‘Glow Path’ (Figure 2.9) which is based on similar technology to its Glow Lines technology described in Section 2.1. This offers the same glow and wearing characteristics as the Glow Lines product but is intended for use across the entire width of asphalt pedestrian and bicycle paths. Successful implementation of the Moon Deck line marking products led to a full width trial in Rochedale, Brisbane in 2018. The product has an expected life of approximately 25 years and costs $105/m^2 (McCosker 2017). In a conversation with Tony Galletly of Brisbane City Council indications were that the 2018 trial in Rochedale was not considered successful, pointing to concerns regarding maintenance and the luminous performance of the product. Furthermore, relying solely on the sun to charge the luminescence resulted in an underperforming, inconsistent appearance caused by shading and cloud cover. The solution to these issues was a priming activity where the lines were charged.

Figure 2.9: Moon Deck pavement markings

Source: Moon Deck (n.d).

Texas A&M based in the USA commenced trialling the use of glow-in-the-dark bike lanes on campus in late 2016 to determine if it can improve safety for road users at a pedestrian crossing (Peters 2017). Published findings on these trials were not found, however when reviewing photos of the site (Figure 2.10 and Figure 2.11) it is evident that the pavement marking is not illuminating (or providing retroreflectivity) on the through road. The pavement marking does not appear to contrast with the pavement surface and may not be detected by automated vehicles. In this instance the pavement marking on the through road is the most critical location as it identifies to drivers that cyclists (or pedestrians) may be entering the road.

Figure 2.10: Cycling lane and pedestrian pavement markings

Source: Houston Chronicle 2016

Figure 2.11: Cycling lane and pedestrian pavement markings

Source: Houston Chronicle 2016

2.2.2 Compliance with Pavement Marking Standards

The requirement for road marking products to meet reflectivity and skid resistance values is in accordance with Specification 604 (MRWA 2017a) and AS 4049.3, as outlined in Section 2.1.2.

Due to the large surface area covered and expected usage by cyclists and pedestrians on footpaths, and vehicles and motorcycles at diverge, merge, turning lanes and pedestrian crossings it is particularly important that the skid resistance values are met after installation and remain above the required levels throughout the operational lifetime.

Pro-Teq claims that its product has been tested by National Measurement Accreditation Service (NAMAS) laboratories in the UK. The tests included were skid resistance, salt ingress, maintenance, temperature sensitivity, wear and abrasion; this would support potential development as a road marking product (SRRB 2014). At the time the SRRB report was written it was reported that the testing had not been completed. No updated information regarding the progress of the testing could be found.

2.2.3 Implications for Autonomous Vehicle Technology

To date the Pro-Teq, TPA and Moon Deck products have only been used on pedestrian and bicycle pathways for improved night-time visibility. Should these be used on the road, challenges with machine vision and the contrast resulting from the green colour could arise (as discussed in Section 2.1.3). Additional challenges may include the identification of pavement markings which are required for decisions related to preparing to slow for pedestrians, identifying where to change lanes and carrying lane changes within the available lane merge/diverge lengths.

2.2.4 Suitability for Implementation

The review of luminescent pavement markings indicates that although they can provide a luminous effect that would convey messages to a road user beyond the lights of their own vehicle or on a footpath without the need for path lighting the technologies are still in the early stages of development and a number of limitations were identified. Based on the information that was available to review the limitations for on-road and off-road use are as per those identified for luminescent line marking in Section 2.1.4 . In addition to those limitations it has also been identified that luminescent pavement markings used to identify locations where vehicles and pedestrians interact (e.g. on-road cycle paths, pedestrian/cyclist crossings) may not perform as well as traditional pavement marking.

Due to the limited published results and lack of quantifiable performance of reflectivity levels (day and night) a trial would need to be undertaken to gain an understanding of performance before widespread installation could be undertaken. As the products are proprietary and still in development it is unlikely that reliable performance data would be able to be provided from a supplier or installer.

Although it has been identified that Luminescent pavement markings may not be suitable for widespread on-road implementation it may be viable to consider widespread off-road trial applications.

The evaluation of luminescent pavement markings is summarised in Table 2.3.

Table 2.3: Evaluation of luminescent pavement marking

Review criteria		Luminescent pavement marking
Current practice domestically and internationally		▪ Pathway trials only – unsuccessful and not implemented on a large scale due to luminescence issues.
Applicability/ performance	Expected lifecycle	▪ 25 years (product dependent and unconfirmed).
	Maintainability	▪ No published information.
	Implications for autonomous vehicle technology	▪ No published information.
	Reflectivity performance in dry conditions	▪ No noted reflectivity, although visibility is high when adequate charge is received during daylight and during the limited time frame before the charge is exhausted. ▪ Quantified Qd levels could not be sourced.
	Reflectivity performance in wet conditions	▪ No noted reflectivity.
Compliance with AS and MRWA standards	Visible ahead of a vehicle	▪ No published information.
	Retroreflectivity	▪ No published information.
	Diffused reflectivity (Qd)	▪ No published information.
	Skid resistance (BPN)	▪ No published information.
Availability/cost	Supplier location	▪ Australia (Moon Deck), Germany (TPA) and the UK (Pro-Teq).
	Cost	▪ $83/m^2 – $206/m^2
Potential safety benefits	Self-explaining road	▪ As the performance and compliance with existing linemarking is unknown it is difficult to hypothesise the safety benefits. For example, the ability to convey pavement marking messages on the road beyond the reach of headlights is advantageous, however the longevity of that delineation throughout the night, unknown performance in wet weather and potentially reduced visibility of linemarking within range of the headlights would be disadvantageous. ▪ Crash reductions could be expected on off-road applications, particularly if lighting was not previously provided. ▪ There are no published studies reporting the safety benefits or disbenefits.
Financial benefits	Implementation and maintenance	▪ Indications of quick installation. No published information of maintenance requirements.

Review criteria		Luminescent pavement marking
	Crash reduction	▪ As the performance and compliance with existing linemarking is unknown it is difficult to hypothesise the safety benefits. For example, the ability to convey pavement marking messages on the road beyond the reach of headlights is advantageous, however the longevity of that delineation throughout the night, unknown performance in wet weather and potentially reduced visibility of linemarking within range of the headlights would be disadvantageous. ▪ Crash reductions could be expected on off-road applications, particularly if lighting was not previously provided. ▪ There are no published studies reporting the safety benefits or disbenefits ▪ No published information.
Relevance to current MRWA practice		▪ Does not demonstrate it would comply within current specifications.

