Review of Milled Rumble Strips on Alberta Roads

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Abstract

A reduction in collision numbers coupled with relatively low cost of installation makes rumble strips an effective safety measure to prevent run-off-road and left-of-center collisions, and is considered highly cost effective based on the overall benefits to society that accrue over the life span of rumble strips. A study on design and construction of milled rumble strip practices was undertaken with the objective of fine tuning Alberta Transportation's (AT) practices, specifically design and construction of rumble strips to accommodate cyclists on Alberta roads. The study also analysed best practices on installing patterned (intermittent) rumble strips on shoulders of the sections of roads with high volumes of bicycles.

The primary objectives of this review included:

1. A review of the cost effectiveness of milled rumble strips on shoulders and centerline by using the most recent collision data for Alberta. The most recent collision data available by the time of this study is up to the year 2012.

2. An analysis of best practices of installing patterned (intermittent) rumble strips on shoulders of the sections of roads with high volumes of bicycles.

3. A general review of the Department's practices with the intent of enhancing or fine tuning where possible with the purpose of improving design and construction practices of milled rumble strips.

1.0 BACKGROUND AND OBJECTIVES

The purpose of rumble strips is to alert errant drivers when they inadvertently leave the travel lanes by producing a humming noise which can be heard inside most passenger vehicles as well as a noticeable vibration which can be felt within the vehicle. The vibration is carefully designed to be noticeable to the vast majority of drivers without being sufficiently rough to hinder vehicle control. Rumble strips have been widely used by Canadian and U.S. state transportation departments with impressive results. Alberta Transportation (AT) was the first adopter among provincial highway authorities in Canada. Shoulder rumble strips are well documented regarding their effectiveness, primarily in reducing the frequency of vehicles departing the roadway to the right on undivided highways and to both the left and right on divided highways. As stated by FHWA, 2011, centerline rumble strips are an effective countermeasure for left-of-center collisions, which are those where a vehicle strays out of the lane to the left and collides with an oncoming vehicle or object off the roadway on the left side. The expected Collision Modification Factors (CMF's) as obtained from the CMF Clearinghouse have a "five-star quality rating" range from 0.55 to 0.91. The CMF is the proportion by which collisions are expected to be reduced after centreline rumble strips are installed. The "five-star quality rating" is the highest level of accuracy in results.

This reduction in collision numbers coupled with relatively low cost of installation makes rumble strips an effective safety measure to prevent run-off-road and left-of-center collisions and is considered highly cost effective based on the overall benefits to society that accrue over the life span of rumble strips.

AT began experimenting with rumble strips in 1992 and once effectiveness was verified, began a systematic program of installation on Alberta roads throughout the province. Initially the Department started with grooved rumble strips but as an effort of continuous improvement, moved on to installing milled rumble strips on selected projects in 1995 to gain more experience with the method. Milled rumble strips have been found to be more expensive than the grooved type however they have several advantages including accuracy of placement, compaction of surface, no cracking etc. Because of the above advantages, the department as a matter of policy adopted the installation of milled centerline and/or shoulder rumble strips through maintenance contracts, new construction, pavement rehabilitation and/or stand-alone rumble strip construction contracts, where warranted.

The primary objectives of this study included:

1. To perform a literature review of available studies that evaluated the impact of rumble strips on collision rates and severities.

2. To estimate the cost effectiveness of milled rumble strips on shoulders and centerline on Alberta highways by using the most recent collision data. The most recent collision data available by the time of this study is up to the year 2012.

3. To analyse best practices of installing patterned (intermittent) rumble strips on shoulders of the sections of roads with high volumes of bicycles.

4. Undertake a general review of the Department's practices with the intent of enhancing or fine tuning where possible with the purpose of improving design and construction practices of milled rumble strips.

2.0 LITERATURE REVIEW ON THE IMPACT OF RUMBLE STRIPS ON COLLISIONS

Alberta Transportation does not currently have an inventory of its rumble strips and therefore cannot provide any provincial data to support the assertion that rumble strips are effective at reducing collisions on Alberta highways. In order to evaluate the experiences with and effectiveness of rumble strips to date, a literature review was completed. Numerous studies have been completed for locations where rumble strips have been installed in various American states. Two relevant Canadian studies were also identified. These studies are described in more detail below.

Nambisan et al., 2007 evaluated safety records on roadways in Nevada on which continuous shoulder rumble strips were installed, using crash data from 1995-2003. When crashes/year values of each of the 306 analyzed segments were compared, it was observed that around 66% of the segments showed a decline in the number of crashes/year. These segments accounted for 81% of total centerline miles of roadway. 12% of the segments showed no change in crashes per year, and 23% showed an increase. Overall the results suggested that the continuous shoulder rumble strip treatment was effective in reducing the number of single-vehicle ran-off-roadway crashes and the corresponding crash rates.

