ANNUAL SUMMARY REPORT

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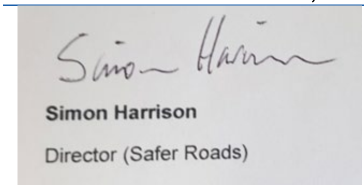

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SUMMARY

The main purpose of the study was to design a trial methodology to install milled rumble strips on Bruce Highway. However, since no TMR region is interested in conducting the trial, the project has been put on hold.

This summary report documents the findings of the literature review on milled rumble strips, stakeholder consultations, and the trial design methodology.

Milled rumble strips have been extensively used in the USA and Canada as a treatment to reduce run-off-road and cross-centreline crashes. Milled rumble strips are made with a specialized milling machine, creating uniform and consistent grooves in asphalt pavement. Aside from the more consistent pattern, many believe milled rumble strips allow for better compaction and reduce tearing and ravelling. They are considered to provide the most audible and vibrating pavement surface.

To date there has been limited use in Australia with Roads and Maritime Services in New South Wales being the only road authority to have undertaken a trial of milled rumble strips. Typically, raised rumble strips/ audio tactile linemarkings (ATLM) are used in Australia and New Zealand.

Although initial installation cost is higher compared to ATLM, milled rumble strips potentially has lower whole-of-life-cost as it has longer treatment life. They are appropriate in all weather conditions including situations where raised rumble strips may not be suitable e.g. areas where pavements are exposed to high temperatures.

Road authorities in Australia have concerns regarding the impact on pavement integrity and maintenance issues such as debris sitting in the grooves. However, literature indicates that debris in the grooves is not an issue and pavement issues are minimised if milled rumble strips are applied to a pavement in good condition with adequate thickness.

It is recommended that a trial of milled rumble strips be conducted on a section of the Bruce Highway with the following characteristics:

- a location away from residential areas to minimise noise impacts
- where no cyclists are allowed
- on pavement with a thickness greater than 50 mm
- a wide sealed shoulder (should provide at least 1.2 m sealed width from the rumble strip to outside edge of the sealed shoulder)
- has no bridge decks, approach slabs or construction joints
- has a pavement seal that does not consist of open graded asphalt
- the pavement is in good condition with a well compacted subgrade and has good drainage characteristics
- the pavement does not exhibit any fatigue cracking.

Before proceeding with the trial of milled rumble strips as recommended, the costs associated with the installation including establishment costs, will need to be considered to ensure the trial is economically feasible. Currently there is only one contractor available in Australia (Roadline Removal/Oz Rumble) that has the milling machine capable of installing the milled rumble strips and is based interstate.

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1 INTRODUCTION

1.1 Background

Milled rumble strips are made with a specialized milling machine, creating uniform and consistent grooves in asphalt pavement. Aside from the more consistent pattern, many believe milled rumble strips allow for better compaction and reduce tearing and ravelling compared to formed and rolled rumble strips. Milled rumble strips are considered to provide the most audible and vibrating pavement surface.

Extensively used overseas, particularly in the US, milled rumble strips are considered to significantly help to reduce the number of run-off-road crashes by providing the best audio warning cue for road users. US research reported a reduction in single vehicle run-off-road crashes of 10 to 24 percent on rural freeways, and 26 to 46 percent on two-lane rural roads due to milled rumble strips (Federal Highway Administration 2011a).

Queensland Department of Transport and Main Roads (the Department) proposes to undertake a milled rumble strips trial on the Bruce Highway. The trial will be designed and constructed in accordance with the US Department of Transportation Design Guide. The Department currently spend approximately $1.2M per annum on repairs to safety barriers on the Bruce Highway. Based on the run-off-road crash reduction potential of rumble strips, installing milled rumble strips will result in a saving in the order of $200,000 p.a. in safety barrier repairs alone. This would be sufficient to pay for the installation.

Despite the safety benefits of rumble strips cyclists are not fond of them. Many bicyclists complain that shoulder rumble strips force them off the shoulder and make them ride in the travel lane. Riding on the rumble strips can cause cyclists to lose control of their bikes and fall. Motorcyclists are potentially at a disadvantage if riding over rumble strips destabilises them. There are concerns that black ATLM or milled rumble strips that a motorcyclist is unlikely to see may introduce a safety risk. White audio tactile linemarkings (ATLM) are generally very conspicuous.

The project will investigate the appropriateness of installing milled rumble strips on the Bruce Highway.

1.2 Objectives

The aim of the study is to investigate whether it is cost-effective to install milled rumble strips and to develop a scientific approach to install and evaluate the milled rumble strips. Specific objectives include the following:

- document the benefits and impacts of milled rumble strips
- how to design, monitor and evaluate the trial (including method to measure the change in run-off crashes)
- provide technical advice regarding the installation and maintenance of milled rumble strips.

1.3 Study Tasks

The project tasks included the following:

- Literature review and stakeholder consultations to document the benefits and impacts on milled rumble strips and to identify the impacts on cyclists and design characteristics that will improve safety for all road users
- Develop study methodology and design of the trial

- Site investigation and selection and pilot study (trial). It is expected that site selection will consider the elements that are important for rumble strip design including crash types to mitigate, rumble strips dimensions (including width, depth and spacing), road type, etc. The trial is expected to be undertaken and funded separately by North Coast and Wide Bay/Burnett Region.
- Data collection, monitoring and evaluation of the implementation and lessons learnt. Data to be collected for the monitoring and evaluation will include implementation issues, traffic movement, noise levels and road crashes.
- Reporting with recommended guidelines for installing milled rumble strips.

This summary report documents the findings of the literature review, stakeholder consultations, and design of the trial.

2 LITERATURE REVIEW

2.1 Introduction

The focus of the literature review was to validate the potential benefits and impacts of milled rumble strips and that it is cost-effective to be installed on Queensland roads with no net negative impacts on pavement strength and maintenance (i.e. installing milled rumble strips will not make things worse). In particular, the review will document:

- the benefits and crash reduction potentials of the different methods of installing rumble strips on roads (specifically milled and raised profiled rumble strips)
- installation and maintenance issues
- impact on pavement strength, if any
- impact on other road users especially cyclists.

To identify relevant research, a literature search was conducted using the resources of ARRB Group's MG Lay Library, the leading land transport library in Australia. These resources included the library's own comprehensive collection of technical land transport literature and information retrieval specialists with extensive experience in the transport field, as well as access to databases of other transport-related libraries throughout Australia and internationally. Used specifically in this literature search were the Australian Transport Index (ATRI) and Transportation Research Information Documentation (TRID) databases. Use of these databases ensured wide coverage for quality research material within the subject area, from both national and international sources.