2.3 Solar-powered Road Studs

Retroreflective Raised Pavement Markers (RRPMs) are used to augment painted lines, stripes and chevrons when it is deemed necessary or desirable to improve their visual properties. As devices that are considered to be at same level as the road surface, RRPMs are intended to be trafficable when placed within a painted island or median strip (AS 1742.2 2009). RRPMs generally provide more effective and durable pavement markings than painted lines because:

(a) they are not generally obscured at night under wet conditions

(b) they provide an audible and tactile signal when traversed by vehicle wheels

(c) they are conspicuous in all conditions.

RRPMs are fitted with a passive retroreflective panel which operates by reflecting a portion of the light from the vehicle headlights back to the driver. Evidently these will only function if and when a vehicles headlights are on the RRPM. In low visibility conditions, passive reflectors receive reduced light intensity from vehicle headlights and hence the intensity of reflected light is insufficient for reliable road-edge marking (Samardzija et al. 2012).

Solar-powered LED road studs provide the same benefits as RRPMs however as they are not reliant on headlights and remain actively illuminated in all weather conditions delineation should be increased beyond the reach of headlights by up to 1 km (Boyce 2009). The expected benefits include identifying road geometry as well as lane drops and divergences beyond the reach of vehicle headlights. Additionally, as the performance should not be affected by a film of water (in wet conditions) the LED road studs should provide a self-explaining road during low-visibility conditions.

Figure 2.12: Aluminium hybrid retroreflective/solar road stud

Source: SA Road Studs (n.d).

Figure 2.13: Solar Flex Aluminium hybrid retroreflective/solar road stud

Source: Roadsafe Company (n.d.b)

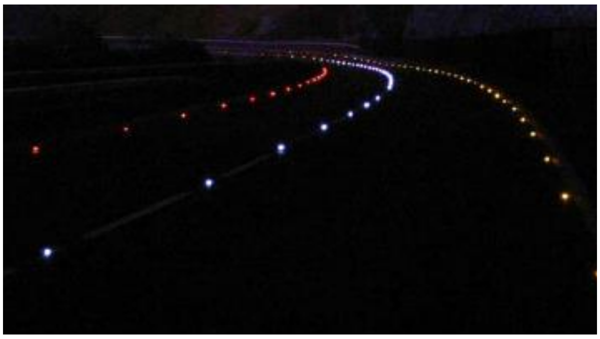
2.3.1 Domestic and International Applications

Hybrid Solar-powered studs – LED light with retroreflective panel

Among the case studies published, trials and implementation of solar-powered road studs have indicated that usage can have a positive impact on road safety using a relatively low-cost technology. Active road studs or internally illuminated pavement markers (IIPMs) are used in the USA and Canada at pedestrian crossings and in Malaysia at traffic light intersections. Research conducted in the UK on IIPMs used for lane delineation found that drivers exerted better lateral control over the vehicle as well as more consistent and earlier braking in a driving simulator study (TRL 2006).

The use of solar-powered road studs was approved by the UK Department of Transport in 2014 (World Highways 2014) and these technologies are currently still in use (UK Roads 2017). A case study in Norfolk UK involved placing hybrid solar-powered road studs (not clearly defined as a hybrid, however the brand mentioned is predominantly a hybrid product) along the centreline of the A143 road in a fog-prone area. Along the route there were 22 accidents in 3 years, of which 40% occurred at night, 60% occurred in wet conditions of which 8 resulted in fatalities. After the installation, the accident frequency dropped from 7.3 to 2.3 per year of which none were at night, 20% were in wet weather and the fatalities dropped to zero (TRL 2006). Other applications of road studs were on the M8 in Glasgow and A24 in Surrey, for which no before-and-after results were included in the report.

Figure 2.14: Clearview hybrid retroreflective/solar road stud on rural road



Source: TRL (2006)

Figure 2.15: Clearview hybrid retroreflective/solar road stud on urban road

Source: TRL (2006)

In 2003, solar-powered road studs, with unknown retroreflective abilities, were trialled in South Africa on a road that had 103 night-time accidents in the 7 months prior to installation. In the 12 months following installation, the number of night-time accidents had been reduced by 70%, suggesting that the clear delineation of the road boundaries could reduce the number of accidents (Holdridge 2012). A recent study by Shahar, Bremond and Villa (2016) on active road studs, using a driving simulator, found that they appeared to produce substantially lower speed variances and decreased lateral displacement around bends when compared to unlit and traditional street lighting conditions.

An Australian study (Styles et al. 2003) found that whilst safety benefits were promising for hybrid solar-powered studs they did not have consistent on-off thresholds in fading light, fog and low temperatures and their performance can be reduced by damage by vehicles and their vulnerability to theft and damage. The ‘Before and after’ statistics an observational study of four hundred vehicles travelling at night along a stretch of road between two bends found that the speed through the installation site was reduced due to the new studs. Also, there was a reduction in the tendency of drivers to travel on or over the centreline. This is a particularly favourable finding as the risk of head-on collisions will be similarly reduced. Installation of the new studs seemed to encourage drivers to place their vehicle further from the centre of the road in only some circumstances; it is suggested that perhaps in some situations travelling close to a well-defined centre line may be more comfortable than travelling close to a poorly-defined road edge and this may account for the variability.

A study by Ross (2008) noted that a trial conducted in British Columbia led to additional installations and development of the technology, leading to more reliable and more durable products, indicating that the initial issue of the road studs being insufficiently robust may have been solved, however this may be product dependent. The Australian based Roadsafe Company (n.d.b) states that its Solar Flex Alu (Figure 2.13) can withstand over 20 tons (approximately 18 tonnes) of loading, are visible from distances greater than 500 m, are available in multiple colours and lasts up to 72 hours after a full charge in a steady state, although the studs can be set to a flashing state which increases there operating time. The company has Solar road studs with and without retroreflective abilities, however the one discussed above does have retroreflectivity.

Indicative prices from Advanced Group (2019), for two-way white retroreflective road studs are $2.50 and $29 for hybrid retroreflective and solar road studs, resulting in solar road studs being approximately 12 times the price of standard RRPMs. Based on a typical spacing of RRPMs on two-lane two-way roads of 24 m (in accordance with MRWA (2017b)), a 1 km stretch would cost approximately $104 for retroreflective road studs and $1208 for hybrid retroreflective and solar road studs, a difference of $1104 per km. It is also important to note that another supplier (The Roadsafe Company) offers a range of solar powered products some with and without retroreflectivity ranging from $41 to $58.

In conversation with staff of Brisbane City Council indications were that experience with solar road studs have shown that their quality and performance vary considerably, as does their cost. They did not disclose which products they used for this trial.