A study in Kentucky (Kirk, 2008) involved a crash analysis using a three-year history for 162 roadway segments with and without shoulder rumble strips. It concluded that:

- Two-lane rural roads with continuous shoulder rumble strips (CSRS) have a statistically significant lower total crash rate than those without CSRS.
- Two-lane rural roads with CSRS have a statistically significant lower crash rate resulting from inattention/drowsiness than roadways without CSRS.
- Crash rates on two-lane rural roads are generally lower when shoulder width is maximized and lane width is minimized

The study recommended that CSRS and subsequent sufficient shoulder width be used on all state maintained two-lane rural highways as shown in Table 1. Kirk's report also mentioned that the Insurance Institute for Highway Safety conducted a comprehensive before and after study evaluating centerline rumble strip applications in seven states. This study concluded that total crashes were reduced by 15% and head-on and opposite direction sideswipe crashes were reduced by 21%.

Marvin and Clark (2003) collected crash data for three-year periods before and after rumble strip installation for segments on the National Highway Interstate System, National Highway Non-Interstate System, and from State Primary Routes throughout Montana. Their analysis revealed that shoulder rumble strips were most effective in reducing the crash rate and severity of off-road and rollover crashes for Interstate highways. Specifically, they calculated a 14% reduction in crash rate and a 23.5% reduction in the severity rate of off-road crashes. Reductions in crash rates for collisions classified as "roll-overs" were 5.5%. However, "roll-over" severity rates increased by 2.7%. They concluded that as a whole, rumble strips seemed to be moderately successful in reducing the occurrence of various situational crashes, especially those caused by drowsiness/inattention.

For Canadian data, the only information identified were two studies completed in British Columbia. The first, by Sayed and de Leur (2008), established collision modification factors (CMF) for various safety improvements on B.C. highways. The CMF for shoulder rumble strips was identified as 0.79 (a reduction of 21%). This CMF targets off-road right collisions and is applicable to range of shoulder rumble strip designs and placement, as well as for horizontal curves and tangents. Their calculated CMF for centerline rumble strips is 0.86 (a reduction of 14%), applicable to the range of centerline rumble strip designs and layout. It is also applicable to horizontal curves, tangent sections, passing lanes and no-passing lanes.

The second Canadian study was completed by Sayed et al. (2010); it evaluated the safety impacts associated with application of shoulder and centerline rumble strips in B.C. The before data corresponded to a three year period before the installation of the strips, and the after data ranged from one to three years after the strips were installed. The evaluation included both milled and rolled rumble strips. The results showed that shoulder and centerline rumble strips can significantly reduce severe collisions and specific collision types, specifically:

- Rumble strips reduced all injury collisions by a statistically significant 18%.
- Shoulder rumble strips reduced off-road right collisions by a statistically significant 22.5%.
- Centerline rumble strips showed a statistically significant reduction of 29.3% in off-road left and head-on collisions.
- Sites with both centerline and shoulder rumble strips showed a statistically significant reduction of 21.4% in off-road right, off-road left, and head-on collisions combined.

By reviewing the results of the literature search, it is evident that both centerline and shoulder rumble strips are effective collision countermeasures. Studies showed that the reduction in collision rate before and after installation of rumble strips could be as high as 29%. This information further solidifies the basis for the percent reductions used in the subsequent analysis to estimate the effect that rumble strips could have on collision rates on Alberta highways.

3.0 COST EFFECTIVENESS ANALYSIS OF MILLED RUMBLE STRIPS

The benefit (shown in the analysis presented below) of installing shoulder rumble strips is the reduction in run-off-the-road collisions and the benefit of installing centerline rumble strips is the reduction in left-of-center collisions. Many American states have completed before / after collision analyses to determine the reduction in collisions due to the installation of shoulder rumble strips and centerline rumble strips on rural highways.

Based on the results of 20 various studies/research projects related to rumble strips that were undertaken by US state departments of Transportation and other agencies, Torbic et al. (2009) mentions that:

- Single Vehicle Run-off-Road (SVROR) collisions were reduced by 10% to 80% due to shoulder rumble strips. The simple average reduction in SVROR crashes from these studies is 36%.

- Total crashes were reduced by 13% to 33% due to shoulder rumble strips. The simple average reduction in total crashes from these studies is 21%.

- Left-of-center collisions were reduced by 34% to 95% due to centerline rumble strips. The simple average reduction in left-of-center crashes from these studies is 65%.

