A Study of Effectiveness of Various Shoulder Rumble Strips on Highway Safety

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ABSTRACT

The Run-off-the-Road (ROTR) type of accident has been a predominant factor in highway fatalities nationwide. This situation has created a major concern and challenge for traffic management within transportation departments. Shoulder rumble strips are new traffic control devices for interstate and limited access roadway systems, which hold great potential for reducing ROTR accidents. Consequently, they have become a critical and attractive subject for highway safety improvements.

Although shoulder rumble trips have been recognized as an effective measure and have been widely tested by 35 state agencies and several countries, the rolled type rumble strip is found most often in the literature. The optimal design patterns among the available types and their effectiveness have not been quantitatively tested and confirmed. This paper reexamines different typical patterns using field tests, implementation surveys from agencies, and mathematical analysis. A model has been developed to determine the optimal patterns. The results reveal that a milled pattern is superior to a rolled pattern for asphalt shoulders in terms of audibility and tactility effectiveness, quality control and ease of construction. The corrugated pattern is practical for concrete shoulders. Evidence is presented that existing implementation of policy and design criteria for rolled rumble strips should be modified and that more research is needed to determine the degree of effectiveness.

This study was sponsored by the Traffic Engineering Division at the Virginia Department of Transportation (VDOT).

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INTRODUCTION

The Run-off-the-Road (ROTR) type of accident has become a predominant factor in highway fatalities nationwide since the last decade. According to a recent report from the Department of Motor Vehicles of Virginia,¹ ROTR accidents accounted for 29 percent of all highway fatalities in Virginia from 1986 through 1991. Moreover, statistical data show a significant increase in the last two years of this six year study period. In 1990 and 1991, approximately 50 percent of fatal crashes involved vehicles running off the roadway due to driver fatigue, inattention, excessive speed, use of alcohol or as a result of driver attempting to evade objects and/or nearby vehicles. One study by the Pennsylvania Turnpike Commission² found that ROTR accidents had risen from 48 percent in 1984 to 57 percent in 1986. Another study from Wyoming³ also indicates that more than 60 percent of the fatal accidents involved vehicles that go off the travelways in their state system. These observations have brought a major concern and challenge to the Virginia Department of Transportation (VDOT) and other state agencies. The trend of increase in ROTR accidents demonstrates a need to develop and implement an effective and practical measure to mitigate this type of collision and to improve highway safety.

Rumble strips are warning devices placed on the shoulders or roadways. They are intended to alert the driver with an audible and tactile warning that the vehicle has completely or partially left the traveled way or is approaching a decision point of critical importance to safety. Although rumble strips have been used for many years, they were not widely tested until the last decade. According to a VDOT recent survey,⁴ 34 agencies in the United States have implemented testing sites on highway shoulders, and similar testing programs have occurred in

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countries such as the United Kingdom, Japan and Denmark.

Although rumble strips hold great potential for reducing ROTR accidents and have been widely tested in the United States (for example, one report⁵ claims that on a highway with extremely monotonous conditions, accident reduction as high as 50 percent may be expected by using rumble strips and that about 19 state agencies have been involved in the research of rumble strips since 1985)⁴, the audible and tactile effectiveness of rumble strips have not been quantitatively confirmed because the conclusions in most of the agency reports resulted from small samples and have not gone through statistic tests and/or quality control procedures. There has been particularly a lack of tests on some of the new rumble strip patterns.

Basically, three types of rumble strips are used on the highway shoulders. These include two on asphalt shoulders (rolled type, Figs. 1 and 2 and milled type, Figs. 3, 4 and 5) and one corrugated type (Fig. 6) on concrete shoulders. The rolled type was developed in the 1970's while the milled type is a relatively new pattern that was created in recent years. Most studies and reports are related to rolled rumble strips.⁵ The Pennsylvania Turnpike Commission study² concluded that the milled type is much more practical than the rolled type based on noise level test, but the study does not indicate what the difference is and the tests were limited to the audible effects only. The objectives of this paper are to identify which type of rumble strip is optimal; and to examine quantitatively both the audible and the tactile effectiveness of the different rumble strips.

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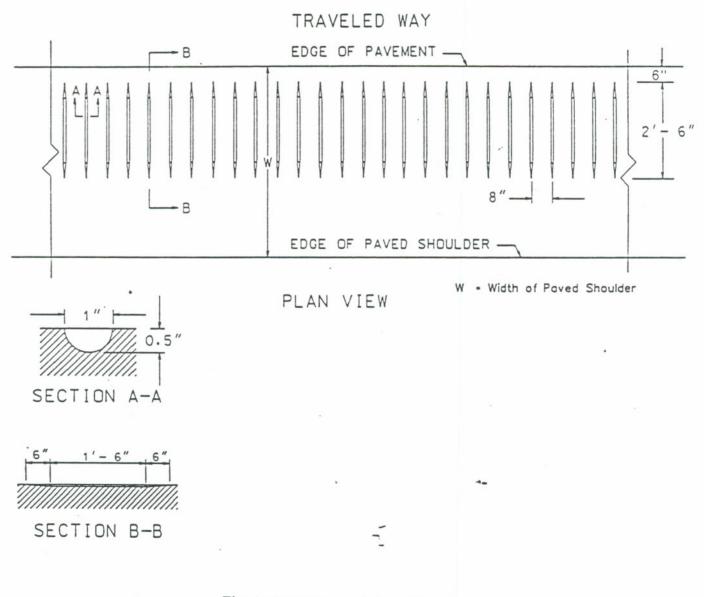