New developments in road stud technology have led to the emergence of intelligent road studs. These applications consist of stud sections which are turned on when vehicles have been detected by sensors and are switched off after the vehicle has passed (Samardzija et al. 2012; Shahar & Bremond 2014 Shahar, Bremond & Villa 2018). The benefits of using intelligent road lighting systems are similar to solar-powered road studs (as discussed in Section 2.3) but with reduced operational time which may extend the life of the LEDs and reduce the required maintenance frequency; however, this will require communication between devices which could increase costs and/or system complexity as well as the number of points of failure. It is envisaged that intelligent road studs will cost more than the already high cost of non-intelligent solar-powered LED studs.

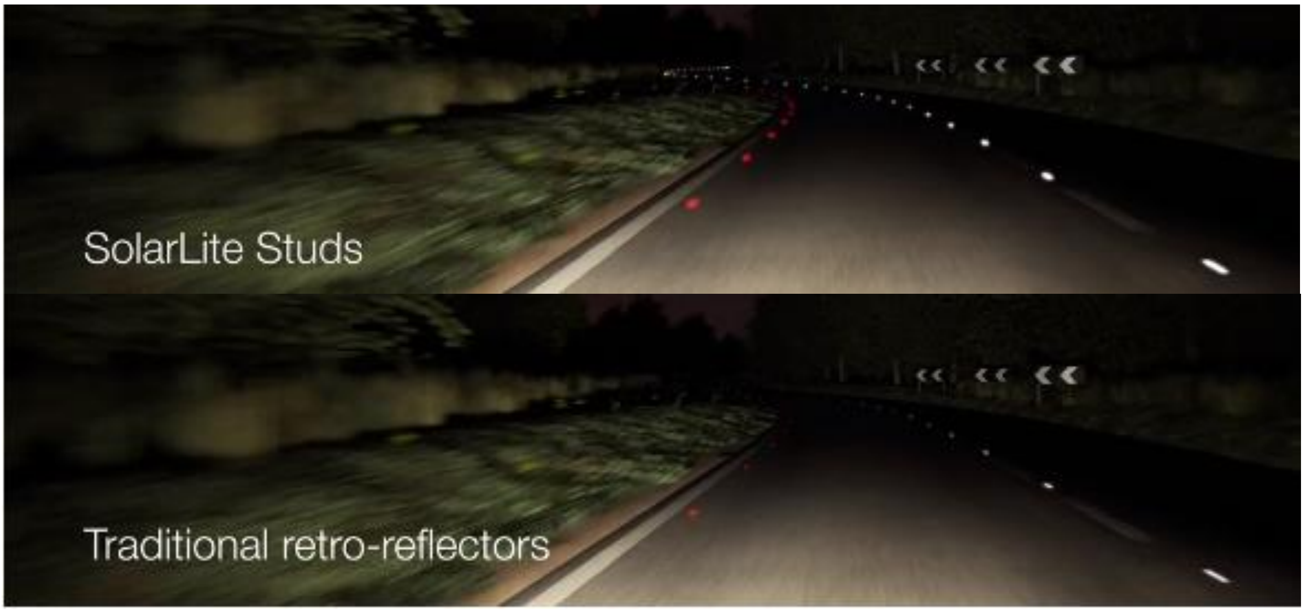
Solar-powered studs – LED light only

A TRL (2006) report states that the most obvious advantage of active studs is increased visibility – forward illumination can be increased from 100m (with passive retroreflective studs) to approx. 900m, irrespective of headlight intensity. 'Preview times' are therefore extended, alerting drivers to potential hazards earlier and leading to a higher level of driving control. ('Preview' is a measure of distance, expressed in time or length, at which the marker must be visible to allow the driver to respond safely. Preview times will depend on sight distance and speed (Mole, 2002)). Active studs can be used where conventional road marking is limited in use, for example, they can provide road layout guidance in daylight hours and in adverse weather conditions. Active studs can detect fading light levels, moisture on the road, fog, icy conditions etc and automatically activate the required level of illumination.

Figure 2.16: SolarLite F Series Flush Road Studs (LED only)

Source: Clearview Intelligence (n.d.c)

Figure 2.17: SolarLite road studs (LED light only)



Source: Clearview Intelligence (n.d.c)

The same TRL report (TRL 2006) tests the benefits of solar studs (Solar-powered LED light only) by using TRL's full mission driving simulator to create a length of rural A-road on which participants' behaviour was assessed when driving the same road with no RRPMs, retroreflective road studs and solar-powered road studs. Thirty six participants were recruited from three age groups: Younger (17-25 years), Middle (26-54 years), and Older (55+ years) to complete the trial. Each participant drove a 37.1km trial route twice (Figure 2.14 and Figure 2.15). The trial route had lead-in and run-out sections but the test section that was used for comparing across stud conditions comprised six repeats of a basic trial section (three of which were the basic section rotated through 180°). Rotating the basic section reduced participants' awareness that they were driving through the same corners repeatedly.

Figure 2.18: On-road hybrid retroreflective/solar road stud on rural road

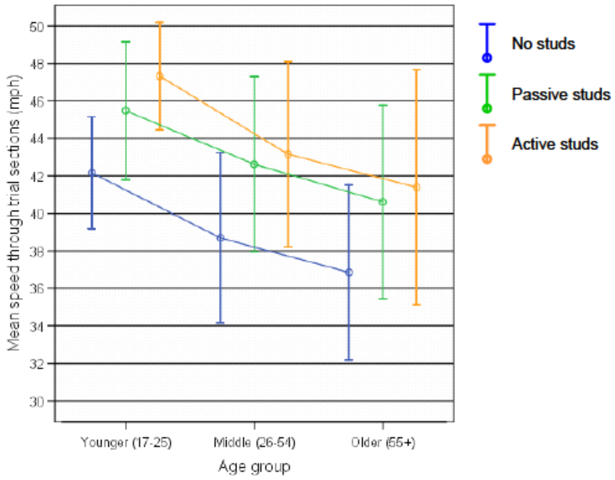
Source: TRL (2006)

Figure 2.19: Simulator retroreflective/solar road stud on rural road

Source: TRL (2006)

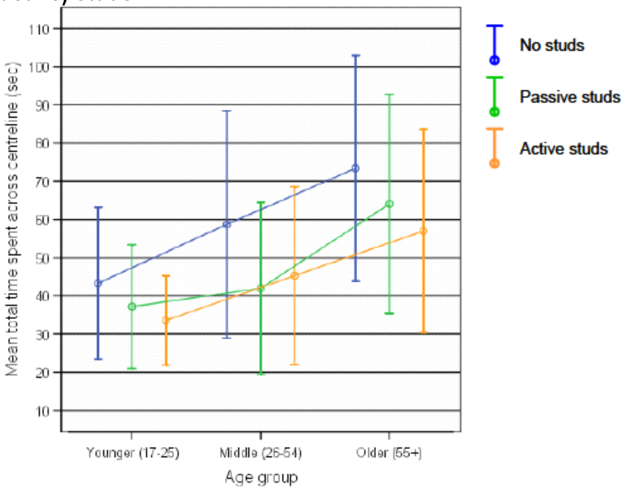
The results (Figure 2.20 and Figure 2.21) demonstrated the following when driving the course when solar studs were provided; higher course speeds and less time crossing the centreline. Each participate completed a questionnaire, collectively responding that they felt safer when driving the course with solar studs and felt the road was more self-explaining with solar studs (Figure 2.22 and Figure 2.23).