The time in which the cost of rumble strips has been recuperated in terms of collision cost savings is referred to as the payback period. Using Alberta's collision data and costs, the payback period for each scenario was calculated. As no such study as the aforementioned has yet been done for Alberta highways, the payback period analysis has been undertaken for 10%, 20% and 30% reductions to demonstrate sensitivity to effectiveness. Based on the published research from the U.S., Alberta Transportation is confident that the 30% reduction is a reasonable expectation on Alberta highways for the types of collisions that can be expected to be reduced by the particular rumble strips.

For centerline rumble strips, the collision rate and costs were calculated for left-of-center collisions on undivided highways only. For shoulder rumble strips, the collision rate and costs were calculated for off-road collisions (right and left) for undivided highways and off-road (right and left) as well as left of center collisions for divided highways.

A summary of the results of the analysis is shown in Table 2. Based on the results in Table 2, it is evident that it takes a very short period of time for the cost of rumble strips to be recovered. Another factor used in the cost-effectiveness analysis was the benefit cost ratio, which is a comparison of the benefits to the costs. If the ratio is greater than one, benefits exceed costs and the project provides net benefits. The benefit cost ratio for a 30% reduction in collisions scenario is shown in Table 3; this table shows that the benefit cost ratios are very high for the rumble strip installations where there is an estimated 30% reduction in collisions. It is also logical to conclude that the benefit increases as the traffic volume increases. Snapshots of the calculations for the preceding economic indicators are shown in Figures 1-13.

The results of both the payback period and benefit cost ratio analyses show that the benefits of installing shoulder and centerline rumble strips in terms of the collision cost savings far outweigh the cost of installation. Even at low AADT volumes, milled rumble strip installation is a very favorable investment because of the relatively low cost of installing rumble strips compared to the savings in costs associated with collisions.

4.0 INTERMITTENT MILLED RUMBLE STRIPS FOR ACCOMMODATING CYCLISTS

4.1 Bicycle Issues

Cyclists on highways have a negative perception of shoulder rumble strips because it prevents them from riding side by side. AT is careful to install rumble strips so that there is an adequate shoulder width to allow cycling on the shoulder in single file. Rumble strips can be expected to enhance safety for cyclists by reducing the incidence of motor vehicles running off the lanes and into the shoulder.

4.2 Survey Results

A survey of 27 U.S. DOTs and four Canadian provincial transportation agencies on their rumble strip practices was conducted as part of a research project in Torbic et al. (2009). The answers to the questions that relate to bicycling are listed:

- A majority of transportation agencies (17 agencies, 54.8%) said that bicycles "affect installation requirements" for their rumble strip policy or guidelines.

- On non-controlled access highways, it is common for transportation agencies to provide periodic gaps in the rumble strips of 10 or 12 ft. (3.0 or 3.6 m), in 40 or 60 ft. (12 or 18 m) cycles, with the primary intention to allow bicyclists to maneuver from the travel lanes to the shoulder and back (i.e., from one side of the rumble strips to the other) without having to encounter the indentations/grooves.

- A larger majority (19 agencies, 61.3%) said they had a "minimum shoulder width requirement for the installation of shoulder rumble strips." Minimums ranged from two to six ft. (0.6 to 1.8 m); four ft. and six ft. (1.2 to 1.8 m) were the most common answers, but four ft. (1.2 m) are considered a bare minimum by bicyclists.

- Nearly 40% (12 agencies, 38.7%) said their rumble strip policy changes depending on "whether shoulder rumble strips will be installed along a designated bicycle route." According to the report: "Responses included: (a) rumble strips are not installed along designated bicycle routes, (b) need to consider available lateral clearance, (c) rumble strip patterns/ dimensions change, and (d) gaps are provided rather than installing the rumble strips on a continuous basis."

- Many agencies (11 agencies, 35.5%) said their policy / standard provides “a gap in the shoulder rumble strip pattern to allow bicyclists to maneuver from the travel lane to the shoulder and back without traversing the rumble strips.” Typical responses were 12 ft. (3.7 m) gaps in 40 or 60 ft. (12 m or 18 m) cycles.

- Notably, but not surprisingly, no agencies collected data on “bicycle-only crashes or non-crash injuries related to rumble strip encounters.”

4.3 Examples of State Policies Accommodating Bicycling

A National Center for Transportation and Industrial Productivity Study by Daniel, 2007, in cooperation with the New Jersey DOT and the US DOT FHWA, reported the following state-specific practices to accommodate bicycling:

- Minimum shoulder width to accommodate rumble strips. Do not use rumble strips if the shoulder width is less than eight ft. (2.4 m). Alaska requires six to seven ft. (1.8 to 2.1 m) shoulders for rumble to be added and periodic 12 ft. (3.7 m) gaps in the rumbles to allow bicycles to cross; and Colorado, in which no rumble strips are added on shoulders less than six ft. (1.8 m) when a guardrail is present, requires a 12 ft. (3.7 m) gap in every 60 ft. section.