Fig. 1 Continuous rolled rumble strips

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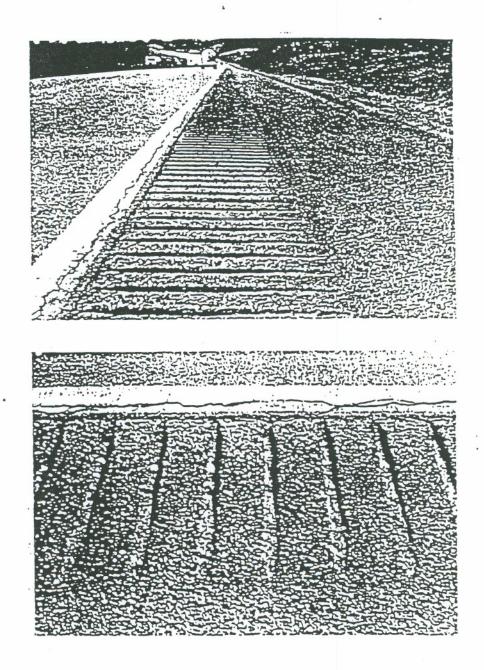
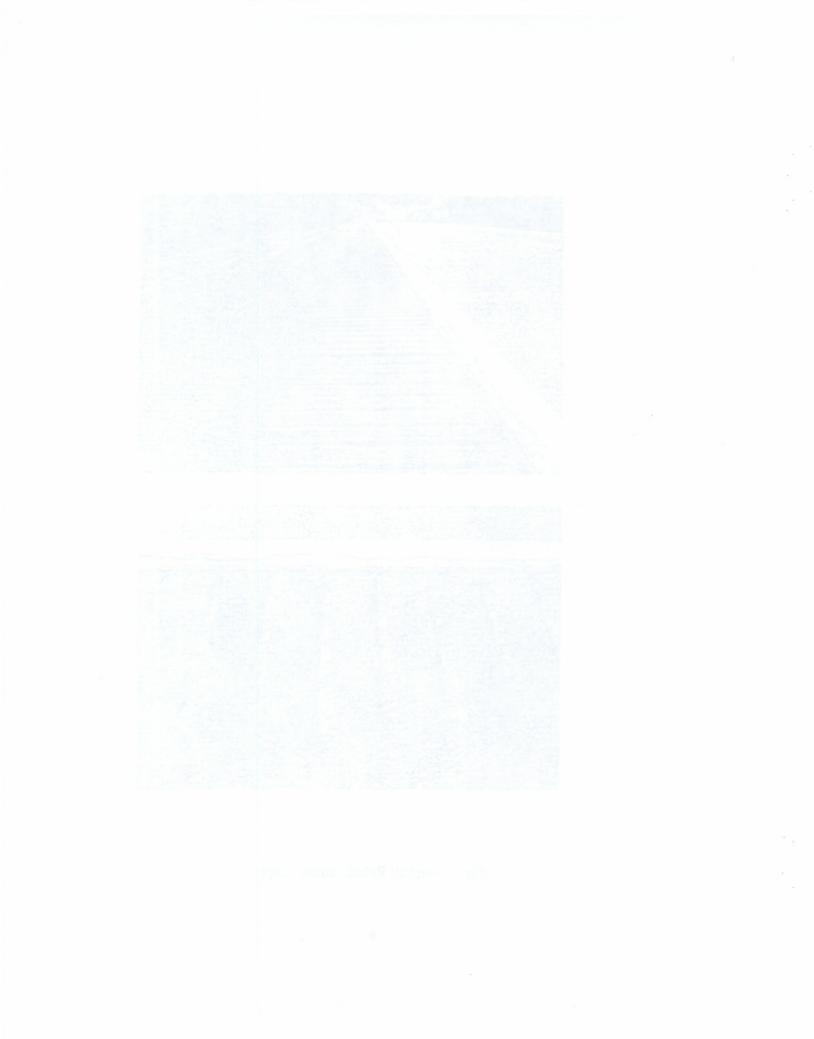