Figure 2.20: Simulated course speeds with solar (active) studs



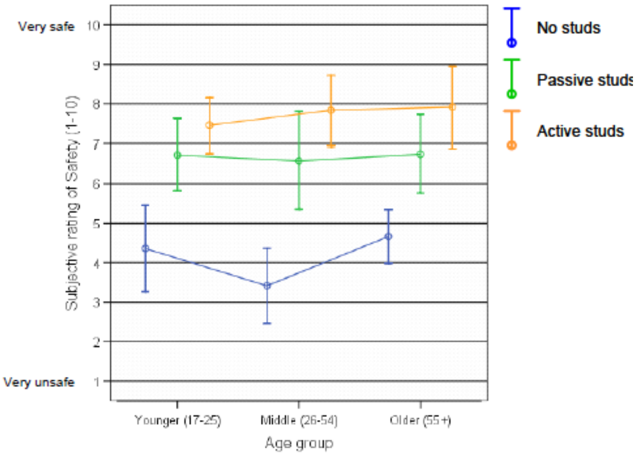
Source: TRL (2006)

Figure 2.21: Simulated course lane position with solar (active) studs



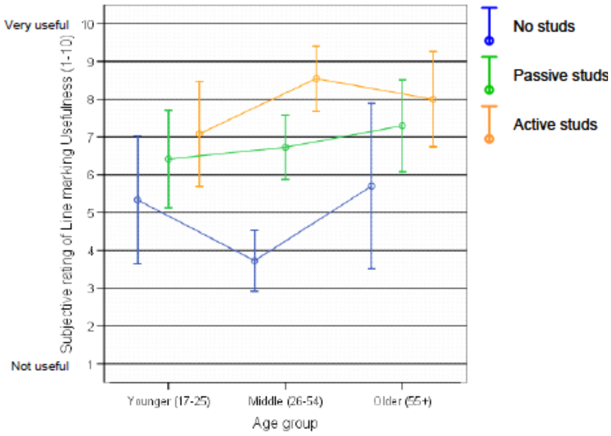
Source: TRL (2006)

Figure 2.22: Simulated course subjective safety ratings



Source: TRL (2006)

Figure 2.23: Simulated course with solar (active) studs contribution towards providing a self-explaining road



Source: TRL (2006)

Figure 2.24: Solar-powered road stud (LED only)

Source: Swinford (2015)

Note: Product name not provided

Swinford (2015) reports that ministers in the UK are prepared to amend traffic legislation to allow a new generation of LED road studs (without retroreflective strips) to be used on British roads which can be seen up to 900 m ahead, 10 times further than retroreflective pavement markers (RRPMs). It is claimed that the lights (Figure 2.24) are capable of working for up to 10 days with just four hours of charge, and cost the same amount over the course of their life as traditional cats eyes. They cost £30 (approximately AUD $54.46 based on XE (2019) exchange rates as at 21 March 2019) and last for between eight and 10 years. By contrast cats eyes cost around £10 (approximately AUD $18.11 based on XE (2019) exchange rates as at 21 March 2019) and last for between two and three years before they need replacing.

2.3.2 Compliance with Pavement Marking Standards

The requirements for RRPMs in accordance with MRWA Specification 604 and AS/NZS 1906.3 are presented in Table 2.4.

Table 2.4: Minimum requirements for RRPMs

Colour	MRWA requirements (mcd/lx)	AS/NZS 1906.3 requirements (mcd/lx)
White	10	70
Yellow	6	35
Red	3	15

Source: MRWA (2017a) for class A markers at minimum observation and entrance angle.

Current requirements regarding the luminosity of active traffic signals and symbolic displays are covered in AS/NZS 2144, specifying minimum luminous intensities in candelas, as summarised in Table 2.5. These requirements would be a useful reference in measuring and evaluating the visibility of LED road studs compared to current RRPMs and technology utilising LEDs.

Caution should also be taken that the LED lights are not too bright, producing a halo effect or creating temporary spotting to a driver's vision.

The Roadsafe Company website (The Roadsafe Company n.d.a) stated that their Solar-powered road studs produced 500 lux This was self-reported a would require testing to confirm, however it does illustrate the potential of current LED technology to output high lumen values.

Table 2.5: Summary of minimum requirements for LED lanterns

Colour	Traffic lights (cd)	Symbolic displays (cd/m^2)
Red	750	5,000
Yellow	1,560	10,400
Green	825	5,500

Note: All minimums are for the geometric centre of the light source (aspects).
Source: AS/NZS 2144

2.3.3 Implications for Autonomous Vehicles

The materials reviewed did not mention if RRPMs would or would not influence automated vehicles. It is understood (but not published) that automated vehicles do not rely on RRPMs.

2.3.4 Suitability for Implementation

Two types of Solar-powered studs were identified; Hybrid solar-powered road stud (LED light and retroreflective panel) and Solar-powered road stud (LED light only).

Both the hybrid and LED only solar-powered road studs indicated to assist in providing a self-explaining road at night by delineating the alignment, lane designation and formation width beyond the head lights of a vehicle. Both the hybrid and LED only products have demonstrated crash reductions through trials (inclusive of in diminished visibility conditions such as fog) and received positive results through vehicle simulator trial when comparing the sense of safety and clear delineation of an alignment (compared to traditional RRPMs). The review identified the following limitations:

- Durability, particularly on roads with heavy vehicles. The later literature reviewed indicated this may have been addressed however there was no tangible evidence found.