- Widen the shoulder to provide at least a four ft. (1.25 m) wide continuous riding surface for bicycling (Florida).

- Provide an offset of four ft. (1.2 m) from edge of shoulder for bicycles and motorcycles (Hawaii).

- Moving the rumble strip as close to the travel lane as possible (Minnesota).

- Use of continuous rumble strips only on limited access facilities.

- Use periodic gaps in the rumble strip on non-controlled access highways. Gaps of 12 ft. (3.7 m) in every 40 to 60 ft. (12 to 18 m) of rumble strips used in Arizona.

- Not allowing rumble strips on roadways used by bicyclists (Maine).

- Reducing the width of the rumble strip (Kentucky).

- Requiring approval of the Pedestrian/Bicycle Coordinator if rumble strips are to be installed on a shoulder width less than eight ft.

4.4 Recommended Best Practices for Accommodating Cyclists

Generally adapted best practices to accommodate cyclists as established by the League of American Bicyclists are listed below:

1. Not installing rumble strips on designated bicycle routes and other roads where bicycling is expected. For non-freeway rural roads, strips should be installed on bicycle routes only after proper study confirms a documented need. AT's policy is to consider the accommodation of bicycle traffic wherever it is known to occur on a regular basis. Such accommodation may include the use of "edge line rumble strips" instead of regular shoulder rumble strips to reduce the impact on the shoulder. Currently AT does not have a standard for what constitutes a "bicycle route".

2. Providing minimum shoulder width – 1.2 m shoulder, or 1.5 m with guardrail are the bare minimum. Better examples include Alaska and Colorado that require a minimum 1.8 m shoulder. AT currently mandates rumble strips for shoulder widths 1.4 m or greater, as this will leave sufficient room for cyclists to ride single file on the shoulder adjacent to the rumble strip pattern.

3. Adjusting placement of the rumble strips by placing strips close to or on the edge line to increase available shoulder area. As per AT's current practice, the normal offset of the rumble strips can be in the range of 150 – 200 mm from the painted shoulder line however rumble strips are placed over top of the shoulder line in the case of edge line rumble strips.

4. Placing rumble strips on the edge line (a rumble stripe) both increases visibility of the white line and maximizes available shoulder area. Although AT is holding trials of edge line rumble strips where the shoulder is between 1.0 and 1.4 m, as mentioned above the policy is to minimize the effects on cycling on known bicycle routes.

5. Adjusting rumble strips dimensions – Pennsylvania, California and Colorado have studied bicycle-tolerable rumble strip designs. The studies come to similar conclusions about the dimensions for such rumble strips:
   - Width: 5 in (127 mm), whereas AT's standard width is 300 mm;
   - Depth: 0.375 in (10 mm), whereas AT's standard depth is 9 mm +/- 2 mm ; and
   - Spacing: 11 or 12 in (280 or 305 mm) when bicyclists need more of the shoulder or rumble strips are needed along a narrow shoulder (Torbic et al. report that narrower strips can "still generate the desired sound level differences in the passenger compartment), whereas AT's standard spacing is 150 mm +/- 40 mm.

6. Providing gaps in regular intervals: to give cyclists a chance to avoid debris along the shoulder, merge, turn, or pass other cyclists, some states include periodic gaps in the strips – at least 12 ft. (3.7 m) in length, every 40 or 60 ft. (12 m or 18 m) length of rumble strip. A supplement to TAC Geometric Design Guide by the British Columbia Ministry of Transportation (BC MoT) recommends a gap of 3.5 m, every 15 m of rumble strips. BC MoT currently uses intermittent rumble strips on bicycle routes.

4.5 Scope of the Study and Results

In realization of the above mentioned facts, AT is convinced to look into the option of installation of intermittent rumble strips on shoulders, in the areas of bicycle traffic/bicycle routes. However it is realized that a possible limitation in adapting this practice could be higher cost of construction for intermittent rumble strips compared with continuous rumble strips, as construction of intermittent rumble strips may involve more effort for marking the gaps and multiple times stop/restart of milling operation.

As a part of this study, a first attempt was made to get some unit cost rates for construction of intermittent rumble strips. However, very limited cost information is currently available regarding intermittent milled rumble strips, no such data is available for AT projects and though the BC MoT installs intermittent rumble strips on their projects, there is no separate pay item for intermittent rumble strips.

Therefore, cost comparison of intermittent and continuous rumble strips was investigated by telephone and email surveys/feedback to various Department employees from regions, officials from BC MoT and contractors from Alberta and British Columbia.