Fig. 2 Asphalt Rolled rumble strips



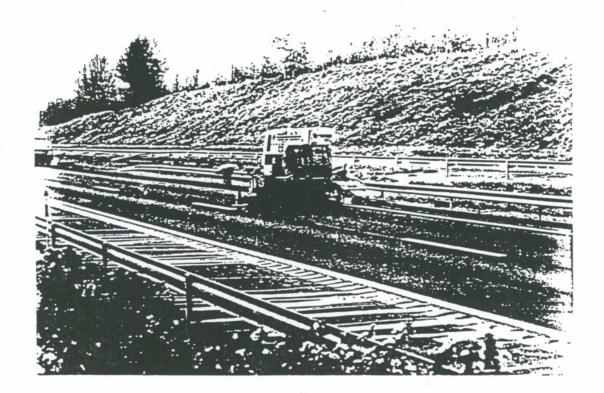


Fig. 3 Milled rumble strips and its construction machine



Fig. 3: Miller Controls and acception of the Control of the Con

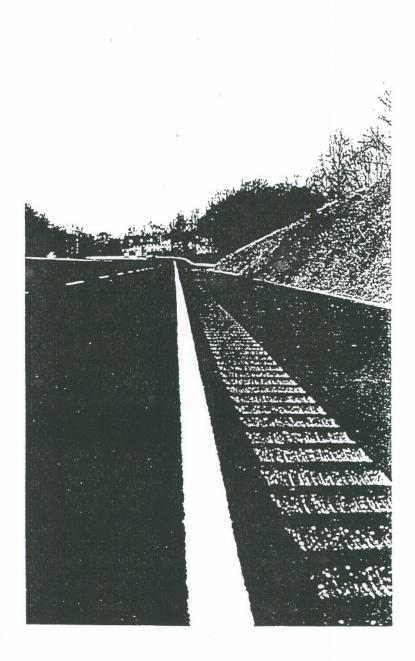
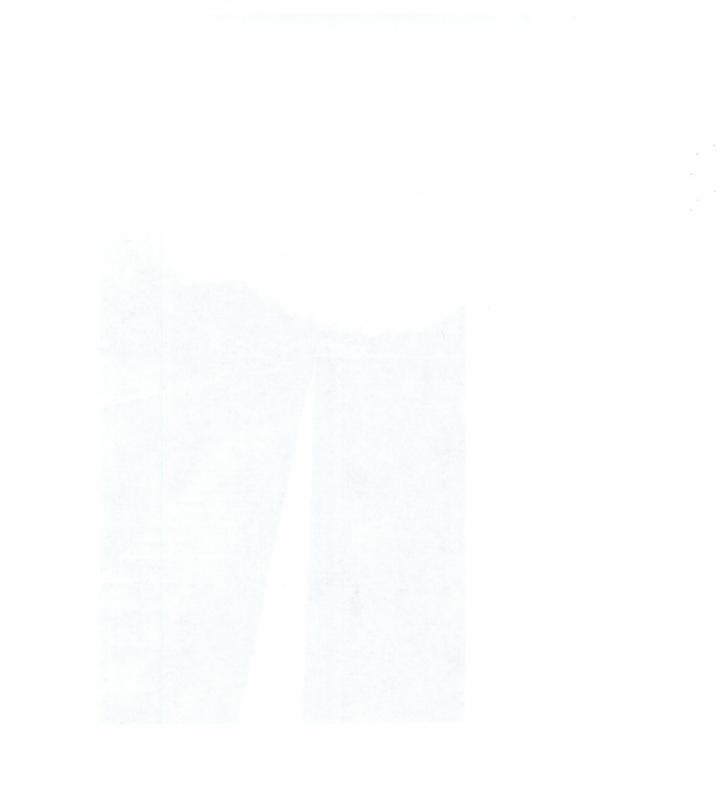
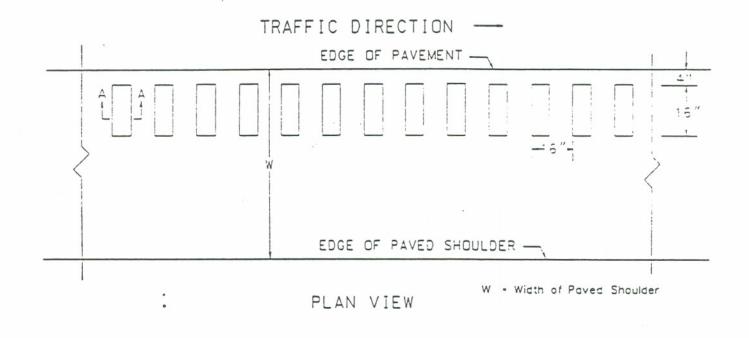
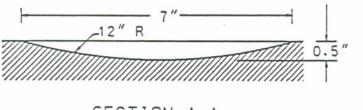


Fig. 4 Continuous Milled rumble strips



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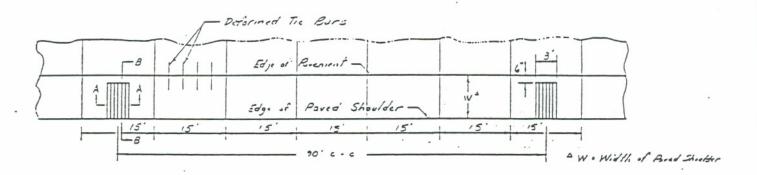
SECTION A-A

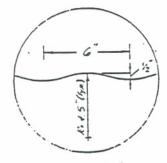
Fig. 5 Asphalt Milled rumble strips

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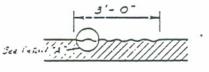
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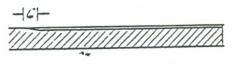


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DETAIL "A"



SECTION A-A



SECTION 8-B

Fig. 6 Concrete Corrugated rumble strips





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RESEARCH PROCEDURE

A combination procedure including field tests, implementation survey from state agencies and mathematical analysis is performed in the study. The optimal design patterns are examined and determined comprehensively by the above approaches.

The overall performance of rumble strips can be found in the following relations:

$$P = f(a_d, a_r, t_d, t_r)_{----} (1)$$

Where P is the effectiveness of rumble strips; a_d is the audible index of traveled ways, a, is the audible index of rumble strips; t_d is the tactile index of traveled ways and t, is the tactile index of rumble strips.