- Studs operating in a flashing state or flickering due to low charge or a malfunction were distracting to drivers
- The cost per stud varies significantly. The cost of a hybrid and LED only stud was not clearly identified.
- The time of which a LED light can remain active varies dependent on product, all of which are not backed up by trial data:
  - Clearview (2019) hybrid surface studs claims to provide light for 3 hours when on full charge (after a sunny day)
  - Clearview (2019) LED only road studs claim to provide 10 hours of light after only a few hours of sunlight to charge
  - Solar Flex AU (Roadsafe Company (n.d.b) hybrid surface studs claims to provide light for 72 hours when on full charge (after a sunny day)
- Some suppliers claim that solar powered studs last 4 times longer than RRPMs, however the number of years is not provided (no trial data to back this up). It also unknown over what time period (years) a solar stud will sustain the claimed times (3-72 hours) of illumination.

The evaluation of solar-powered road studs is summarised in Table 2.6.

Table 2.6: Evaluation of luminescent solar-powered road studs

Review criteria		Solar-powered road studs
Current practice domestically and internationally		▪ Multiple trials – improved safety benefits with inconsistent reports on durability.
Applicability/ performance	Expected lifecycle	▪ Some suppliers claim that solar-powered studs last up to 4 times longer than traditional RRPMs.
	Maintainability	▪ No published information, however, individual units should be easily replaceable.
	Implications for autonomous vehicle technology	▪ No published information.
	Reflectivity performance in dry conditions	▪ Hybrids have retroreflective aspects which could perform at current specifications as well as a claimed 72 hr illuminated steady state (not backed by independent testing or trials). ▪ Anecdotal evidence suggests that visibility may be superior to conventional RRPMs as they are internally illuminated.
	Reflectivity performance in wet conditions	▪ No published information. ▪ Anecdotal evidence suggests that visibility may be superior to conventional RRPMs as they are internally illuminated.
Compliance with AS and MRWA standards	Visible ahead of a vehicle	▪ Greater than 500 m (product dependent and unconfirmed).
	Retroreflectivity	▪ No published information.
	Skid resistance (BPN)	▪ No published information.
Availability/cost	Supplier location	▪ Australia (Advanced Group, The Roadsafe Company), South Africa, USA and UK.
	Cost	▪ $29 (Without retro reflectivity) – $58 (With retro reflectivity) each.
Potential safety benefits	Self-explaining road	▪ The safety benefits may be related to the road user's ability to see the road curvature at a greater distance than current retroreflective road markings allow. ▪ A controlled driver behaviour simulator study identified less frequent centre line crossovers and a high level of confidence in identifying and driving a rural road with solar-powered road studs.
Financial benefits	Implementation and maintenance	▪ Individual units do not require wiring. Anecdotal evidence indicates that they may be easily installed and replaced although no published information could be sourced.
	Crash reduction	▪ Reduction of run-off road crash rate from 7.2 to 2.3 per year, none of the 2.3 per year were at night. ▪ 70% reduction in night-time accidents (all severities).

Review criteria	Solar-powered road studs
Relevance to current MRWA practice	▪ MRWA Specification 604 Clause 53 *Performance Criteria for Raised Reflective Pavement Markers*. ▪ AS/NZS 2144 *Traffic Signal Lanterns*.

2.4 Solar–powered Guardrail Lights

Guardrails, also referred to as road safety barriers, are physical barriers designed to prevent vehicles from impacting roadside obstacles and running off the road. MRWA classifies safety barriers into three categories: flexible systems such as wire rope or water-filled barriers, semi-rigid systems made of steel, and rigid systems constructed using concrete (MRWA 2017c). Semi-rigid barriers are typically used for sharp curves in the road as flexible barriers may not be able to withstand impact while rigid barriers do not allow any deflection.

The purpose of barriers is to mitigate the consequences of run-off-road accidents. Clear marking of the barriers serves the purpose of ensuring that they do not become a contributing factor to other types of incidents, as well as communicating the road geometry to the driver. Retroreflective markers typically used for delineation on road safety barriers are referred to as delineators; the limitation with retroreflective delineators is that they will only illuminate when a light source (headlights) strikes the reflective aspect of the delineator. Similar to RRPMs, guardrail reflectors receive a reduced light intensity from vehicles in poor visibility conditions such as fog and rain and thus the intensity of reflected light may be insufficient.

Illuminated delineators can be designed to provide illumination from a wider range of viewing angles, giving a more consistent, complete, and clear indication of road curvature compared to retroreflective options (Voight 2008).

2.4.1 Domestic and International Applications

Literature regarding LED delineators in guardrail applications is limited, covering only the performance of barriers during impacts for project trials conducted in the USA.

A study by Voight et al. (2008) reported the findings of a trial conducted near Mount Pleasant, Texas on a curve in a rural area with no safety lighting where road users were frequently leaving the road and running into traffic control devices such as chevrons. In an effort to enhance curve delineation, solar-powered markers were mounted on the existing chevron posts (Figure 2.25). However, the observed luminous intensity was less than desired, owing to large trees in the area limiting solar charging. To remedy the charge limitation issues, the solar-powered system was modified, and the solar component replaced to a hardwired alternating current (AC) power source, which led to an improvement in the luminous intensity. In order to conserve power, the system was activated by vehicles exceeding the speed limit measured by an upstream radar. The system cost approximately USD $15 000 and Texas Department of Transportation (TxDOT) personnel noted that was not a low-cost option; however, it was warranted given the specific site conditions (Voight et al. 2008). A formal evaluation had not been completed at the time the report was published.

Figure 2.25: LED (only) applications for horizontal alignments(Mount Pleasant, Texas)

Source: Swinford (2015)

Note: Product name not provided

Based on the perceived success of the project near Mount Pleasant, a project in Texarkana, Texas made use of illuminated markers on a fly-over with a history of road users impacting the barrier (Figure 2.26). The markers were powered by an AC power source over half a mile (approximately 800 m), which created some technical challenges relating to voltage drops along the length. Personnel from TxDOT indicated that the system cost USD $56 000. A formal evaluation of the effectiveness of the system had not been completed at the time the report was written, however anecdotal feedback from the local authorities reported less evidence of impacts with the barriers after the system was installed (Voight et al. 2008). The finalised system configurations discussed above were not solar-powered, however they did perform the same task as a solar-powered delineator, with anecdotal evidence that illuminated delineators would improve conditions.

Figure 2.26: LED (only) applications for horizontal alignments (Texarkana, Texas)

Source: Voight et al. (2008).

Examples of independent solar-powered hybrid retroreflective/ LED delineators are shown in Figure 2.27. Emails with P. Hardi from The Road Safe Company on March 12, 2019 indicated that these independent solar-powered hybrid retroreflective/ LED delineators guardrail markers cost AUD $45 per unit.