Based on all the feedback, it is concluded that although intermittent rumble strips involve additional effort, this will be offset by not discounting the gaps for measurement and payment purposes. Consequently AT expects there will be no significant cost increase, provided the method of measurement does not exclude gaps from the measured payable quantities.

5.0 RECOMMENDATIONS FOR ALBERTA TRANSPORTATION

1. The Department should look for opportunities to enhance safety on existing rural highways by installing rumble strips in locations where they are warranted but were not installed for some reason i.e. undertake a catch-up program for centerline and shoulder rumble strips. This program should be done in order of priority based on cost effectiveness. While there is currently no inventory available, implementation should begin on the highways that could benefit the most based on their current safety performance, traffic volumes, and potential for improvement in reducing collisions. It is very desirable to focus implementation on long continuous segments of busy highways as they generally have the greatest frequency of run-off-road and left-of-centre collisions. Also, the provision of consistent rumble strip treatment along a highway is more desirable than inconsistent treatment in order to satisfy driver expectations.

2. Obtain an inventory of provincial highway rumble strips as soon as it is cost-effective to do so.

3. Develop a standard drawing for intermittent shoulder rumble strips as per the dimensions in this document. Undertake a small section of trial installation and evaluate the cost and performance within a one year period*. Extend the evaluation period if required to obtain data. If this is found to be successful, consider adopting the intermittent patterns as the standard.

4. Undertake a trial for installation of shoulder rumble strips on the edge line. Evaluate within one year*. Extend the evaluation period if required to obtain data.

5. Undertake a trial of narrow rumble strip (possibly 175 mm). Evaluate within a year*. Extend the evaluation period if required to obtain data.

6. Prepare a standard that defines a “bicycle route” on Alberta highways. AT is interested in developing a “Cycling Information Map” as funding allows. A suggested way of developing the map is for it to show various highway routes that are rated based on a set of threshold criteria for cycling as GOOD, MODERATE, and FAIR. This rating system is based off of Wisconsin Department of Transportation’s road evaluation method and is intended to assist cyclists in selecting their routes.

*It has been noted that a one year evaluation period may be too short to obtain a sufficient sample of collisions. AT should consider completing a future “feasibility assessment” on using drone-based video conflict analysis for a before-after study. Since conflicts are more common than collisions, more data could be collected in a shorter period of time thus resulting in faster evaluation.

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Table 1: Rumble Strip Placement in Kentucky

Total Pavement Width (ft)	Lane Width (ft)	Paved Shoulder (ft)	Centerline	Edgeline
28	12	2	yes	yes
27	12	1.5	yes	yes
26	11	2	yes	yes
25	11	1.5	yes	yes
24	11	1	yes	yes
23	10	1.5	yes	yes
22	10	1	yes	yes
21	9	1.5	yes	yes
20	9	1	yes	yes
19	8	1.5	yes	no
18	8	1	yes	no
17	7.5	1	no	yes
16	7	1	no	yes
15	6.5	1	no	yes
14	6	1	no	yes

Table 2: Estimated Payback Period for Rumble Strips Based on a Reduction in the Collisions Related to that Rumble Strip Type (not all collisions)

	Payback Period (Months)								
AADT	AADT = 1,000			AADT = 5,000			AADT = 10,000		
% Reduction	30%	20%	10%	30%	20%	10%	30%	20%	10%
Milled Rumble Strip - Centerline (undivided highways)	2.6	3.9	7.8	0.52	0.78	1.6	0.26	0.39	0.78
Milled Rumble Strips -Shoulder (undivided highways)	4.2	6.2	12	0.83	1.2	2.5	0.42	0.62	1.2
Milled Rumble Strips- Shoulder (divided highways)	15	23	45	3.0	4.5	9.1	1.5	2.3	4.5

Table 3: Benefit Cost Ratio for Rumble Strips Based on a Service Life of 20 Years

Type of Rumble Strip	**Benefit/Cost Ratio for 30%* reduction in collisions**		
	AADT = 1,000	AADT = 5,000	AADT = 10,000
Milled Rumble Strip - Centerline (undivided highways)	92.1	461	921
Milled Rumble Strips - Shoulder (undivided highway)	57.8	289	578
Milled Rumble Strips - Shoulder (divided highway)	15.8	79.2	158

* 30% reduction is used in the analysis as it is the % reduction frequently reported by agencies that have done studies into the effectiveness of rumble strips on their highways. The % reduction is applied only to the types of collisions that are expected to be affected by that type of rumble strip (not all collisions).