To determine the optimal design pattern P_o , it is necessary to find out the difference between a_d and a_r , and between t_d and t_r . That is, the optimal pattern is a function of excesses of both audible and tactile indexes, not the absolute values of each. This concept can be expressed as below:

 $P_{o} = \Phi [(\bar{a}_{r} - \bar{a}_{d}, \bar{t}_{r} - \bar{t}_{d})]_{-----}$ (2)

Where \bar{a}_r is the sample mean of a_r

 \bar{a}_d is the sample mean of a_d

t, is the sample mean of t,

 \overline{t}_d is the sampel mean of t_d

In order to get the index of a and t and make the data comparable, the following procedures and assumptions are followed:

1. Both audible and tactile tests are performed using a testing van equipped with computerized instruments.

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2. The audible index is measured by a sound level meter and the tactile index is measured by pavement roughness testing instruments. Both are performed and measured at the same locations during the same time periods.

3. It is assumed that the pavement roughness index is the basic indication of vehicle vibration during driving, thus, for the purpose of comparison the tactile index can be deemed to be in proportion to the roughness index.

4. The small differences of testing results between the cars and the testing van can be neglected.

5. The following testing condition are considered as the typical cases for the study.

- Testing rumble strip patterns: continuous asphalt rolled type (Fig. 1); continuous asphalt milled type (Fig. 5) and intermittent concrete corrugated type (Fig. 6)

- Testing speeds: 55 mph and 65 mph

- Angle of ROTR: 5 degrees

- Roadway conditions: Dry and clean

- Testing weather: Sunny

- Testing Time: September and October, 1994, off peak hours of weekdays.

ROUGHNESS TEST

The pavement roughness tests for traveled ways and rumble strips were performed and completed by a computerized roughness testing instrument, and the test results were printed automatically during the tests. Figs. 7 and 8 show typical printout sheets for rolled and milled

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rumble strips. Roughness levels are denoted by IRI (International Roughness Index) in the testing systems. In order to obtain an accurate testing result, the total tests were performed at 112 different locations on I-85 and I-295 in Virginia.

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Fig. 7 Typical computer printout sheet

for rolled rumble strip roughness tests on I-85

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22.000	20.493	1.506	0.11	0.167	369.39	441.07	405.23	

Fig. 8 Typical computer printerout sheet for

milled rumble strip roughness tests on I-85

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The testing locations include:

32 locations for asphalt traveled way tests.

48 locations for asphalt rolled rumble strip tests

20 locations for asphalt milled rumble strip tests

5 locations for concrete traveled way tests

7 locations for concrete corrugated rumble strip tests

In figures 7 and 8, the IRI 1 is the rumble strip index under the case that driver side tires were on the rumble strips. The IRI 2 is the index under the case that passenger side tires were on the rumble strips. The average IRI represents the average of IRI 1 and IRI 2. The top line numbers are for the traveled way pavement and the remaining numbers represent the true IRI records of various testing paths during the tests.

The results of roughness tests at 112 locations on I-85 and I-295 are presented on Table 1.

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No.	Testing Items	Testing Van Speeds (mph)	IRI	Notes
1.	Asphalt Traveled Way	55	73.99	I-85
2.	Asphalt Traveled Way	65	81.11	I-85
3.	Asphalt Traveled Way	65	108.50	I-85
4.	Asphalt Traveled Way	65	123.79	I-85
5.	Asphalt Traveled Way	55	71.17	I-85
6.	Asphalt Traveled Way	65	72.88	I-85
7.	Asphalt Traveled Way	55	74.96	I-85
8.	Asphalt Traveled Way	65	75.35	I-85
9.	Asphalt Traveled Way	65	64.07	I-85
10.	Asphalt Traveled Way	65	62.15	I-85
11.	Asphalt Traveled Way	65	62.15	I-85
12.	Asphalt Traveled Way	65	63.56	I-85
13.	Asphalt Traveled Way	65	63.17	I-85
14.	Asphalt Traveled Way	65	65.23	I-85
15.	Asphalt Traveled Way	65	94.79	I-85
16.	Asphalt Traveled Way	65	101.04	I-85
17.	Asphalt Traveled Way	65	100.67	I-85
18.	Asphalt Traveled Way	65	95.36	I-85
19.	Asphalt Traveled Way	65	104.90	I-85
20.	Asphalt Traveled Way	65	102.52	I-85
21.	Asphalt Traveled Way	65	125.68	I-85
22.	Asphalt Traveled Way	65	127.79	I-85
23.	Asphalt Traveled Way	65	121.60	I-85
24.	Asphalt Traveled Way	65	119.27	I-85
25.	Asphalt Traveled Way	65	124.99	I-85
26.	Asphalt Traveled Way	65	116.66	I-85
27.	Asphalt Traveled Way	65	71.42	I-85
28.	Asphalt Traveled Way	65	69.65	I-85
29.	Asphalt Traveled Way	65	81.66	I-85
30.	Asphalt Traveled Way	65	76.65	I-85
31.	Asphalt Traveled Way	65	72.17	I-85
32.	Asphalt Traveled Way	65	70.31	I-85