A United States based supplier (Isolardesign 2018) provides the Solar Guard Rail product (Figure 2.28). This product has only an LED (no retroreflective panel as a backup). The supplier claims that it is visible from up to 800 m at night in good and bad weather conditions. It is unclear how this product mounts to the guardrail, however based on the images it appears it mounts flush to the surface and is the same product as used in the Texas trails (Figure 2.26).

Figure 2.27: Hybrid retroreflective/solar LED guardrail markers

Source: The Roadsafe Company (n.d.a).

Figure 2.28: Solar-powered LED (only) guardrail markers

Source: Isolardesign 2018

Similarly, to solar-powered road studs, it's hypothesised that solar-powered guardrail lights may also be easily stolen if not fixed securely, however if they are fixed securely, they present as a hazard for errant motorcyclists. A fixture that protrudes from the Guardrail profile may induce bone breakages or internal injuries to a motorcyclist. Consideration to the bolts/mounts that may be left after damage or theft also need to be considered, Figure 2.29 shows the underside of a delineator which indicates it may be mounted on a lug like fixture.

Figure 2.29: Hybrid retroreflective/solar LED guardrail markers

Source: Wistron (n.d.a)

2.4.2 Compliance with Pavement Marking Standards

Delineators are small retroreflectors or panels of retroreflective material which may be used separately or attached to guideposts or safety barriers as effective aids for night driving. Class 1A retroreflective delineators applied to barriers need to conform to AS/NZS 1906.2 (MRWA 2018a). The requirements are listed in Table 2.7.

Table 2.7: Reflectivity requirements for non-pavement applications

Colour	Reflectively requirement (cd/lx)
White	7
Yellow	5.25
Red	1.4

Note: For minimum entrance and observation angles.
Source: AS/NZS 1906:2-2007.

Similar to the solar-powered road studs, requirements regarding the luminosity of active traffic signals and symbolic displays are covered in AS/NZS 2144, specifying minimum luminous intensities in candelas, as summarised in Table 2.8. These requirements would be a useful reference in measuring and evaluating the visibility of LED delineators compared with current RRPMs and technology utilising LEDs.

Caution should also be taken that the LED lights are not too bright, producing a halo effect, or creating temporary spotting to a driver's vision.

Table 2.8: Summary of minimum requirements for LED lanterns

Colour	Traffic lights (cd)	Symbolic displays (cd/m^2)
Red	750	5,000
Yellow	1,560	10,400
Green	825	5,500

Note: All minimums are for the geometric centre of the light source (aspects).
Source: AS/NZS 2144.

2.4.3 Implications for Autonomous Vehicles

The implications for autonomous vehicles and whether solar-powered guardrail delineators may be readily detected using machine vision and LDWS are not reported in any of the reviewed literature. However, the literature indicates that delineators may be linked to radar technology to provide vehicle-activated delineation at installation locations.

2.4.4 Suitability for Implementation

Information regarding solar-powered guardrail light installations or trials was limited. However a number of trials using powered (hard wired) solar-powered guardrail light installations were found, these indicated that the benefits of implementing this technology would be similar those of providing solar road studs (as discussed in Section 2.3).

The Roadsafe Company (n.d.b) states that the hybrid retroreflective solar LED guardrail markers have a 4-year lifespan, can be seen from distances greater than 1 km and have a working life of approximately 80 hours in a steady state emitting 2000 mcd when fully charged, not tested. Although the literature evaluated the effect of wired installations, commercially available solar-powered delineators which are independently powered by attached solar panels may be assumed to have the same benefits. In the event that a vehicle impacts the barrier, damaged delineators could be individually replaced as each delineator is independent of another.

Table 2.9 summarises the evaluation of luminescent solar-powered guardrails.

Table 2.9: Evaluation of luminescent solar-powered guardrails

Review criteria		Solar-powered guardrails
Current practice domestically and internationally		▪ Few trials – solar-powered options were unsuccessful; however, AC-connected options were anecdotally successful.
Applicability/ performance	Expected lifecycle	▪ 4 years (product dependent and unconfirmed).
	Maintainability	▪ No published information, however, individual units should be easily replaceable.
	Implications for autonomous vehicle technology	▪ No published information.
	Reflectivity performance in dry conditions	▪ Hybrids have retroreflective aspects which could perform at current specifications as well as 80 hrs LED illumination (2,000 mcd) at a steady state (not tested). ▪ Anecdotal evidence suggests that visibility may be superior to conventional delineators as they are internally illuminated.
	Reflectivity performance in wet conditions	▪ No published information. ▪ Anecdotal evidence suggests that visibility may be superior to conventional delineators as they are internally illuminated.
Compliance with AS and MRWA standards	Visible ahead of a vehicle	▪ Greater than 1 km (product dependent and unconfirmed).
	Retroreflectivity	▪ No published information.
Availability/cost	Supplier location	▪ Australia (The Roadsafe Company), UK and USA.
	Cost	▪ $45 each.
Potential safety benefits	Self-explaining road	▪ The safety benefits may be related to the road user's ability to see the road curvature at a greater distance than current retroreflective delineators allow. ▪ No quantitative data could be sourced.
Financial benefits	Implementation and maintenance	▪ Individual units do not require wiring. Anecdotal evidence indicates that they may be easily installed and replaced although no published information could be sourced.
	Crash reduction	▪ No published information.
Relevance to current MRWA practice		▪ MRWA *Design of Guide Posts* (MRWA 2018a). ▪ AS/NZS 1906.2 *Retroreflective Devices (Non-pavement Application)*. ▪ AS/NZS 2144 *Traffic Signal Lanterns*.

2.5 Summary and Discussion

The literature review generally found that there was limited published information for each of the different technologies due to their novelty, and, as such, no safety benefit analyses could be conducted. In relation to autonomous vehicles, no published information could be sourced for any of the reviewed technologies to indicate their suitability for machine vision or lane detection warning systems.

Luminescent line marking and luminescent pavement marking both had little to no information regarding performance indicators or any potential safety benefits for road users. Both technologies were noted to have underperformed in field trials. At a cost of up to $206/m^2$, luminescent pavement marking is not currently economically feasible for implementation.

Previous studies evaluating the effectiveness of solar-powered road studs have indicated that this technology has the potential to reduce night-time crash incidence . This includes a reduction up to 70% in night-time accidents (all severities) on a trial section in South Africa. However, the information from these studies was insufficient to conduct a safety benefit analysis compared to current road delineation practice in WA, namely the use of RRPMs. Solar-powered road studs are available on the commercial market as hybrid solar-powered LEDs and retroreflective pavement markers at a cost ranging from $29 to $44 each and may be implemented in intelligent traffic systems.