In addition, an internet search using Google was undertaken to source relevant literature on rumble strips.

2.2 Types of Rumble Strips

Rumble strips (profile lines) consist of series of grooves or raised strips placed along the road shoulder or centreline of the road. When a vehicle tyre runs over the profiled lines it generates a vibration or noise to alert the driver to move back into their lane. They are effective in reducing run-off-road and cross-centreline crashes especially those caused by fatigue, drowsiness, distraction, or otherwise inattentive driving (Federal Highway Administration 2011a). They can also improve the visibility of the linemarkings during the night and in wet weather.

Rumble stripes is term used when rumble strips are painted with a retroreflective coating to increase the visibility of the pavement edge at night or during adverse weather conditions.

There are four types of rumble strips – milled, raised, rolled and formed rumble strips. They differ primarily on how they are installed, their shape size, and the amount of noise and vibration produced. A brief description of these four types are provided below.

2.2.1 Milled rumble strips

Milled rumble strips are made by a machine with a rotary cutting head which creates a groove into the pavement (Figure 2.1). Tyres passing over the milled rumble strips drop into the groove, which causes tyre noise and vehicle vibration. In general, the wider and deeper the rumble strip the greater the noise and vibration.

Typical milled rumble strips widths are 127 – 178 mm with 305 mm spacing and a depth of approximately 13 mm. The typical length used is 305 – 406 mm, but smaller versions have become more popular on two-lane roadways. The length, width and depth can easily be adjusted using different size cutting heads, and the spacing can also be easily adjusted.

The major concern with milled rumble strips is the high installation cost (Bucko & Khorashadi 2001). Milled rumble strips are the most expensive type of rumble strips (Pennsylvania Department of Transport (1999). Currently, many road agencies are employing milled rumble strips as they can be installed on existing road pavements (Ahmed, Sharif & Ksaibati 2015). Milled rumble strips are also more durable and most effective (Hatfield 2009; Himes et al. 2017). Some other benefits include accuracy of placement, compaction of surface and no cracking (Soltykevych, 2016). They are most appropriate in countries where snow removal is a major issue.

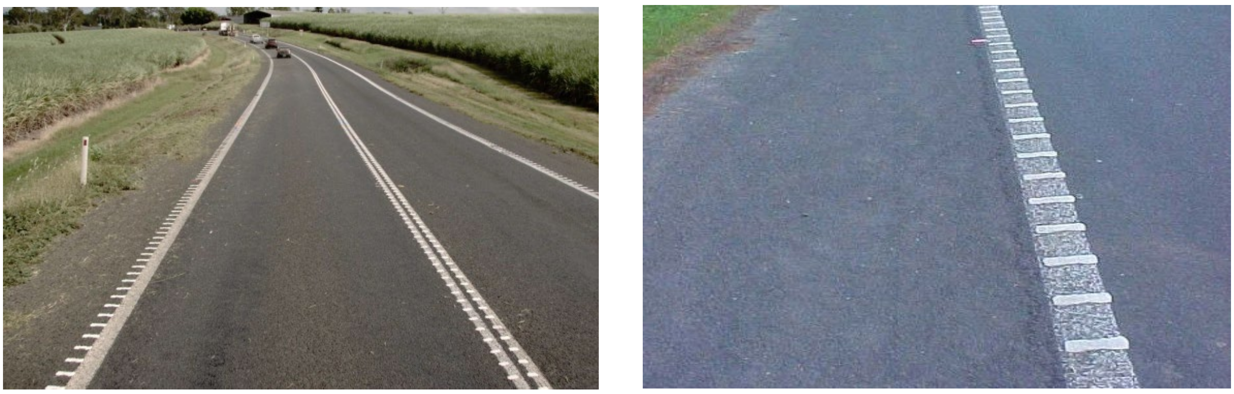
Figure 2.1: Milled rumble strips

a. Source: Hawkins et al. (2016) b. Source: Federal Highway Administration (2017)

2.2.2 Raised rumble strips (Audio tactile linemarkings)

Raised rumble strips including audio tactile linemarkings (ATLM) are 50 -305 mm wide rounded or rectangular markers or strips adhered to new or existing pavements (Figure 2.2). Their height can range from 6 to 13 mm. They are used in warmer climates that do not require snow removal. They have the added benefit of providing improved visibility especially during wet road conditions. ATLM is more likely to enhance lane-marking visibility especially in night-time and wet pavement condition (Hatfield, 2009, Himes et al. 2017). They are not practical in snowy regions due to significant damaging effects of regular snow ploughing on ATLM (Himes et al. 2017). ATLM may be considered in zones where milled rumble strips are not practical, e.g. bridge decks, thin surface courses such as, chip seals (Himes et al. 2017). The raised rumble strips can be installed at any time. Various materials can be used for constructing raised rumble strips such as asphalt bars, rubbers materials, etc. (Ahmed, Sharif & Ksaibati 2015). Road Authorities in Australia and New Zealand typically use raised profiled centre and edge lines.

Figure 2.2: Raised rumble strips



Source: ARRB Group Source: iRAP (2010)

2.2.3 Rolled rumble Strips

Rolled rumble strips are rounded or V-shaped grooves pressed into hot asphalt pavements and shoulders when the constructed or reconstructed surface course is compacted. The strips are made by a roller with steel pipes welded to drums, which make the depressions as they pass over the hot pavement. The sound and vibration of rolled rumble strips is typically much less noticeable than milled rumble strips, but varies based on width, depth, and spacing. Rolled rumble strips are inexpensive, but requires critical maintenance. They can be installed during the pavement construction (Ahmed, Sharif & Ksaibati 2015).

2.2.4 Formed rumble strips

Formed rumble strips mirror the rolled type in shape but are made by pressing forms into concrete pavements as they are being constructed (32 mm deep, 40 mm wide rounded or V-shaped grooves).