Table 1 Testing Results of Pavement Roughness

Table 1 i esting Results of Pavement Roughness

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Table 1 (Con't) Testing Results of Pavement Roughness

No.	Testing Items	Testing Van Speeds (mph)	IRI	Notes
1.	Asphalt, Rolled Rumble Strips	55	90.05	I-85
2.	Asphalt, Rolled . Rumble Strips	55	123.51	I-85
3.	Asphalt, Rolled Rumble Strips	65	87.99	I-85
4.	Asphalt, Rolled Rumble Strips	65	123.47	I-85
5.	Asphalt, Rolled Rumble Strips	. 55	102.27	I-85
6.	Asphalt, Rolled Rumble Strips	55	134.34	I-85
7.	Asphalt, Rolled Rumble Strips	65	116.61	I-85
8.	Asphalt, Rolled Rumble Strips	65	128.13	I-85
9. 10.	Asphalt, Rolled Rumble Strips	55	103.06	I-85
10.	Asphalt, Rolled Rumble Strips	55	134.70	I-85

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No.	Testing Items	Testing Van Speeds (mph)	IRI	Notes
11.	Asphalt, Rolled Rumble Strips	65	102.26	I-85
12.	Asphalt, Rolled			
	Rumble Strips	65	119.50	I-85
13.	Asphalt, Rolled			
	Rumble Strips	65	111.77	I-85
14.	Asphalt, Rolled			
	Rumble Strips	65	133.43	I-85
15.	Asphalt, Rolled			
	Rumble Strips	65	109.43	I-85
16.	Asphalt, Rolled			
	Rumble Strips	65	145.49	I-85
17.	Asphalt, Rolled			
	Rumble Strips	65	109.43	I-85
18.	Asphalt, Rolled			
	Rumble Strips	65	145.49	I-85
19.	Asphalt, Rolled			
	Rumble Strips	65	106.78	I-85
20.	Asphalt, Rolled			
	Rumble Strips	65	142.65	I-85
21.	Asphalt, Rolled	65	100.62	I-85
	Rumble Strips			

Table 1 (Con't) Testing Results of Pavement Roughness

Table I. (Con'). Testing Results of Payerent Roughney.

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Testing Items	Testing Van Speeds (mph)	IRI	Notes
Asphalt, Rolled		1.12	
Rumble Strips	65	143.26	I-85
Asphalt, Rolled	¥		
Rumble Strips	65	108.29	I-85
Asphalt, Rolled			
Rumble Strips	65	155.62	I-85
Asphalt, Rolled			
Rumble Strips	65	123.24	I-85
Asphalt, Rolled			
Rumble Strips	65	146.86	I-85
Asphalt, Rolled			
Rumble Strips	65	124.36	I-85
Asphalt, Rolled			
Rumble Strips	65	142.20	I-85
Asphalt, Rolled		• ag 116	
Rumble Strips	65	97.97	I-85
Asphalt, Rolled			
Rumble Strips	65	130.84	I-85
Asphalt, Rolled			
Rumble Strips	65	96.95	I-85
	Asphalt, Rolled Rumble Strips Asphalt, Rolled Rumble Strips	Speeds (mph)Asphalt, Rolled Rumble Strips65Asphalt, Rolled Rumble Strips65	Speeds (mph)Asphalt, Rolled Rumble Strips65143.26Asphalt, Rolled Rumble Strips65108.29Asphalt, Rolled Rumble Strips65155.62Asphalt, Rolled Rumble Strips65123.24Asphalt, Rolled Rumble Strips65146.86Asphalt, Rolled Rumble Strips65124.36Asphalt, Rolled Rumble Strips65142.20Asphalt, Rolled Rumble Strips6597.97Asphalt, Rolled Rumble Strips65130.84Asphalt, Rolled Rumble Strips65130.84

Table 1 (Con't) Testing Results of Pavement Roughness

Table 1 (Con't) Texing Results of Pavement Roughness

2.5

No.	Testing Items	Testing Van Speeds (mph)	IRI	Notes
1.	Asphalt, Milled Rumble Strip	65	514.28	I-85
2.	Asphalt, Milled Rumble Strip	65	577.11	1-85
3.	Asphalt, Milled Rumble Strip	. 65	449.52	I-85
4.	Asphalt, Milled Rumble Strip	65	530.89	I-85
5.	Asphalt, Milled Rumble Strip	. 65	455.63	I-85
6.	Asphalt, Milled Rumble Strip	65	425.46	I-85
7.	Asphalt, Milled Rumble Strip	. 65	652.34	I-85
8.	Asphalt, Milled Rumble Strip	65	539.10	I-85
9.	Asphalt, Milled Rumble Strip	65	594.37	I-85
10.	Asphalt, Milled Rumble Strip	65	507.52	I-85
11.	Asphalt, Milled Rumble Strip	65	558.19	I-85
12.	Asphalt, Milled Rumble Strip	65	491.73	I-85
13.	Asphalt, Milled Rumble Strip	65	579.93	I-85