In reviewing the literature, very little was found on the association between solar-powered guardrail lights and safety improvements for road users. Previous studies noted that AC-powered guardrail lights at problem areas could successfully reduce the number of accidents, although this was based on anecdotal evidence and, as such, a safety benefit analysis compared to current delineation technologies could not be conducted. One Australian supplier priced hybrid solar-powered LEDs and retroreflective delineators at approximately $45 each.

While the literature review did not confirm the applicability of luminescent line marking or luminescent pavement marking, MRWA may consider undertaking performance trials for solar-powered road studs and solar-powered guardrail lights to evaluate their performance and the costs and benefits from usage. The proposed performance trial requirements for these technologies is outlined in Section 3.

A summary of each of the lane demarcation technologies reviewed for this project is presented in Table 2.10.

Table 2.10: Summary of reviewed technologies

Review criteria		Luminescent line markings	Luminescent pavement marking	Solar-powered road studs	Solar-powered guardrail lights
Current practice domestically and internationally		▪ Netherlands-based trial only – unsuccessful and not implemented on a large scale.	▪ Pathway trials only – unsuccessful and not implemented on a large scale due to luminescence issues.	▪ Multiple trials – improved safety benefits with inconsistent reports on durability.	▪ Few trials – solar-powered options were unsuccessful; however, AC-connected options were anecdotally successful.
Applicability/ performance	Expected lifecycle	▪ 25 years (product dependent and unconfirmed).	▪ 25 years (product dependent and unconfirmed).	▪ Some suppliers claim that solar-powered studs last up to 4 times longer than traditional RRPMs.	▪ 4 years (product dependent and unconfirmed).
	Maintainability	▪ No published information.	▪ No published information.	▪ No published information, however, individual units should be easily replaceable.	▪ No published information, however, individual units should be easily replaceable.
	Implications for autonomous vehicle technology	▪ No published information.	▪ No published information.	▪ No published information. Additionally, intelligent systems utilising IIPMs have been developed.	▪ No published information.
	Reflectivity performance in dry conditions	▪ No noted reflectivity, although visibility is high when adequate charge is received during daylight and during the limited time frame before the charge is exhausted. ▪ Quantified Qd levels could not be sourced.	▪ No noted reflectivity, although visibility is high when adequate charge is received during daylight and during the limited time frame before the charge is exhausted. ▪ Quantified Qd levels could not be sourced.	▪ Hybrids have retroreflective aspects which could perform at current specifications as well as a claimed 72 hr illuminated steady state (not backed by independent testing or trials). ▪ Anecdotal evidence suggests that visibility may be superior to conventional RRPMs as they are internally illuminated.	▪ Hybrids have retroreflective aspects which could perform at current specifications as well as 80 hrs LED illumination (2,000 mcd) at a steady state (not tested). ▪ Anecdotal evidence suggests that visibility may be superior to conventional delineators as they are internally illuminated.
	Reflectivity performance in wet conditions	▪ No noted reflectivity. ▪ Visibility diminishes in wet conditions which has been indicated to be inadequate for road delineation.	▪ No noted reflectivity.	▪ No published information. ▪ Anecdotal evidence suggests that visibility may be superior to conventional RRPMs as they are internally illuminated.	▪ No published information. ▪ Anecdotal evidence suggests that visibility may be superior to conventional delineators as they are internally illuminated.
Compliance with AS and MRWA standards	Visible ahead of a vehicle	▪ Yes, when charge is not exhausted. However, visibility is diminished immediately in front of the vehicle under headlights.	▪ No published information regarding vehicle visibility.	▪ Greater than 500 m (product dependent and unconfirmed).	▪ Greater than 1 km (product dependent and unconfirmed).
	Retroreflectivity	▪ No published information.	▪ No published information.	▪ No published information.	▪ No published information.
	Diffused reflectivity (Qd)	▪ No published information.	▪ No published information.	▪ No published information.	▪ No published information.
	Skid resistance (BPN)	▪ No published information.	▪ No published information.	▪ No published information.	▪ N/A.
Availability/cost	Supplier location	▪ Australia (Moon Deck) and the Netherlands (Heijmans).	▪ Australia (Moon Deck), Germany (TPA) and the UK (Pro-Teq).	▪ Australia (Advanced Group, The Roadsafe Company), South Africa, USA and UK.	▪ Australia (The Roadsafe Company), UK and USA.
	Cost	▪ No published information.	▪ \$83/m^2 – \$206/m^2.	▪ \$29 (Without retro reflectivity) – \$58 (With retro reflectivity) each.	▪ \$45 each.
Potential safety benefits	Self-explaining road	▪ The safety benefits may be related to the road user's ability to see the road curvature at a greater distance than current retroreflective road markings allow, although trials have shown this can have adverse effects on driver behaviour. ▪ No quantitative data could be sourced.	▪ As the performance and compliance with existing linemarking is unknown it is difficult to hypothesise the safety benefits. For example, the ability to convey pavement marking messages on the road beyond the reach of headlights is advantageous, however the longevity of that delineation throughout the night, unknown performance in wet weather and potentially reduced visibility of linemarking within range of the headlights would be disadvantageous. ▪ Crash reductions could be expected on off-road applications, particularly if lighting was not previously provided. ▪ There are no published studies reporting the safety benefits or disbenefits.	▪ The safety benefits may be related to the road user's ability to see the road curvature at a greater distance than current retroreflective road markings allow. ▪ A controlled driver behaviour simulator study identified less frequent centre line crossovers and a high level of confidence in identifying and driving a rural road with solar-powered road studs.	▪ The safety benefits may be related to the road user's ability to see the road curvature at a greater distance than current retroreflective delineators allow. ▪ No quantitative data could be sourced.
Financial benefits	Implementation and maintenance	▪ No published information.	▪ Indications of quick installation. No published information of maintenance requirements.	▪ Individual units do not require wiring. Anecdotal evidence indicates that they may be easily installed and replaced although no published information could be sourced.	▪ Individual units do not require wiring. Anecdotal evidence indicates that they may be easily installed and replaced although no published information could be sourced.