2.3 Uses of Rumble Strips

There are four ways of applying rumble strips as listed below (Federal Highway Administration 2017):

- **Centreline rumble strips (CLRS)** – installed to prevent head-on and cross-centreline crashes (Figure 2.3). They are typically used on two-lane, two-way roads to warn drivers whose vehicles are drifting into the opposing lane (crossing the centreline). Effectiveness of centreline rumble strips include (Datta, Gates & Savolainen 2012):
  - reduction in cross-centreline crashes, including head-on and sideswipe opposite type of crashes
  - drivers are less likely to encroach onto the centreline in the presence of CLRS
  - drivers are more likely to position themselves away from the centreline
  - negligible impact on passing manoeuvres.
- **Shoulder rumble strips (SRS)** – are an effective countermeasure to reduce run-off-road crashes (Figure 2.4). They are primarily used to warn drivers that they have drifted from their travel lane. Shoulder rumble strip effectiveness include (Datta, Gates & Savolainen 2012):
  - single vehicle run-off-the-road crashes are reduced
  - drivers are less likely to encroach onto the shoulder
  - drivers are more likely to position themselves away from the shoulder.
- **Edgeline rumble strips** – are a variation of shoulder rumble strips with the pavement linemarkings placed within or near the rumble strips, to improve the visibility of the linemarking (Figure 2.5). Federal Highway Administration (2011b) suggests the use of edge line rumble strips where it will allow additional shoulder area beyond the rumble strip for use by a bicyclist, pedestrian or other road user. TMR's Road Safety Policy requires the use of ATLM on all high speed roiads with at least 500 mm wide sealed shoulder and a history of fatigue related crashes.
- **Transverse rumble strips** – are installed perpendicular to the flow of traffic and placed in the trafficable section to alert drivers of an unexpected change in the roadway, such as the need to change lanes, slow down or stop, or changes in the roadway alignment (Figure 2.6). Typical locations for these rumble strips are on approaches to intersections, toll plazas, horizontal curves, and work zones. Some concerns with the use of transverse rumble strips are:
  - increased noise impact on nearby residences

— motorists using opposing lane to avoid rumble strip
— can be hazardous to motorcyclists and bicyclists.

Figure 2.3: Centreline rumble strips

Source: ARRB Group

Source: ARRB Group

Figure 2.4: Shoulder rumble strips

Source: Hawkins et al. 2016

Source: ARRB Group

Figure 2.5: Edge line rumble strips

Source: Federal Highway Administration (2015a)

Figure 2.6: Transverse rumble strips


Source: Federal Highway Administration (2006)


Source: (Ahmed, Sharif & Ksaibati 2015)

2.4 Benefits and Effectiveness of Rumble Strips

The safety benefit of rumble strips (reducing run-off-road crashes) is well documented. These include:

- Economic considerations – the installation cost of rumble strips is low (cost-effective) compared to the costs that are saved by the prevention of injury crashes (Vanapalli 2006). Studies based on reduction in crash cost indicated that the benefit cost ratio for rumble strips can be as high as 100 to 1 (i.e., $100 saved for each $1 outlay). Benefit cost ratios generally reduce with lower traffic volumes, speeds, and shoulder widths.
- Crash reductions – large reductions in run-off-road, lane departure, head-on and total crashes have been clearly correlated to the installation of rumble strips (Austroads, 2010). The Highway Safety Manual (2010) indicates 10 to 93 percent reductions in lane and road departure crashes on different types of roadways. Typical crash reduction potentials of rumble strips by type are shown in Table 2.1.
- Improved visibility – rumble strips improves night time marking visibility (particularly in wet conditions) and can also increase longevity of the markings due to reduced wear from tires (Texas Transportation Institute 2009). ATLM is more likely to enhance lane-marking visibility especially in night-time and wet pavement condition compared to milled rumble strips (Hatfield, 2009, Himes et al. 2017).
- Maintenance advantage – adding traditional pavement markings on top of rumble strips will lengthen the pavement marking service life since drivers are less likely to drive over them because of the visual queue (Texas Transportation Institute, 2009).
- Driver behaviour and lane tracking - rumble strips are effective in alerting fatigue and inattentive drivers of hazards and departing from the roadway after crossing the rumble strips and hence drivers maintain proper lateral placement and improved safety. Studies indicate that (Datta et al 2012; Datta et al. 2015).
  - drivers tend to move away from centreline and position their vehicles more centrally in the roadways lane
  - encroachments across the centreline and edgelines are reduced
  - improvement in lane positioning occurred both at horizontal (curve section) and tangent sections
  - vehicle overtaking is not affected by installation CLRS
  - there are no significant changes in the mean and 85th percentile speeds due to rumble strips.

Table 2.1: Crash reduction potential of rumble strips

Treatment type	Crash type	Crash reduction; reference; study type
Milled rumble strips – shoulder	Run-off-road crashes	▪ 35%; Washington State Department of Transportation (2011); before and after ▪ 10% to 24% on rural freeways; Federal Highway Administration (2011) ▪ 26% to 46% on two-lane rural roads; Federal Highway Administration (2011) ▪ 31 to 70%; Turochy (2003) ▪ 10% on rural freeways; Torbic et al. (2009) ▪ 16% on rural two-lane roads; Torbic et al. (2009) ▪ 27%; Hatfield et al. (2009); before/after method ▪ 49%, Hatfield et al. (2009)
Milled rumble strips – shoulder	FSI run-off-road crashes	▪ 17% on rural freeways; Torbic et al. (2009) ▪ 36% on rural two-lane roads; Torbic et al. (2009) ▪ 36% for rural two-lane roads; Richard &Wilder (2011). ▪ 48% in run-of-road crash fatalities; Turochy (2003).
Milled rumble strips – shoulder	All injury crashes	▪ 38 to 79% (Federal Highway Administration, 2011). ▪ 25%; Hatfield et al. (2009); Treatment and control method
Raised rumble strips – shoulder	Run-off-road crashes	▪ 18% on all freeways; Griffith (1999); ▪ 21% on rural freeways; Griffith (1999); ▪ 76%; Hatfield et al. (2009); before/after method ▪ 20 to 80%; Baas et al. (2004)
Raised rumble strips – shoulder	All injury crashes	▪ 39%, Hatfield et al. (2009); before/after method ▪ 27%; Baas et al. (2004)
Milled rumble strips – centre line	Head-on crashes	▪ 30 to 34%; Turochy (2003) ▪ 34 to 55%, Hatfield et al. (2009); before/after method
Milled rumble strips – centre line	FSI head-on crashes	▪ 38 to 50% on rural two-lane roads Federal Highway Administration (2011) ▪ 37 to 91% on urban two-lane roads for (Head-on and opposite direction sideswipe collisions), (Federal Highway Administration (2011)
Milled rumble strips – centre line	Cross-centreline crashes	▪ 25%; Persaud (2004) ▪ 30% on 2-lane, 2-way rural roads; Torbic (2010) ▪ 40% on 2-lane, 2-way urban roads; Torbic (2010) ▪ 92%; Datta et al. 2015); Naïve before-and-after and EB methods
Milled rumble strips – centre line	FSI cross-centreline crashes	▪ 61%; AECOM 2008; comparison group ▪ 44% on 2-lane, 2-way rural roads; Torbic (2010) ▪ 64% on 2-lane, 2-way urban roads; Torbic (2010)
Milled rumble strips – centre line	All crashes	▪ 12% on 2-lane, 2-way rural roads; Persaud (2004) ▪ 9% on 2-lane, 2-way rural roads; Torbic (2010) ▪ 40% on 2-lane, 2-way urban roads; Torbic (2010) ▪ 15% on 2-lane rural roads Vadeby & Anund, 2017; empirical Bayes before and after ▪ 29%; Hatfield et al., 2009)); before/after method ▪ 20% FSI (all crash types); (Vadeby& Anund (2017)
Raised rumble strips – Centreline	Cross centreline crashes	▪ 21 to 37%; Baas et al. (2004)