Figure 1: Number of Collisions by Type and Total Collision Rate (2008-2012 inclusive) (Office of Traffic Safety Data, Alberta Transportation)

Centreline Rumble Strips (undivided highway)				
Collision Type	**Fatal**	**Injury**	**PDO**	
Head on	220	271	84	
Off Road Left	87	1658	3156	
Sideswipe - opposite direction	41	396	839	
Collision Rate per 100 million vehicle km	**12.7**	(Length of data segments = 22,259 km)		
Shoulder Rumble Strips (undivided highway)				
Collision Type	**Fatal**	**Injury**	**PDO**	
Off Road Left	87	1658	3156	
Off Road Right	103	2330	5669	
Collision Rate per 100 million vehicle km	**26.75**	(Length of data segments = 22,259 km)		
Shoulder Rumble Strips (divided highway)				
Collision Type	**Fatal**	**Injury**	**PDO**	
Off Road Left	38	1125	3224	
Off Road Right	30	1107	3831	
Head On	30	46	19	
Sideswipe - opposite direction	6	81	144	
Collision Rate per 100 million vehicle km	**19.5**	(Length of data segments = 2,140 km)		

Figure 2: Collision Costs as Determined by AT's Office of Traffic Safety (Canadian Dollars)

Unit cost of collisions (Social Costs)	
Fatal	$9,120,367
Injury	$66,744
Property damage Only (PDO)	$5,851

Figure 3: Costs for Collisions Potentially Mitigated by Rumble Strips

	Centreline Rumble Strips			Shoulder Rumble Strips			Shoulder Rumble Strips		
	(Undivided highway)			(Undivided highway)			(Divided highway)		
	No.	**%**	**$**	**No.**	**%**	**$**	**No.**	**%**	**$**
Total number of Fatal collisions	348	5.15	$470,066	190	1.46	$133,267	104	1.07	$ 97,977
Total number of Injury collisions	2325	34.43	$22,983	3988	30.67	$ 20,470	2359	24.37	$ 16,264
Total number of PDO collisions	4079	60.41	$3,535	8825	67.87	$ 3,971	7218	74.56	$ 4,362
Total	6752	100		13003	100		9681	100	
Average cost per collision		**A**	**$496,584**		**B**	**$157,708**		**C**	**$ 118,603**

Figure 4: Rumble Strip Installation Costs

Construction cost of rumble strips - shoulder		=	$800	/Km
Painting of centerline		=	$300	/Km
Construction cost of rumble strips - centerline		=	$896	/Km
Cost of fog coat (if required)		=	$300	/Km

Figure 5: Economic Analysis – Centerline Rumble Strips, AADT = 1000

Centerline Rumble Strips			**SCENARIO 1**		**SCENARIO 2**		**SCENARIO 3**		
(On Undivided Highways Only)			(30% Reduction)		(20% Reduction)		(10% Reduction)		
			Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for left of center collisions, undivided highway (collisions/100 MVKm)	**D**		12.7		12.7	12.38	12.7		
AADT	**E**		1000		1000		1000		
Collisions / Km / Year for 1000 AADT (D x 365.25 x E / 100,000,000)	**F**			0.046		0.046		0.046	
Total collision cost per year = F x A ($496,584)	**G**			23,035		23,035		23,035	
Total Left of Center collisions cost / year = G x Factor (100%)	**H**		1	23035	1	23035	1	23035	
Cost benefit (% reduction in left of center collisions)	**I**		0.3	6910	0.2	4607	0.1	2303	
Construction cost of centerline rumble strips / km	**J**		0	1500		1500		1500	
Payback period (J/I)	**K**			0.22		0.33		0.65	
				2.6	**Months**	**3.9**	**Months**	**7.8**	**Months**
Benefit Cost Ratio for service life of 20 years			20	**92.1**					

Figure 6: Economic Analysis - Shoulder Rumble Strips, Undivided Highway, AADT = 1000

Shoulder Rumble Strips:		**SCENARIO 1**		**SCENARIO 2**		**SCENARIO 3**		
(Undivided Highway)		(30% Reduction)		(20% Reduction)		(10% Reduction)		
		Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for run-off-the-road collisions (left and right), undivided highways (collisions/100 MVKm)	**L**	26.75		26.75		26.75		
AADT	**M**	1000		1000		1000		
Collisions / Km / Year for 1000 AADT (L x 365.25 x M / 100,000,000)	**N**		0.098		0.098	0	0.098	
Total collision cost per year = N x B ($157,708)	**O**		15,409		15,409		15,409	
Total run-off-the-road collisions cost / year = O x Factor (100%)	**P**	1	15409	1	15409	1	15409	
Cost benefit (% reduction in off-the-road collisions)	**Q**	0.3	4623	0.2	3082	0.1	1541	
Construction cost of 2 shoulder rumble strips / km	**R**	1600		1600		1600		
Payback period (R/Q)	**S**		0.35		0.52		1.04	
			4.2	***Months***	***6.2***	***Months***	***12***	***Months***
Benefit Cost Ratio for service life of 20 years		20	**57.8**					