Review criteria		Luminescent line markings	Luminescent pavement marking	Solar-powered road studs	Solar-powered guardrail lights
	Crash reduction	▪ As the performance and compliance with existing linemarking is unknown it is difficult to hypothesise the safety benefits. For example, the ability to delineate the road beyond the reach of headlights is highly advantageous, however the longevity of that delineation throughout the night, unknown performance in wet weather and potentially reduced visibility of linemarking within range of the headlights would be disadvantageous. ▪ There are no published studies reporting the safety benefits or disbenefits.	▪ As the performance and compliance with existing linemarking is unknown it is difficult to hypothesise the safety benefits. For example, the ability to convey pavement marking messages on the road beyond the reach of headlights is advantageous, however the longevity of that delineation throughout the night, unknown performance in wet weather and potentially reduced visibility of linemarking within range of the headlights would be disadvantageous. ▪ Crash reductions could be expected on off-road applications, particularly if lighting was not previously provided. ▪ There are no published studies reporting the safety benefits or disbenefits ▪ No published information.	▪ Reduction of run-off road crash rate from 7.2 to 2.3 per year, none of the 2.3 per year were at night. ▪ 70% reduction in night-time accidents (all severities).	▪ No published information.
Relevance to current MRWA practice		▪ MRWA Specification 604 Clause 52 *Performance Criteria for Longitudinal Lines* – although there are currently no reported performance criteria.	▪ Does not demonstrate it would comply within current specifications.	▪ MRWA Specification 604 Clause 53 *Performance Criteria for Raised Reflective Pavement Markers*. ▪ AS/NZS 2144 *Traffic Signal Lanterns.*	▪ MRWA *Design of Guide Posts* (MRWA 2018a). ▪ AS/NZS 1906.2 *Retroreflective Devices (Non-pavement Application).* ▪ AS/NZS 2144 *Traffic Signal Lanterns.*

3 PROPOSED PERFORMANCE TRIAL REQUIREMENTS

Based on the findings from the literature review and the limited information regarding the performance indicators of the reviewed technologies, it is recommended that MRWA considers undertaking a performance trial. The performance trial will include solar-powered road studs and solar-powered guardrail lights. It is envisaged that a trial will assist in determining how the technologies fit into current specifications and if any safety benefits may be achieved with usage.

As the performance of some products are unknown two trials should be carried out:

1. A trial to establish the performance of each product in locations with low crash risk and low historical crashes.
   - Monitor the performance of the product for up to 2 years, measuring reflectivity, luminescence and durability of each product at the trial and control sites to provide comparative data in both wet (simulated) and dry conditions:
     - reflectivity may be measured using the Delta LTL-M reflectometer integrated with ARRB's Hawkeye system on a network survey vehicle (NSV)
     - measure LED luminaire requirements in accordance with IESNA LM 80-08 *IES Approved Method: Measuring Lumen Maintenance of LED Light Sources*; this will also include regular monitoring regarding how the products hold a charge over a period of time and whether this can be maintained through the night
     - durability may be measured by regularly inspecting the markers noting any missing markers, body condition relative to cracking and general damage, lens damage and colour deterioration in accordance with AS 1906.3.
2. A trial of technologies deemed suitable in Trial 1 on high risk roads to measure safety performance.
   - Select one or more sites for the trial based on a crash analysis of road use movement (RUM) groups 4 (head-on) and 20 to 34 (off carriageway on straight/curve, out of control on straight/curve) on state-controlled roads where the crash rate is higher than the state average.
   - Select one or more control sites within 2 km of the trial sites, preferable on the same road or link.
   - Monitor crashes. This should include reported and unreported; camera monitoring may be required to capture property damage only crashes and near miss incidences.
   - Monitor the performance of the product over three years, measuring reflectivity, luminescence and durability of each product at the trial and control sites to provide comparative data in both wet (simulated) and dry conditions:
     - reflectivity may be measured using the Delta LTL-M reflectometer integrated with ARRB's Hawkeye system on a network survey vehicle (NSV)
     - measure LED luminaire requirements in accordance with IESNA LM 80-08 *IES Approved Method: Measuring Lumen Maintenance of LED Light Sources*; this will also include regular monitoring regarding how the products hold a charge over a period of time and whether this can be maintained through the night
   - Evaluate the before and after crash data, as well as the product performance data.
     - Identify the performance of the product.

- Identify the safety benefits
- Identify the whole of life cost of the product
- Identify the whole of life cost based inclusive of the safety benefits (crash cost reductions).

The results of the trial will provide the information required for the possible implementation of any of the products and future changes to the MRWA specifications for pavement marking and road delineation.

4 CONCLUSIONS AND RECOMMENDATIONS

A review of the currently available solar technologies for lane demarcation was undertaken to investigate the relevant applications to MRWA that may maximise the value for money and safety benefits in WA. It is evident that there are a number of developing technologies that are commercially available. However, due to the limited implementation of these products a limited number of published studies and trials regarding road safety implications and product applicability could be found. From the information that was found the following conclusions and recommendations are provided for each solar technology.

Luminescent linemarking

Luminescent linemarking is still in its early development stages. Whilst it provides some benefits (namely a self-explaining road beyond the reach of headlights) the technology has some deficiencies. These deficiencies include limited performance in the wet, limited illumination time at night (also limited by daylight hours), does not appear to provide retroreflectivity as a contingency or adequate diffused reflectivity during the day (contract against pavement) which may have an effect on automated vehicles.

The rectification of these deficiencies are subject to further development of luminance linemarking products, until such time a trial of this product is not recommended.

Luminescent pavement marking

Luminescent pavement marking is still in its early development stages. Whilst it provides some benefits (namely a self-explaining road beyond the reach of headlights) the technology has some deficiencies. These deficiencies include limited performance in the wet, limited illumination time at night (also limited by daylight hours), does not appear to provide retroreflectivity as a contingency or adequate diffused reflectivity during the day (contract against pavement) which may have an effect on automated vehicles.

The rectification of these deficiencies are subject to further development of luminance linemarking products, until such time a trial of this product is not recommended on a road surface, or a pathway intersection with a road surface. Although some deficiencies are clearly identified, luminescent pavement may be suitable to be trialled or implemented on off-road pedestrian and cycle paths.

Solar-powered road studs

Solar-powered road studs demonstrate promising performance and safety benefits, whilst there are some limitations these are mostly unknowns that are either advertised through supplier marketing material or perhaps withheld by suppliers due to commercial competition between suppliers.

A trial should be undertaken on a low risk road to evaluate performance against the review criteria (Table 2.10). Should a product demonstrate to perform a trial should be undertaken on high risk roads to evaluate the safety benefits.

Solar-powered guardrail lights

Solar-powered guardrail lights demonstrate promising performance and safety benefits, whilst there are some limitations these are mostly unknowns that are either advertised through supplier marketing material or perhaps withheld by suppliers due to commercial competition between suppliers.

A trial should be undertaken on a low risk road to evaluate performance against the review criteria (Table 2.10). The performance trial should specifically focus on identifying the influence of shadowing (at different times of the year) when placed on guardrail. Should a product demonstrate to perform a trial should be undertaken on high risk roads to evaluate the safety benefits.

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