2.5 Impacts of Rumble Strips

Despite the well documented advantages of rumble strips, several issues and concerns have been identified regarding the implementation of rumble strips. Noise, pavement strength, maintenance, and the adverse effects on bicyclists and motorcyclists are among the most recognized concerns.

2.5.1 Noise

Ideally, rumble strip design requires high in-vehicle vibration noise and lower external decibel levels (Federal Lands Highway Division Safety Team, 2015). To minimise the noise impact, the Transportation Association of Canada found that terminating rumble strips at least 200 m away from residential/urban areas produced tolerable noise impacts on residents (Texas Transportation Institute, 2009).

2.5.2 Pavement deterioration and maintenance

Generally, deterioration of the asphalt pavement due to rumble strip installation is not a problem. By design raised rumble strips have no impact on the integrity and strength of the pavement. Milled rumble strips on the other hand, could compromise pavement strength:

- Past experiences indicate minimal early deterioration of milled shoulder rumble strips on either cement or asphalt pavements or open graded pavements (Federal Highway Administration 2015a).
- Milled rumble strips have been linked to pavement deterioration when placed on pavements with inadequate structure. Federal Lands Highway Division Safety Team (2015) suggests that milled rumble strips should be avoided on:
  - bridge decks and approach slabs to bridges
  - pavement less than 50 mm in depth
  - pavement with poorly compacted subgrade or has poor drainage characteristics
  - pavement exhibiting any fatigue cracking, i.e. pavement not in optimal conditions.
- Poor performance has been associated with installations in bituminous surface treatment pavement and hot mix asphalt pavement with low density – open graded pavements should be avoided (WSDOT, 2013).

If deterioration is a concern, an asphalt fog seal can be placed over the milled-in-strips to reduce oxidation and moisture penetration (Sharif, 2015).

Texas Transportation Institute (2009) reported that no additional maintenance of milled rumble strips is required as long as the strips are placed on pavement in a good condition. There has been concerns regarding accumulation of debris in the grove, but this concern is refuted in some studies (Federal Highway Administration 2015a). Milled rumble strips are reported to require minimal maintenance (Russel and Rys 2005). When installed on a good pavement type, milled rumble strips have a longer treatment life compared to ATLMs.

Visual field assessments and imagery reviews by Datta et al. (2015) concluded that milled rumble strips did not have any significant short-term detrimental effect on the pavement life. Any sand or water accumulated in the grooves is cleared by air movement caused by passing traffic.

2.5.3 Impact on Bicyclists

When there is not enough shoulder width (minimum 1.2 m wide) provided, bicyclists maybe forced off the shoulder and made to ride in the travel lane or ride over the rumble strips which can impose a greater risk on them. The vibrations from rumble strips and riding on them can cause cyclists to lose control of their bikes and fall. To provide adequately for cyclists using the paved shoulder:

- The Federal Lands Highway Division Safety Team (2015) indicates the installation of SRS should maintain a minimum clear shoulder width of 1.2 m from the rumble strip, with an additional 305 mm recommended if shoulder is parallel to a guardrail.
- The Texas Transportation Institute (2009) recommends a minimum clear path of:
  - 305 mm from rumble strip to travel way
  - 1.2 m from rumble strip to outside edge of the paved shoulder
  - 1.525 m to adjacent guardrail / kerb / other obstacles

— Rumble strips should not be placed on downhill grades exceeding 5% for more than 150 m (500 ft) in length for cyclist routes.

In providing more lateral clearance for cyclists on roads with narrower lane widths, SRS can be designed with smaller widths of around 152 mm whilst still achieving the desired sound levels (Torbic, 2010).

2.5.4 Impact on Motorcyclists

Texas Transportation Institute (2009) study reported increased crash risk for motorcyclists due to rumble strips. They reported motorcycle wheels may get caught in the rumble strips ultimately interfering with the steering increasing the chance of a crash especially for centreline rumble strips

In a recent study, the California Highway Patrol concluded that there is no significant shortcoming for motorcyclists travelling at high speeds (80 km/h or more) over the various types of rumble strips. Himes et al. (2017) undertook an observation of rural highways with CLRS and reported that:

"*No steering, braking, or throttle adjustments were found during rumble strip crossing. Post-examination interviews confirmed that no riders had difficulty or concern with crossing rumble strips*".

Miller (2008) analysed eight years crash data in Minnesota, and concluded that CLRS did not pose a hazard to motorcyclists (Miller 2008; cited in Himes et al. 2017). The author reported that only 29 of total 9 845 motorcycle crashes happened where rumble strips were present.

2.6 Milled Rumble Strips Design Guidelines

2.6.1 Design dimensions

The design dimensions for milled rumble strips are shown in Figure 2.7. Two key dimensions that have the greatest effect on the alerting sound and vibration of rumble strips are depth (D) and width longitudinal to the road (C). A comprehensive study regarding dimensions of rumble strips in the U.S and Canada was undertaken by Torbic (2009). The most common dimensions for milled SRSs and CLRSs is presented in Table 2.2. Milled rumble strips are typically 178 mm wide by 13 mm deep and 305 mm spacing, with strip groove lengths of between 305 and 406 mm.