Table 1 (Con't) Testing Results of Pavement Roughness

Table 1 (Con't) Te that kesults of Perement Roughness

		ne state stiller Aumus Surp	

No.	Testing Items	Testing Van Speeds (mph)	IRI	Notes
14.	Asphalt, Milled Rumble Strip	65	552.70	I-85
15.	Asphalt, Milled Rumble Strip	65	547.14	I-85
16.	Asphalt, Milled Rumble Strip	65	537.05	I-85
17.	Asphalt, Milled Rumble Strip	65	486.89	I-85
18.	Asphalt, Milled Rumble Strip	65	576.22	I-85
19.	Asphalt, Milled Rumble Strip	65	522.23	I-85
20.	Asphalt, Milled Rumble Strip	65	567.37	I-85

Table 1 (Con't) Testing Results of Pavement Roughness

Table 1 (Con'i) Counte Results of Pavoment Koughness

No.	Testing Items	Testing Van Speeds (mph)	IRI	Notes
		÷		
1.	Concrete Traveled Way	65	134.20	I-295
2.	Concrete Traveled Way	55	134.58	I-295
3.	Concrete Traveled Way	65	145.32	I-295
4.	Concrete Traveled Way	55	139.52	1-295
5.	Concrete Traveled Way	55	119.84	I-295

Table 1 (Con't) Testing Results of Pavement Roughness

Table 1 (Cont) (County Results of Farmers

No.	Testing Items	Testing Van Speeds (mph)	IRI	Notes
1.	Concrete Corrugate Rumble Strip	65	205.43	I-295
2.	Concrete Corrugate Rumble Strip	65	205.28	I-295
3.	Concrete Corrugate Rumble Strip	65	175.57	1-295
4.	Concrete Corrugate Rumble Strip	65	179.92	I-295
5.	Concrete Corrugate Rumble Strip	65	186.44	I-295
6.	Concrete Corrugate Rumble Strip	65	185.15	I-295
7.	Concrete Corrugate Rumble Strip	65	186.44	I-295

Table 1 (Con't) Testing Results of Pavement Roughness

Table 1. ((on)) - Tenny Results of Pavenness coupt new

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SOUND LEVEL TESTS

The sound level test results are shown in Table 2.

Tests for the effects of rumble strips on vicinity environments were also performed during the testing period. The tests included a comparison of the sound levels between the case 1 of testing van driving on the milled rumble strips and case 2 of typical truck driving on the asphalt traveled way. Operational speeds were 65 mph and the sound levels were measured 200 feet away from the roadway edges. The readings were 60 decibels and 69 decibels for case 1 and case 2 respectively.

SOUND LEVEL TESTS

The regrit level fee recipies the wown in Table C

No.	Testing Items	Testing Van Speeds (mph)	Sound Level (In decibels)	Notes
				-
1.	Asphalt Traveled Way	65	75	I-85
2.	Asphalt Traveled Way	65	75	I-85
3.	Asphalt Traveled Way	65	75	I-85
4.	Asphalt Traveled Way	65	75	I-85
5.	Asphalt Traveled Way	65	76	I-85
6.	Asphalt Traveled Way	65	74	I-85
7.	Asphalt Traveled Way	65	76	I-85
8.	Asphalt Traveled Way	65	74	I-85
9.	Asphalt Traveled Way	65	76	I-85
10.	Asphalt Traveled Way	65	76	I-85
11.	Asphalt Traveled Way	65	74	I-85
12.	Asphalt Traveled Way	65	74	I-85
1.	Asphalt Rolled Rumble Strips	55	7,9	I-85
2.	Asphalt Rolled Rumble Strips	65	76	I-85
3.	Asphalt Rolled Rumble Strips	55	74	I-85
4.	Asphalt Rolled Rumble Strips	65	77	I-85
5.	Asphalt Rolled Rumble Strips	55	74	I-85

 Table 2
 Testing Results of Sound Levels of Pavements

Table 2 Tosting Results of Sound Levels of Pavements

	65	

No.	Testing Items	Testing Van Speeds (mph)	Sound Level (In decibels)	Notes
6.	Asphalt Rolled Rumble Strips	55	77	I-85
7.	Asphalt Rolled Rumble Strips	65	76	I-85
8.	Asphalt Rolled Rumble Strips	65	77	I-85
9.	Asphalt Rolled Rumble Strips	65	76	I-85
10.	Asphalt Rolled Rumble Strips	65	76	I-85
11.	Asphalt Rolled Rumble Strips	65	78	I-85
12.	Asphalt Rolled Rumble Strips	65	78	I-85
13.	Asphalt Rolled Rumble Strips	65	78	I-85
14.	Asphalt Rolled Rumble Strips	65	78	I-85
15.	Asphalt Rolled Rumble Strips	65	. 78	I-85
16.	Asphalt Rolled Rumble Strips	65	78	I-85
17.	Asphalt Rolled Rumble Strips	65	78	I-85
18.	Asphalt Rolled Rumble Strips	65	78	I-85

Table 2 (Con't) Testing Results of Sound Levels of Pavements

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No.	Testing Items	Testing Van Speeds (mph)	Sound Level (In decibels)	Notes
19.	Asphalt Rolled Rumble Strips	65	78	I-85
20.	Asphalt Rolled Rumble Strips	65	78	I-85
21.	Asphalt Rolled Rumble Strips	65	79	I-85
22.	Asphalt Rolled Rumble Strips	65	78	I-85
23.	Asphalt Rolled Rumble Strips	65	78	I-85