Figure 7: Economic Analysis - Shoulder Rumble Strips, Divided Highway, AADT = 1000

Shoulder Rumble Strips:		**SCENARIO 1**		**SCENARIO 2**		**SCENARIO 3**		
(Divided Highway)		(30% Reduction)		(20% Reduction)		(10% Reduction)		
		Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for run-off-the-road collisions (left and right) and left of center, divided highways (collisions/100 MVKm)	**T**	19.5		19.5		19.5		
AADT	**U**	1000		1000		1000		
Collisions / Km / Year for 1000 AADT (L x 365.25 x m / 100,000,000)	**V**		0.071		0.071	0	0.071	
Total collision cost per year = V x C ($118,603)	**W**		8,447		8,447		8,447	
Total run-off-the-road and left of center collisions cost / year = W x Factor (100%)	**X**	1	8447	1	8447	1	8447	
Cost benefit (% reduction in off-the-road and left of center collisions)	**Y**	0.3	2534	0.2	1689	0.1	845	
Construction cost of 4 shoulder rumble strips / km	**Z**	3200		3200		3200		
Payback period (Z/Y)	**AA**		1.26		1.89		3.79	
			15	***Months***	***23***	***Months***	***45***	***Months***
Benefit Cost Ratio for service life of 20 years		20	**15.8**					

Figure 8: Economic Analysis - Centerline Rumble Strips, AADT = 5000

Centerline Rumble Strips			**SCENARIO 1**		**SCENARIO 2**		**SCENARIO 3**		
(On Undivided Highways Only)			(30% Reduction)		(20% Reduction)		(10% Reduction)		
			Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for left of centre collisions, undivided highway (collisions/100 MVKm)	**D**		12.7		12.7	12.38	12.7		
AADT	**E**		5000		5000		5000		
Collisions / Km / Year for 5000 AADT (D x 365.25 x E / 100,000,000)	**F**			0.232		0.232		0.232	
Total collision cost per year = F x A ($496,584)	**G**			115,175		115,175		115,175	
Total Left of Center collisions cost / year = G x Factor (100%)	**H**		1	115175	1	115175	1	115175	
Cost benefit (% reduction in left of center collisions)	**I**		0.3	34552	0.2	23035	0.1	11517	
Construction cost of centerline rumble strips / km	**J**		0	1500		1500		1500	
Payback period (J/I)	**K**			0.04		0.07		0.13	
				0.52	**Months**	**0.78**	**Months**	**1.6**	**Months**
Benefit Cost Ratio for service life of 20 years			20	**461**					

Figure 9: Economic Analysis - Shoulder Rumble Strips, Undivided Highway, AADT = 5000

Shoulder Rumble Strips:			**SCENARIO 1**		**SCENARIO 2**		**SCENARIO 3**		
(Undivided Highway)			(30% Reduction)		(20% Reduction)		(10% Reduction)		
			Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for run-off-the-road collisions (left and right), undivided highways (collisions/100 MVKm)	**L**		26.75		26.75		26.75		
AADT	**M**		5000		5000		5000		
Collisions / Km / Year for 5000 AADT (L x 365.25 x M / 100,000,000)	**N**			0.489		0.489	0	0.489	
Total collision cost per year = N x B ($157,708)	**O**			77,044		77,044		77,044	
Total run-off-the-road collisions cost / year = O x Factor (100%)	**P**		1	77044	1	77044	1	77044	
Cost benefit (% reduction in off-the-road collisions)	**Q**		0.3	23113	0.2	15409	0.1	7704	
Construction cost of 2 shoulder rumble strips / km	**R**		1600		1600		1600		
Payback period (R/Q)	**S**			0.07		0.10		0.21	
				0.83	***Months***	***1.2***	***Months***	***2.5***	***Months***
Benefit Cost Ratio for service life of 20 years			20	**289**					

Figure 10: Economic Analysis - Shoulder Rumble Strips, Divided Highway, AADT = 5000