Figure 2.7: Illustration of milled rumble strip dimensions

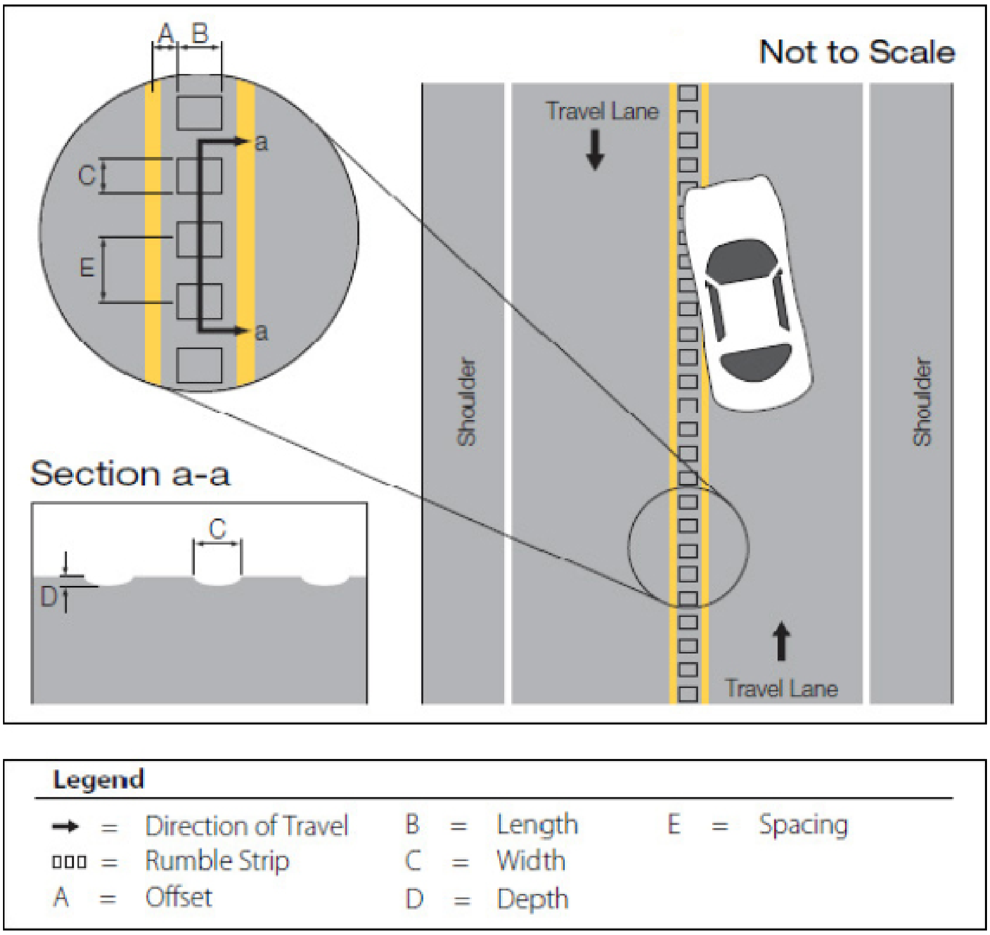


Table 2.2: Milled rumble strips typical dimensions

Dimension	Shoulder rumble strips		Centreline rumble strips	
	Imperial unit (inches)	Metric (mm)	Imperial unit (inches)	Metric (mm)
Width	7	178	7	178
Depth	0.5 to 0.625	13 to 16	0.5	13
Spacing	12	305	12	305
Length	16	406	12 or 16	305 or 406

Source: Compiled from Torbic (2009)

2.6.2 Design factors and application

The factors that govern the design and application of rumble strips/stripes include: the area type, traffic volume, speed limit, lane width, shoulder width, clear path, crash history, pavement type, pavement depth and bicycle volume (Ahmed, Sharif & Ksaibati 2015).

Application considerations include (US Department of Transportation, 2011):

- Corridor v spot treatment – difficult to determine where drivers will be become distracted / drowsy and thus crash history should be used to determine where high priority road corridors are and should be treated. Isolating spots will be prudent and not as effective.

- Divided highways – rumble strips should be placed on both the left and the right shoulders of the lanes. Study in Michigan of freeway lane departure crashes showed that approximately equal percentage of vehicles in crashes drifted to the left as to the right.
- Centreline and shoulder rumble strips – Missouri study of installation of rumble strips showed the greatest reduction in serious injury crashes were found when both centre and shoulder rumble strips were installed with wider markings.
- Consideration should be given to road users such as drivers who may be hesitant to cross the centreline to overtake cyclists if rumble strips are present (over the centreline).
- Best practice is to install rumble strips immediately prior to placing the surface treatment in order to seal the installation (WSDOT, 2013).
- Speed limit – rumble strips are generally installed on high speed roads, 80 km/h and above.
- On two-lane, two-way roads, the combined lane and shoulder width should be at least 4.25 m (14 ft).
- On bicycle route installation of SRS:
  - should maintain a minimum clear shoulder width of 1.2 m from the rumble strip
  - should provide additional 305 mm if shoulder is parallel to a guardrail
  - should be 1.525 m to adjacent guardrail / curb / other obstacles
  - should not be placed on downhill grades exceeding 5% for more than 150 m (500 ft) in length on cyclist routes.

2.6.3 Pavements issues related to milled rumble strips

The pavement variables to consider in the successful implementation of milled rumble strips include (Federal Highway Administration 2015a):

- Existing pavement condition and age – milled rumble strips do not typically cause issues when installed in pavement rated fair or better, in older pavements that show high degrees of deformation or cracking distress, the milling process can exacerbate existing issues. Some US states only installed milled rumble strips on pavements which are less than five years old.
- Pavement type and thickness – Milled rumble strips have been applied to all pavement types, both new and existing: cement concrete, asphalt, ultra-thin asphalt, chip seal, micro-surfacing, etc.) provided they have a minimum thickness of “bound” pavement material before rumble strips are installed. The “bound” pavement materials are a combination of all layers of the materials listed above but excluding cold-in-place (CIP) recycling. The Federal Highway Administration (2015a) discourage the use of milled rumble strips on chip seal. If it is to be applied, it is best to mill the rumble strips before applying the chip seal (Washington Department of Transportation 2011). In the US, the pavement thickness varies between states (Table 2.3), though a minimum thickness of 50 mm has been suggested to maintain pavement integrity.
- Location and condition of longitudinal construction joints – milled rumble strips are not appropriate on bridge decks and approach slabs. Though construction joints are not influential in deciding to install milled rumble strips, the following are used to avoid cutting rumble strips directly into the joint:
  - milling two smaller rumble strips on either side of the centreline joint;
  - offsetting the rumble strip to one side of the joint (this is more common for edge line or shoulder rumble strips. The most typical lateral offset is about 100 mm from the travel way or shoulder joint)

— offsetting the joint during pavement construction or overlay so the CLRS can be placed in the centre of the roadway.