Table 2 (Con't) Testing Results of Sound Levels of Pavements

Table 2 (Gorit) Texnig Results of Sound Levels of Povenents

No.	Testing Items	Testing Van Speeds (mph)	Sound Level (In decibels)	Notes
1.	Asphalt Milled			
1.	Rumble Strips	65	86	I-85
2.	Asphalt Milled Rumble Strips	65	86	I-85
3.	Asphalt Milled Rumble Strips	65	86	I-85
4.	Asphalt Milled Rumble Strips	65	86	I-85
5.	Asphalt Milled Rumble Strips	65	85	I-85
6.	Asphalt Milled Rumble Strips	65	86	I-85
7.	Asphalt Milled Rumble Strips	65	86	I-85
8.	Asphalt Milled Rumble Strips	65	86	I-85
1.	Concrete Traveled Way	55	76	I-295
2.	Concrete Traveled Way	65	79	I-295
1.	Concrete Corrugate Rumble Strips	55	83	I-295
2.	Concrete Corrugate Rumble Strips	65	86	I-295

Table 2 (Cont') Testing Results of Sound Levels of Pavements

Table 7 (Cost) To may Result of Strind Levels of Parenteets

THEORETIC ANALYSIS OF TIRE DROPS

The comparisons of car tire drops between milled and rolled rumble strips can be calculated as shown below.

In the U.S. the diameter of most car tires is 24 inches. When the car speed is equal or lower than the critical speed V_d , the tire drops of cars are the functions of the widths of grooves.

(1) For milled rumble strips (Fig. 9)

From Fig. 5, the groove width is 7 inches, and the depth is 1/2 inches, thus

 $Y = (12^2 - 3.5^2)^{1/2} = 11.48$ inches

 $\Delta y = 12-11.48 = 0.52$ inches > 0.5 inches

Therefore, the tire will drop into the bottom of groove.

(2) For rolled rumble strips (Fig. 10)

From Fig 1. the width is 1 inches and depth is 0.5 inches,

 $y = (12^2 - 0.5^2)^{\frac{1}{2}} = 11.99$ inches $\Delta y = 12 - 11.99 = 0.01$ inches < 0.5 inches

Therefore, the tire will not drop into the bottom of groove. Actually, when the car speeds are higher than V_d , the tire drops are smaller than the above computed numbers.

THEORETIC ANALYSIS OF TIRE DROPS

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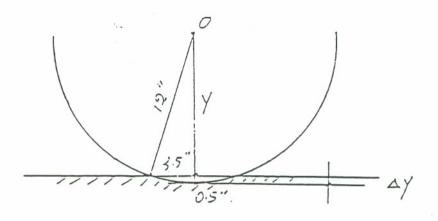


Fig. 9. Tire drops for milled rumble strips

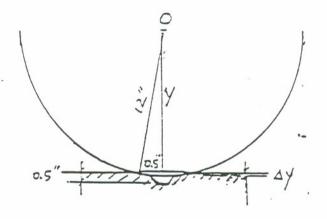


Fig. 10. Tire drop for rolled rumble strips



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The theoretic analysis reveals that the differences between the tire drops for the rolled and milled rumble strips vary by 50 times for speeds less than V_d . For speeds higher than the critical speed, such as 55 or 65 mph, the drops will be less than the computed numbers. However, the difference is still significant based on field observations. A special test is needed to determine the precise drops.

FINDINGS OF FIELD TESTS

The final results for both the roughness tests and sound level tests on I-85 and I-295 are tabulated in Table 3. Based on the Concept Shown on equation (2), the findings of tests can be summarized below:

(1) For the roughness tests, the excesses are 32.6%, 54.5% and 444.6% for comparisons between rolled rumble strips and traveled way, corrugate rumble strips and traveled way as well as milled rumble strips and traveled way respectively. Thus, the milled rumble strip excess IRI is 1260% or 12.6 times more than that of rolled rumble strips and that the milled rumble strip excess is 716% or 7.16 times more than that of corrugated rumble strips.

(2) For sound level tests under 65 mph, the sound excesses are 2.5 decibels, 7 decibels and 10.87 decibels for comparisons between rolled rumble strips and traveled way, corrugated rumble strips and traveled way as well as milled rumble strips and traveled way respectively. Thus, for the sound excess levels, the milled rumble strips excess is 335% or 3.35 times more than that of rolled rumble strips and the milled rumble strips excess is 55.3% or 0.553 times more than that of corrugated rumble strips.

The theoretic analysis reveals that the differences between the tirk drops for the roted and milled numble strips vary by 50 times for speeds less than v_a. For speeds higher than the crutcal speed, such as 20 milled and milled strips vary by 50 times for speeds less than v_a. For speeds higher than the crutcal speed, such as 20 milled and milled strips vary by 50 times for speeds less than v_a. For speeds higher than the crutcal speed, such as 20 milled and milled strips vary by 50 times for speeds less than v_a. For speeds higher than the crutcal speed, such as 20 milled and the crutcal speed strips are speeds with the speed strips of the crutcal speed speed strips are speed as a special time the computed to the crutcal speed strips of the crutcal speed speeds less the computed times is reached to determine the crutcal speed speeds less three times the computed times is reached to determine the crutcal speed special times are special times.