Shoulder Rumble Strips:			**SCENARIO 1**		**SCENARIO 2**		**SCENARIO 3**		
(Divided Highway)			(30% Reduction)		(20% Reduction)		(10% Reduction)		
			Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for run-off-the-road collisions (left and right) and left of center, divided highways (collisions/100 MVKm)	**T**		19.5		19.5		19.5		
AADT	**U**		5000		5000		5000		
Collisions / Km / Year for 5000 AADT (L x 365.25 x m / 100,000,000)	**V**			0.356		0.356	0	0.356	
Total collision cost per year = V x C ($118,603)	**W**			42,237		42,237		42,237	
Total run-off-the-road and left of center collisions cost / year = W x Factor (100%)	**X**		1	42237	1	42237	1	42237	
Cost benefit (% reduction in off-the-road and left of center collisions)	**Y**		0.3	12671	0.2	8447	0.1	4224	
Construction cost of 4 shoulder rumble strips / km	**Z**		3200		3200		3200		
Payback period (Z/Y)	**AA**			0.25		0.38		0.76	
				3.0	***Months***	***4.5***	***Months***	***9.1***	***Months***
Benefit Cost Ratio for service life of 20 years			20	**79.2**					

Figure 11: Economic Analysis - Centerline Rumble Strips, AADT = 10,000

Centerline Rumble Strips			**SCENARIO 1**		**SCENARIO 2**		**SCENARIO 3**		
(On Undivided Highways Only)			(30% Reduction)		(20% Reduction)		(10% Reduction)		
			Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for left of center collisions, undivided highway (collisions/100 MVKm)	**D**		12.7		12.7	12.38	12.7		
AADT	**E**		10000		10000		10000		
Collisions / Km / Year for 10000 AADT (D x 365.25 x E / 100,000,000)	**F**			0.464		0.464		0.464	
Total collision cost per year = F x A ($496,584)	**G**			230,349		230,349		230,349	
Total left of centre collisions cost / year = G x Factor (100%)	**H**		1	230349	1	230349	1	230349	
Cost benefit (% reduction in left of center collisions)	**I**		0.3	69105	0.2	46070	0.1	23035	
Construction cost of centerline rumble strips / km	**J**		0	1500		1500		1500	
Payback period (J/I)	**K**			0.02		0.03		0.07	
				0.26	**Months**	**0.39**	**Months**	**0.78**	**Months**
Benefit Cost Ratio for 20 year service life			20	**921**					

Figure 12: Economic Analysis - Shoulder Rumble Strips, Undivided Highway, AADT = 10,000

Shoulder Rumble Strips:			**SCENARIO 1**		**SCENARIO 2**		**SCENARIO 3**		
(Undivided Highway)			(30% Reduction)		(20% Reduction)		(10% Reduction)		
			Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for run-off-the-road collisions (left and right), undivided highways (collisions/100 MVKm)	**L**		26.75		26.75		26.75		
AADT	**M**		10000		10000		10000		
Collisions / Km / Year for 10000 AADT (L x 365.25 x M / 100,000,000)	**N**			0.977		0.977	0	0.977	
Total collision cost per year = N x B ($157,708)	**O**			154,088		154,088		154,088	
Total run-off-road collisions cost / year = O x Factor (100%)	**P**		1	154088	1	154088	1	154088	
Cost benefit (% reduction in off-the-road collisions)	**Q**		0.3	46226	0.2	30818	0.1	15409	
Construction cost of 2 shoulder rumble strips / km	**R**		1600		1600		1600		
Payback period (R/Q)	**S**			0.03		0.05		0.10	
				0.42	***Months***	***0.62***	***Months***	***1.2***	***Months***
Benefit Cost Ratio for 20 year service life			20	**578**					

Figure 13: Economic Analysis - Shoulder Rumble Strips, Divided Highway, AADT = 10,000

Shoulder Rumble Strips:			**SCENARIO 1**		**SCENERIO 2**		**SCENARIO 3**		
(Divided Highway)			(30% Reduction)		(20% Reduction)		(10% Reduction)		
			Input	**Result**	**Input**	**Result**	**Input**	**Result**	
Average annual collision rate for run-off-the-road collisions (left and right) and left of center, divided highways (collisions/100 MVKm)	**T**		19.5		19.5		19.5		
AADT	**U**		10000		10000		10000		
Collisions / Km / Year for 10000 AADT (L x 365.25 x m / 100,000,000)	**V**			0.712		0.712	0	0.712	
Total collision cost per year = V x C ($118,603)	**W**			84,474		84,474		84,474	
Total run-off-the-road and left of center collisions cost / year = W x Factor (100%)	**X**		1	84474	1	84474	1	84474	
Cost benefit (% reduction in off-the-road and left of center collisions)	**Y**		0.3	25342	0.2	16895	0.1	8447	
Construction cost of 4 shoulder rumble strips / km	**Z**		3200		3200		3200		
Payback period (Z/Y)	**AA**			0.13		0.19		0.38	
				1.5	***Months***	***2.3***	***Months***	***4.5***	***Months***
Benefit Cost Ratio for a 20 year service life			20	**158**					