Table 2.3: Required pavement thickness for milled rumble strips by US states

State	Required pavement thickness for rumble strip installation
Missouri	1.75 inch (44.45 mm)
New York	2.5 inch (63.5 mm)
Pennsylvania	Less than 1 year old – 1.5 inch (38.1 mm) Older – greater than 2.5 inch (63.5 mm)
Texas	2.5 inch (63.5 mm)
Washington	3 inch (76.2 mm)

Source: Federal Highway Administration 2015a

2.7 Benefits of Milled Rumble Strips vs ATLMs

Compared to raised and ATLMs, the benefits and disbenefits of milled rumble strips include:

Table 2.4: Comparative analysis of milled and ATLMs

Parameter	Milled rumble strips	ATLMs
Treatment life	20 years or more (life of the pavement)	1 to 5 years
Initial cost	Higher	Lower
Whole-of-life cost due to lower maintenance cost	Lower	Higher
Debris level/ ongoing maintenance	May be higher than ATLMs	Nil or less than for milled rumble strips
Noise and vibration levels	Higher compared to ATLMs	Slight lower
Pavement types - coverage	Not appropriate for thin pavements (less than 50 mm) and thin surface courses such as, chip seals	Appropriate for all pavement types
Road features and sections	Not appropriate on bridge decks and bridge approach slabs	All road features
Weather conditions	Appropriate in all weather conditions	Not appropriate in areas where snow clearing is required
Improved visibility	No impact (edge line milled rumble strip excluded)	Increased level
Pavement deterioration	No major impact	No impact

3 CONSULTATION

ARRB consulted relevant stakeholders and inter-state road authorities on their experiences on the application of milled rumble strips. The focus was on the impacts of milled rumble strips installation on pavement and maintenance issues. The contact details and mode of contact are provided in Table 3.1.

The consultation identified that only Road and Maritime Services (RMS) in New South Wales as the only road authority that had trialled the use of milled rumble strips. A private contractor in Victoria was trialling the milled rumble strips, however contact details were unable to be obtained.

Table 3.1: Contact details and consultation method

Road Authority	Contact person	Phone number	Email	Contact mode
RMS, New South Wales	Ivan Babic	0411 237 446	ivan.babic@rms.nsw.gov.au	Phone communication
VicRoads, Victoria	Daniel Cassar	Unknown	Unknown	Email
Main Roads WA	Ron Koorengevel	08 93234704	ron.koorengevel@mainroads.wa.gov.au	Phone communication
AAPA	Erik Denneman	07 3360 7940	erik.denneman@aapa.asn.au	Email and phone communication
Roadline removal/Oz Rumble	Nathan Dickey	0429 523 847	admin@roadlineremoval.com.au	Email communication
Roadline removal/Oz Rumble	Paul Sebalj	0499 775 502	admin@roadlineremoval.com.au	Phone and email communication

3.1 New South Wales

RMS trialled milled rumble strips on a section of concrete pavement in New South Wales. The trial consisted of a 1.2 km of milled shoulder rumble strip on a concrete pavement, which was located on a right-hand bend. Painted edge lines were placed over half of the rumble strip. Initially, there were concerns that debris and materials would sit in the grooves and the pavement may be compromised. However, to date the treatment section had not experienced any of these issues.

RMS are considering undertaking further trials on concrete, asphalt and chip seal pavements to investigate how the milled rumble strips perform on different surfaces. In the future trials they would offset the rumble strips outside the linemarking. This would possibly reduce noise as vehicles have to cross the edgeline before driving over the grooves.

For future trials on spray seal surfaces, the method will involve milling out on the old surface then putting reseal over the top, in case there has been any impact on the pavement. If the grooves are milled deep enough it may be possible to get two reseals over the top.

The main reason RMS are considering the use of milled rumble strips is based on its lower whole-of-life cost, i.e. it has long treatment life and no significant maintenance cost once it is installed. RMS had some issues with ATLM not providing value for money, particularly in hot areas where the tactile edgelines has pressed into pavement and generally has not lasted as long as expected. They envisage that milled rumble strips would not be a standard treatment but used in some locations on the network.

Indicative costs for milled rumble strips is approximately $2,800 per kilometre for asphalt and $4000 to $4500 for concrete pavements. This is more expensive than ATLM, which is approximately $1500 to $2000 per kilometre (note the cost for the ATLM will be a bit more for an older pavement surface that required priming before application of the ATLM. Also, ATLM may last for 4 to 8 years, whereas milled rumble strips last until the end of the pavement life.

3.2 Victoria

VicRoads have not used milled rumble strips. However, they were aware of milled rumble strips being trialled on a private road in Victoria. The road was a chip seal. VicRoads was not involved in the trial. ARRB has not been able to obtain contact information from the private owner.

VicRoads have their Safer System Roads Infrastructure Program which has developed a cost effective method of installing rumble strips. They place black blobs of thermoplastic adjacent to the white line.

3.3 Western Australia

Main Roads WA (MRWA) considered the use of milled rumble strips, however, as their road network consists largely of spray seal, they had concerns that milled rumble strips would impact on the integrity of the pavement and hence, have not trialled or used them.

3.4 Other States and New Zealand

All other States in Australia and New Zealand use raised profiled rumble strips and have no experience on the use of milled rumble strips.

3.5 AAPA

APPA was first contacted by email followed but a phone call, but ARRB is yet to receive feedback from them.

4 DESIGN OF TRIAL

Based on the literature review findings, research indicates that rumble strips are an effective treatment to reduce run-off-road crashes. The main concern associated with the use of milled rumble strips relate to pavement strength and integrity. Research indicates that these concerns are not an issue when milled rumble strips are placed on pavements in good condition. Therefore, based on the findings it was agreed that the trial of the milled rumble strips goes ahead starting with the development of a methodology for a trial.