The fractive plat for both the coughtast tests and sound level tests on 1-65 and 1-14, are substand in Table 31. Based on the Cohorpi Shrivin on equation (2), the findings of tests with tests with tests to be belia.

(E) For the foughtness term. The excession are 12 eV, 50 2 is consistent 68 for an quartering term of a reliable strips and neveled way, consequences in this veries and an visit very as well as million of the strips and an visit and a strips of the strips and an visit and the strips and termination of the strips of the strips and termination of the strips and termination of the strips of the strips and termination of the strips of the strips and termination of the strip as well as million of the strips are strips and termination of the strips of the strips and termination of the strips are strips.

(2. Non-sound level tests under als mpli, its travel as ever up 0.5 decideds [1] estimate and [1] [2] decideds for comparisons between relied numble strips and traveled way, coin queel families whereast travelet relation will as man to religit of the sint (naveled way) espectively. (And, 30) the nonext recess levels, the utilied travelet strips access in 135% or 0.5% then using the traveled to be strips and the indefinition strips access is 5% or 0.5% there man that the ofference travelet surps.

Table 3 Summary of Field Tests

Testing Items	Means of Roughness (In IRI)				Means of Sound Levels (In dB)								
					55	mph				65 mj	ph		LOCATIONS
	Travel Way	R.S.	Excess	% Increase	Travel Way	R.S.	Excess	% Increase	Travel Way	R.S.	Excess	1 Increase	
 Roll/Travelway (Asphalt) 	88.72	121.3	32.6	36.7%	72	75	3	48	75	77.5	2.5	3.33%	I-85
 Mill/Travelway (Asphalt) 	88.72	533.28	444.6	501%					75	85.87	10.87	14.5%	I-85
• Mill/Roll (Asphalt)				1263%								335%	I-85
 Corrugated/ Travelway (Concrete) 	134.69	189.2	54.5	40.5%	76	83	7	9.2%	79	86	7	8.86%	I-295
<pre>Mill/ Corrugate (Asphalt)</pre>				716%								55.3%	I-295 I-85
• Enviro Effects			,						69 Truck	60 Van	9	-13%	I-85 200 ft away f Roadway

(For Roughness, Sound Levels and Environmental Effects)

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(3) Field test results show that the roughness indexes are not sensitive for speeds but sensitive for sound levels. The faster the speed, the higher the sound index.

(4) The percentage increases of IRI are 36.7%, 40.5% and 501% for comparisons of rolled rumble strips and traveled way, corrugate rumble strips and traveled way as well as milled rumble strips and traveled way respectively.

(5) The effects of noise resulting from rumble strips on freeway shoulders can be ignored.

FINDINGS FROM VDOT SURVEYS

According to the VDOT "Survey for Rumble Strip Implementations,"⁴ 14 state agencies have tested or installed milled rumble strips. The survey revealed that an increasing number of agencies have adopted or favor the milled rumble strip although some performance differences between both are still not clear. The prime reasons are as below:

- The quality of rolled type is difficult to control in the field, which will lower the B/C ratio.
- The effectiveness for both sound levels and vibration levels for the rolled type are much less than that of the the milled type.
- The construction time is very limited and not easy to handle.
- Rolled rumble strips have very little effect on trucks.

CONCLUSIONS AND RECOMMENDATIONS

Field tests for pavement roughness and sound levels on various typical rumble strips indicate

(c) factor tech constructions from on the one totaget area structures and not beneficiate fait specific cut wainstitue for sound fevericit. Fractizated the specificitie togeteenther second and as

(a) The according to increases of IPI and 06.735 40.538 and 501°C introcomparistence control of the second structure increases of IPI and 05.758 and traveled way as we'll as million relation structs and traveled way as we'll as million relationship and traveled way as we'll as million relationship.

(2) The streets of doite resulting from threlds staps on freeway choulders can be ignored.

EDDINGS FROM VIDT SERVICYS

*Loomonia to the NOCC *Survey the Romble Strip Implementations," 14 mile against the control of a casualled in Clerk remains wright. The servey research that an interacting constant of spectral cases for a standard or the or the suffect straight withough some performance lifth controls between both are written or clear. The property of the area to ball to be to be formation of the controls.

- 3. If non-sector there are a subscription of eachier interfaced in mathematic process and it.
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- The electroment for hore social levels and vibration, fively for the collect one are unit is loss that when its in unified read.
 - The construction time is yes? Instead and not easily of families.
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that the optimal design pattern is the milled rumble strip. The differences between milled type and rolled type reach 12.6 times and 3.35 times for the excesses of the roughness IRI and sound levels respectively. A recent VDOT survey from 18 state agencies also conclude that rolled type has had some disadvantages such as quality control, lower effectiveness, limited construction time and weak effects on truck operation in implementation. The effects of speeds are not sensitive for their roughness index but are sensitive for sound levels. The environmental effects of noise resulting from freeway rumble strips can be ignored, as its reading is always lower than the sound level resulting from a truck running on the traveled way. For designing the rumble strips, the groove width is the critical factor for the rolled type, and the groove length for milled type may need to be extended to increase the warning time of the ROTR vehicles. The policy and the criteria for existing rolled rumble strips do need some modifications and research. (i) Construction in the second structure of the constructure of the construction of the constructure of

ACKNOWLEDGEMENTS

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