4.1 Objective

The objective of the trial is to install milled shoulder rumble strips to confirm research findings that milled shoulder rumble strips (validate the impacts and benefits):

- do not impact on the integrity of the pavement (when installed on an asphalt surface in good condition)
- do not have ongoing maintenance requirements
- are effective in reducing run-off-road crashes
- reduce the number of safety barrier strikes
- impact on cyclists (pending discussion with TMR)

4.2 Site Selection

4.2.1 Trial sites

The trial will be conducted on sections of the Bruce Highway. Exact site details will be determined in consultation with TMR. The trial locations may include two sections of milled rumble strip treatment and one control site, all within close proximity of each other. It is expected that there will be safety barriers along some sections of the trial sites.

The specific section(s) on the Bruce Highway appropriate for the trial will have the following characteristics:

- an asphalt pavement (not open graded asphalt) in good condition with a well compacted subgrade and good drainage characteristics
- a pavement thickness greater than 50 mm
- the pavement does not exhibit any fatigue cracking
- sealed shoulder width of at least 2.0 m (the US commonly use min of 1.2 m shoulder). This is important where there is safety barrier to provide enough space for the milling machine to fit between the edge line and the safety barrier when installing the rumble strip.
- not close to residential areas to minimise noise impacts (at least 200m from residence)
- where cyclists are prohibited
- where possible avoid bridge decks, approach slabs or construction joints, otherwise discontinue the rumble strips at these locations
- has safety barrier along the road shoulder for some of the sections
- high run-off-road crash locations.

The characteristics for the control site include:

- close to the trial sites (preferably in between the two treatment sites)

- has similar road characteristics – lane width, shoulder, delineation, etc. to the treatment sites
- has no rumble strips

It will be important to match trial locations as closely as possible (to control for any natural or design differences. A member of ARRB staff will visit the site to check its features and supervise the set-up of the data collection sites and associated measurement.

4.2.2 Cycling impact site (optional)

If required, an additional site, preferably a cycle route (not on the Bruce Highway) may be considered, to assess the impact of milled rumble strips on cyclists. This is out of scope and will require further discussion with TMR.

4.2.3 Site characteristics

Based on the characteristics outlined above the following sites have been selected for the pilot study. The proposed minimum length of each site is 2.5 kilometres, this could be increased depending on TMR budget.

Table 4.1: Site details (TBC)

Site	Location	Length	Funding
Site1 Bruce Hwy	TBC	2.5 km	North Coast and Wide Bay/Burnett Region
Site 2 Bruce Hwy	TBC	2.5 km	North Coast and Wide Bay/Burnett Region
Control site Bruce Hwy	TBC	2.5 km	North Coast and Wide Bay/Burnett Region
Possible Site 3 cyclist route*	TBC	TBC	Optional – TMR to consider funding
Control site for cyclist route*	TBC	TBC	Optional – TMR to consider funding

* Out of scope.

4.2.4 Data Requirements

The following data will be required from TMR to assist in the selection of suitable trial sites:

- AADT, % heavy vehicles, % cyclists (for cycle route site only)
- Pavement data – type, depth, seal type, age etc
- Crash data and barrier hits. Run-off-road crash and barrier hits data on Bruce Highway section within North Coast and Wide Bay/Burnett Region will be analysed to aid in identifying high risk sections to be considered as trial sites.

4.3 Design and dimension of milled rumble strips

The trial will consist of a shoulder rumble strip placed outside the edge line on the passenger (left hand) side shoulder only.

The most common spacings used in the US for milled rumble strips as reported in NCHRP (2009) and FHWA (2015a) will be adopted for the trial. Unless limited by the construction equipment the rumble strip dimensions for the trail as defined in Figure 2.1b will be:

- Length: 406 mm (16 in.) (NCHRP 2009)
- Width: 178 mm (7 in.) (NCHRP 2009)
- Depth: 13 to 16 mm (0.5 to 0.625 in.) (NCHRP 2009)
- Spacing: 305 mm (12 in.) (NCHRP 2009)

- Offset: 100 mm from the outside of the edge line (FHWA 2015a)

The Oz Rumble machine can produce a milled rumble strips either 300 mm or 200 mm in length, with the other dimension consistent with those listed above. At this stage the machine capability and dimension able to be produced by Ramsay Contractors is unknown.

4.4 Cost of trial

This section outlines the cost to TMR associated with conducting the trial of milled rumble strips. It does not include the labour cost to TMR.

4.4.1 Installation of rumble strips

The cost of the milling will depend on the total length of the sites.

Oz Rumble provided ARRB with the following indicative costs:

- 300 mm long Oz Rumble Cut $3,200 per km (excluding GST)
- 200 mm long Oz Rumble Cut $2,800 per km (excluding GST)
- One off establishment/mobilisation fee of $14,000 (excluding GST) (truck currently in Victoria)
- Price allows for 2 suction sweepers only to collect loose material (possibly 3 required for 300mm wide).
- Price does not allow cart material away other than empty sweepers at approved stack sites preferably close to the site.
- Price does not allow for any traffic control.
- The milling machine operates at approximately 1 km/h.

Note Oz Rumble have indicated that once more detailed site information is available they can provide a more competitive price.

Traffic control will be required during the installation of the rumble strips. The location of the sites will determine whether the works are carried in the day or night time. TMR may provide their own in-house traffic control or it may be outsourced at a cost to the project.

The milling process produces waste material that needs to be disposed of. The sweepers will collect the material and stock pile it at an agreed location close to the sites. However, if this material is to be carted away to another site, it will be an additional cost to the project.

4.5 Monitoring and Evaluation

4.5.1 Evaluation Parameters

The aim of the evaluation will be to assess the impact, relative safety and operational benefits of the trial milled rumble strips. The evaluation parameters that have been considered are outlined below. A recommendation is provided for each parameter:

- Impacts on the pavement – Advice from ARRB pavement team indicates no impact on pavement strength, except possibly drainage issues. As the rumble strips will be located outside the edge line and not in vehicle wheel paths, physical testing of the pavement is not required. A visual assessment would be appropriate to assess the integrity of the pavement. It is recommended that a visual assessment to identify any pavement defects be conducted as part of the trial.

- Debris in the grooves – assessing whether material collects in the grooves of the rumble strips. A visual inspection would be appropriate to determine whether materials/debris in the grooves will be a major maintenance issue for milled rumble strips. It is recommended that this be undertaken as part of the monitoring and evaluation of this trial.
- Barrier hits and crash analysis – it is unlikely, that crash numbers will be sufficiently high for meaningful statistical analysis within the first 12 months. This is due to short duration of the trial and the short lengths of road to be treated. It is recommended that within the first 12 months, simple descriptive and comparison between the before and after period will be undertaken. It is further recommended that a detailed statistical analysis of the barrier hits and crash data be conducted 24 to 36 months after treatment to enable conclusive evidence on the safety benefits of milled rumble strips to be determined.
- Vehicle speeds – assessment of changes in vehicle speeds due to the treatment. The milled rumble strips will be located outside the edge line and will have the same colour as the pavement surface. It is anticipated that vehicles speeds would not be influenced by the rumble strips. Hence the recommendation is not to collect vehicle speed data as part of the trial. However, if TMR, as part of its normal activities does collect before and after speed data from the trial sites then this data could be analysed and use in the monitoring of the trial.
- Driver behaviours and excursions across the edge line and rumble strips – data on these for the before and after the treatment can be captured via video cameras and compared. However, to assess the crossing of the edge line/rumble strips for the entire length of the rumble strips would require a series of cameras spaced at regular intervals which would be costly. A single camera could be installed at each site, but it would only indicate crossing of the edge line/rumble strip at that location, resulting in a very small data set, and an inaccurate assessment of the effectiveness of the rumble strip. It is recommended not to collect excursions across the edge line/rumble strip due to high data collection cost.
- Noise and vibration levels – Research indicates different dimensions of milled rumble strips provide different amounts of sound and vibration in the vehicle. Tires passing over the milled rumble strips drop into the grove, which causes the noise and vehicle vibrations. In general, the wider and deeper the rumble strips, the more noise and vibration. Previous studies have already concluded that milled rumble strips produce more noise and vibration compared to raised rumble strips (FHWA 2015b). Hence, the recommendation is not to include the measurements of noise and vibration as part of this trial.

4.5.2 Evaluation method

A before and after study with control method will be adopted for the trial. This will involve collection and comparison of the data before and after the implementation of the milled rumble strips. A control site will be used to take into account external circumstances, such as weather, and to isolate of the effects of the milled rumble strips.

4.5.3 Data collection

Data collection stages include:

- Before installation
- After installation periods
  - 3 months
  - 12 months
  - 24-36 months (TBA – variation needed).

Refer to Table 4.2 for the recommended data collection requirements for each of the evaluation periods.

Table 4.2: Recommended data collection requirements for each evaluation period

Parameter	Data/test	Evaluation periods			
		Before	3 months after	12 months after	24-36 months after
Pavement integrity	Visual assessment	Yes	Yes	Yes	Yes
Debris in grooves	Visual assessment	Yes	Yes	Yes	Yes
Crash analysis	Crash data from TMR	Yes	Yes (simple comparison)	Yes (simple comparison)	Yes (statistical analysis)
Safety barrier strikes	Barrier strikes data from TMR	Yes	Yes (simple comparison)	Yes (simple comparison)	Yes (statistical analysis)

The visual assessment of the pavement will be conducted by an experienced member of ARRB pavement team. The visual assessment of debris in the grooves of the rumble strips will also be conducted at the same time. It is assumed no traffic control is required during these inspections.

4.5.4 Data analysis and reporting

A progress project report will be prepared at the end of Year 1, which will include the site information, before data, discussion of the installation process and any issues associated with the trial. The final report will be prepared at the end of Year 2 and will include the analysis and comparison of the before data, and the 3 and 12 months data.

Year 3 (TBC with TMR) would involve a before and after crash data analysis and barrier hit assessment to determine the effectiveness of the treatment in reducing barrier hits and run-off-road crashes and a visual pavement assessment.

4.6 Timing and Trial Schedule

Table 4.3 outlines the project schedule for each of the key stages of the pilot trial. However, since no TMR Region is interested to undertake the trial, the project has been put on-hold.

Table 4.3: Project timing

Task	Completion Date
Year 1	
Develop trial methodology	31 Dec 2017
Collection of before data	31 Mar 2018
Installation of milled rumble strip (on-hold)*	30 April 2018
Year 1 progress report	30 June 2018
Year 2	
Collection of 3 months after data	Three months after installation
Collection of 12 months after data	12 months after installation date
Data analysis and Year 2 Report	30 June 2019
Year 3	
Collection of 24-36 months data and Year 3 Report (For TMR consideration - variation to original project brief)	36 months after installation

* Project put on hold, North Coast and Wide Bay/Burnett Region is unable to implement the trail and no other TMR region is interested in doing so.

5 CONCLUSIONS AND RECOMMENDATIONS

Milled rumble strips have been extensively used in the USA and Canada as a treatment to reduce run-off-road and cross-centreline crashes. To date there has been limited use in Australia with Roads and Maritime Services in New South Wales being the only road authority to have undertaken a trial of milled rumble strips. Typically, raised rumble strips/ audio tactile linemarkings (ATLM) are used in Australia and New Zealand.

Although initial installation cost is higher compared to ATLM, milled rumble strips potentially has lower whole-of-life-cost as it has longer treatment life. They are appropriate in all weather conditions including situations where raised rumble strips may not be suitable e.g. areas where pavements are exposed to high temperatures.

Road authorities in Australia have concerns regarding the impact on pavement integrity and maintenance issues such as debris sitting in the grooves. However, literature indicates that debris in the grooves is not an issue and pavement issues are minimised if milled rumble strips are applied to a pavement in good condition with adequate thickness.

It is recommended that a trial of milled rumble strips be conducted on a section of the Bruce Highway with the following characteristics:

- a location away from residential areas to minimise noise impacts
- where no cyclists are allowed
- on pavement with a thickness greater than 50 mm
- a wide sealed shoulder (should provide at least 1.2 m sealed width from the rumble strip to outside edge of the sealed shoulder)
- has no bridge decks, approach slabs or construction joints
- has a pavement seal that does not consist of open graded asphalt
- the pavement is in good condition with a well compacted subgrade and has good drainage characteristics
- the pavement does not exhibit any fatigue cracking.

Before proceeding with the trial of milled rumble strips as recommended, the costs associated with the installation including establishment costs, will need to be considered to ensure the trial is economically feasible. Currently there is only one contractor available in Australia (Roadline Removal/Oz Rumble) that has the milling machine capable on installing the milled rumble strips and is based interstate.

North Coast and Wide Bay/Burnett Region that proposed the study is now unable to conduct the trial. Furthermore, no TMR Region is interested in undertaking the trial, hence the project has been put on-hold until a suitable region willing to undertake the trial is found.

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